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# Analysis and optimization of underground thermal energy storage using depleted oil wells

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ABSTRACT

Underground thermal energy storage (UTES) is an important technology to utilize the industrial waste heat and the fluctuating renewable energy. This paper proposed a new deep UTES system by using single depleted oil well (DOW), and the coaxial borehole heat exchanger with insulation is introduced to retrofit the DOW for seasonal TES. At first, a comprehensive model combing wellbore and formation heat transfer was built, evaluating the performance of heat storage in summer and space heating in winter. Monte Carlo method was used for parameters sensitivity analysis, to obtain the correlation between storage efficiency and five influence parameters. The results indicated that inlet temperature showed the strongest influence on the storage efficiency. By the optimal design, it was found that for an existing heat source, there was an optimal well depth to obtain maximum storage efficiency. During the annual operation, total heat storage for the DOW with depth of 2000 m was about $4.7 \times 10^6$ MJ and total heat extraction was about $2.9 \times 10^6$ MJ more than $8 \times 10^5$ MJ from that without previous heat storage progress. Consequently, the DOW-UTES system could be used to implement seasonal heat storage or waste heat recovery in summer to provide space heating in winter.



## 1. Introduction

Thermal energy storage (TES) is an innovative technology for thermal management and utilization, especially for seasonal solar energy storage and waste heat recovery. The advantage of TES system is mainly to reduce the imbalance between the demand and the supply of thermal energy, thereby improving the thermal-economic performance of the system [1,2]. As an important TES technology, underground thermal energy storage (UTES) uses the ground to store heat and cold. Determined by the geological, hydro geological and other conditions, the UTES systems mainly are divided into ATES (aquifer TES) [3,4], BTES (boreholes TES) [5,6] and CTES (cavern TES) [7,8]. In ATES systems, groundwater of aquifer is used to store thermal energy, and the groundwater is injected into and extracted out from a number of water wells. BTES system is equipped with the borehole heat exchanger (BHE) to store thermal energy in solid medium surrounding the closely spaced boreholes. CTES systems utilize underground cavern to store heat from hot water or compressed gas. ATES and BTES have been applied commercially today, and BTES systems are the most commonly used among of the three systems, especially application in geothermal source heat pump (GSHP) [9,10].

For most of BHE, the depth of boreholes is between 50 and 200 m, and the ground temperature is usually below 25 °C, which is called shallow BHE [2,11]. Due to the depth limit, the less geothermal resource can be achieved, causing to that in GSHP system, for achieving enough spacing heating or cooling rate, amount of energy piles (boreholes) are required, even up to a few hundred boreholes. Therefore, the shallow BHE systems are well suited to supply heat to smaller, decentralized applications, such as: like single family and multifamily dwellings, as well as some institutional and commercial facilities [12,13]. However, for the waste heat source from thermal power stations or solar panels in summer, the supply temperature is even higher than 90 °C and more heat need to be removed, if using the shallow BHE for high-temperature heat storage, more boreholes and larger surface area will be required. Based on this background, the deep BTES system as well as deep BHE is concerned recently for utilizing the high-temperature heat source [14–17]. Also, many deep BHE projects were implemented in Germany, Switzerland and other countries which require less space at the surface, especially show advantage

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**Nomenclature**

*Variables*

| | |
|---|---|
| $a$ | geothermal gradient, K $m^{-1}$ |
| $A_i$ | inner pipe area, $m^2$ |
| $A_o$ | outer pipe area, $m^2$ |
| dQ/dz | heat flux from formation, W $m^{-1}$ |
| $dQ_{io}/dz$ | heat flux from inner pipe to out pipe area, W $m^{-1}$ |
| $d_e$ | feature size of pipe, m |
| *ds1* | inner pipe thickness, m |
| *ds2* | puter pipe thickness, m |
| $E_h$ | storage efficiency, % |
| $f$ | two-phase friction factor, dimensionless |
| $f(t)$ | transient heat conduction function, dimensionless |
| $H$ | total well depth, m |
| $h_{in}$ | inlet fluid enthalpy, kJ $kg^{-1}$ |
| $h_{out}$ | outlet fluid enthalpy, kJ $kg^{-1}$ |
| $h_f$ | convective heat transfer coefficient, W $m^{-2}$ $K^{-1}$ |
| $m$ | mass flow rate, kg $s^{-1}$ |
| $M$ | volume flow rate $m^3$ $h^{-1}$ |
| $Q_e$ | heat extraction rate, W |
| $Q_s$ | heat storage rate, W |
| $r_1$ | inner radius of inner pipe, m |
| $r_2$ | inner radius outer pipe radius, m |
| $r_h$ | radius of wellbore wall, m |
| $T_e$ | earth temperature, °C |
| $T_{ei}$ | initial earth temperature, °C |
| $T_{fi}$ | fluid temperature in inner pipe, °C |
| $T_{fo}$ | fluid temperature in inner pipe, °C |
| $T_h$ | wellbore wall temperature, °C |
| $U_o$ | heat transfer coefficient W/($m^2$ K) |
| $v$ | fluid velocity, m/s |
| $z$ | well depth, m |

