COMPREHENSIVE REVIEW ON THE APPLICATION PROGRESS OF SHALLOW GEOTHERMAL ENERGY UTILIZATION AND ARTIFICIAL NEURAL NETWORK IN DETECTION TECHNOLOGY

by

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Shallow geothermal energy refers to geothermal resources within 200 m below the surface, which has the advantages of stable temperature, strong sustainability, environmental protection and economy, and has been widely used by residents in various regions since ancient times. With the acceleration of industrialization and urbanization and the further expansion of human demand for energy, the development and utilization of shallow geothermal energy has gradually moved from the surface to the deep. In this process, researchers have conducted in-depth research on geothermal energy heat exchange equipment, temperature measurement and other technologies, and introduced artificial intelligence to predict underground temperature and humidity, and made a lot of progress. Focusing on the ground source side of shallow geothermal energy, this paper comprehensively expounds the research progress in the past 10 years from the aspects of the observability of geothermal energy utilization, the thermal response testing technology of buried pipe, the heat transfer model and the application of artificial intelligence, summarizes the difficulties at this stage, and points out the direction of future solutions.

Key words*: shallow geothermal energy, thermal response test,
artificial neural network, numerical simulation*

Introduction

The geothermal energy utilization can be traced back to ancient civilizations, with early applications primarily focused on surface hydrothermal resources due to technological limitations. Ancient India and pre-Columbian America employed geothermal springs for religious rituals and therapeutic purposes [1], while ancient Rome pioneered commercialized thermal bath operations [2]. In ancient China, geothermal springs were not only utilized for medical rehabilitation (*e.g.*, Huaqing Pool and Xiaotangshan) but also extended to agricultural production (hot water irrigation) and daily domestic uses (cooking and washing). The surge in energy demand following the Industrial Revolution and growing environmental concerns over fossil fuels propelled geothermal energy - recognized for its cleanliness and sustainability – into a phase of large-scale development since the mid 20th century [3].

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National geothermal development capacity is intrinsically linked to resource endowment. The spatial distribution of geothermal resources exhibits distinct tectonic correlations: high temperature resources (150-350 °C) predominantly concentrate along four major plate boundaries (Mediterranean-Himalayan, Red Sea-East African Rift, Circum-Pacific, and Mid-Atlantic), while medium-low temperature resources (<150 °C) are widely distributed within intraplate regions. Countries situated in geothermal belts typically possess diversified geothermal resources, particularly abundant high temperature reserves, which explains why current leading geothermal power producers are predominantly located in these tectonic active zones.

As of 2020, geothermal power generation has been implemented in 46 countries worldwide, with total output reaching 95095.80 GWh [4]. The USA (18366 GWh) [5], Indonesia, and Philippines constitute the top three producers, represented by iconic facilities such as The Geysers in California [6], Gunung Salak in Indonesia, and Tiwi/Tongonan fields in Philippines [7, 8]. European countries are accelerating deployment, exemplified by Germany's operational 37 geothermal plants and planned 16 cogeneration facilities, demonstrating sustained expansion in geothermal development, fig. 1. China's geothermal power generation shows relatively sluggish growth, with 2020 output reaching merely 174.60 GWh (0.184% of global total). The concentration of high grade geothermal resources in western mountainous regions with harsh environmental conditions presents significant development challenges. Consequently, exploitation of low grade shallow geothermal energy has become a strategic priority for China's future geothermal development.

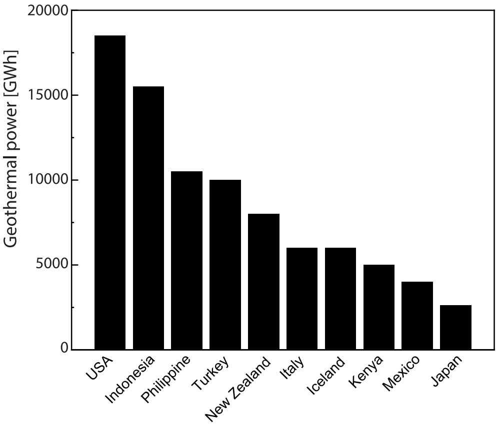

Figure 1. Global geothermal power generation ranking in 2020

Beyond power generation, geothermal energy demonstrates extensive direct applications spanning space heating/cooling, industrial/agricultural operations, and therapeutic uses [9]. As documented at the 2020 World Geothermal Congress, the number of countries/regions adopting direct geothermal utilization expanded dramatically from 28 in 1995 to 88 by 2020 [10]. The global installed capacity for direct geothermal utilization attained an aggregate of 108 GW by 2020, demonstrating a 52% expansion from 2015 levels through accelerated technological adoption and policy-driven market penetration, with China leading the ranking followed by the United States, Sweden, Germany, and Turkey, fig. 2.