*Greek letters*

| | |
|---|---|
| $\alpha_e$ | thermal diffusivity of the formation, $m^2$ $s^{-1}$ |
| $\lambda_{cas}$ | casing thermal conductivity, W $m^{-1}$ $K^{-1}$ |
| $\lambda_{cem}$ | cement thermal conductivity, W $m^{-1}$ $K^{-1}$ |
| $\lambda_e$ | formation thermal conductivity, W $m^{-1}$ $K^{-1}$ |
| $\rho$ | density, kg $m^{-3}$ |
| $\rho c$ | volumetric specific heat capacity, J $m^{-3}$ $K^{-1}$ |
| $\tau$ | injection time,h |
| $\tau_D$ | dimensionless time |

in densely populated urban areas. Sapinska gave a good survey for the projects [12], for example, the borehole of RWTH-1 in Aachen of Germany is 2500 m deep used to direct heating of the building and cooling the building by an adsorption unit; the borehole depth for well Jachówka 2 K in Sucha Beskidzka (Poland) is up to 4281 m used to test the possibility of using the hole as deep BHE [12].

Whether in shallow system or deep system, the BHE is the most important unit in BTES system, and the heat transfer and thermal performance of BHE has been investigated by many researchers [18–21]. Based on the studies of BHE heat transfer, Kohl [22] turned to focus on the deep BHE system, a project at Weggis in Switzerland for space heating was concerned and the borehole derived from an abandoned oil well with depth of about 2300 m. It was concluded that the specific yield of deep systems was much higher than in conventional shallow BHE systems. Le Lous investigated the thermal performance of a coaxial BHE with 5000 m deep [15], they found that over 25-year periods of operation, the potential installed capacity could arrive at approximately 125–600 kW. Holmberg [16] give a chart of heat load for the coaxial BHE with depths from 300 to 1000 m, the chart was suggest guiding sizing deep BHE installations. Wang [17] investigated a deep GSHP system, and three deep boreholes with depth of 2000 m were instrumented in a special project. The experiment showed that the average heating capacity of each borehole was 286.4 kW and the COP of heat pump unit could reach to 6.4. Apart from spacing heating by deep BHE, Bär tended to evaluate the performance of thermal energy storage using the medium deep BHE with completion depth of about 100m-1000 m [14]. They concluded that using the medium deep BTES with high-temperature source from renewable energy or waste heat could be a very promising approach for space heating and cooling. Schulte et al. [23] presented an optimal method to design geometry array of medium deep BHE for TES, the depth of BHE was concerned from 100 m to 500 m. Welsch [24] investigated the characteristics of deep BTES for seasonal energy storage, the simulation results showed that 83% of the heat storage in summer could be extracted from the deep BTES system in winter.

However, although the deep BTES systems are characterized with larger storage capacity with fewer boreholes, the utilizations of deep BTES systems seem to be put into practice rarely and are limited to simulation. It is mainly because of the high-cost drilling of boreholes and the drilling cost increases sharply with the depth [24]. It was found that the average cost for drilling a borehole to depth of about 3000 m in Poland was 5 million USD [12]. Especially, the statistics shows that the cost of drilling even can occupy 50% of the total cost of the geothermal project [25]. Obviously, using the abandoned oil well as a deep borehole can cut off the cost of drilling, and the investments for their retrofit would just be limited to eventual cleaning out and completion of a BHE. It was reported that the costs for adaptation of abandoned well to a deep BHE was 200000 Euro [12].

Statistics shows that about 20–30 millions oil wells have been abandoned around the world when oil reservoir is depleted without economic feasibility [26]. In recent years, many researchers focused on the utilization of geothermal energy from abandoned well [25]. Kujawa et al. [27] introduced a coaxial BHE to extract heat from surrounding rocks of abandoned well. The retrofitted system was closed loop where working fluid circulates in coaxial BHE, without extracting groundwater from stratum; it can avoid groundwater recession, corrosion and scaling problems. Davis and Michaelides [28] firstly evaluated power generation by a simple Rankine cycle using the retrofitted DOW system. Bu et al. [29] considered the transient heat transfer in surrounding rock of DOW for power production, and the 2-D rock temperature distributions was given. Ebrahimi and Torshizi [30] performed a parametric optimization of the ORC for power generation using AOW; R125 was chosen as the optimal working fluids. Cheng [31] examine the effect of formation heat transfer on geothermal production and power generation from AOW; they also studied on the optimization of working fluids for different power generation system using abandoned wells [32]. Mokhtari [33] implemented economic and exergy analysis to optimize the DOW power generation system, the economic analysis showed that the price of electricity produced by using DOW was generally less than about 0.03 $/kWh [25]. Considering the insufficient power generation efficiency using the DOW, Nian [34] turned to study on the space heating for direct utilization of geothermal energy in DOW, it concluded that the maximum heating cost by using DOW was about half of that by conventional heating method.