Research status of thermal response test of GSHP buried pipe

Ground heat exchanger (GHE), serving as the core units in ground source heat pump (GSHP) systems, facilitate energy exchange between mechanical units and soil, with their performance critically determining system operational efficiencyand constituting, alongside drilling engineering, the primary initial investment cost. Given the fundamental dependence of GSHP design on subsurface thermal environments, accurate determination of thermophysical parameters (thermal conductivity, thermal diffusivity*, etc.*) in geological formations forms the essential technical foundation for efficient building geothermal system applications. Current thermal conductivity measurement techniques bifurcate into laboratory-based and in-situ approaches, fig. 3.

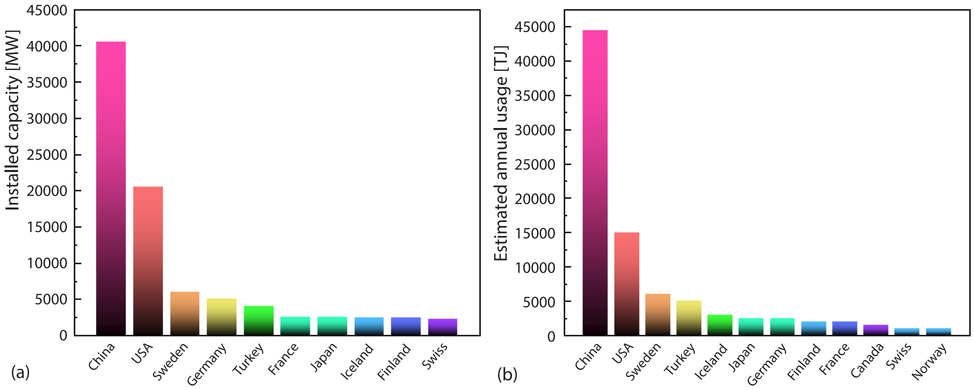

Figure 2. World geothermal energy installed capacity and utilization ranking in 2020; (a) installed capacity [MW_t] and (b) estimated annual usage [TJ]

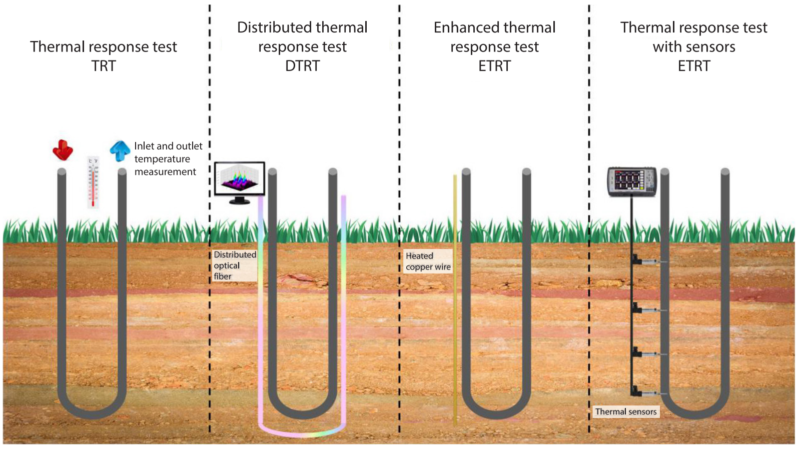

Figure 3. Common thermal response test methods

Laboratory analyses employ steady-state/transient methods: needle probe, guarded hot plate*, etc.* [11-13], to examine retrieved soil/rock samples, yet parameter distortion frequently occurs due to temperature/humidity variations during sample transportation, rendering results merely approximate estimations of formation thermal properties.

Thermal response testing has undergone significant technological evolution from Mogensen's (1983) conventional TRT method [14], which determines formation thermal properties through inverse modelling of heat exchanger fluid temperatures but suffers from inherent limitations due to its exclusive reliance on inlet/outlet measurements. The breakthrough came with Acuña's integration of distributed temperature sensing (DTS) technology, establishing distributed thermal response testing (DTRT) [15] as a superior methodology that enables comprehensive borehole performance evaluation through continuous fiber-optic temperature profiling. This advancement has spawned numerous applications including Freifeld's innovative 1-D thermal conductivity inversion [16], Fujii's detailed analysis of 60 m deep *U*-tubes, and Acuna's revealing multi-flowrate experiments [17], all supported by sophisticated theoretical frameworks developed by Beier (coaxial/*U*-tube models) [18] and Sakata (multilayer conceptual framework) [19]. While representing a major leap forward, current DTRT implementations still face challenges related to standardization and interpretation uncertainties. The subsequent development of enhanced TRT (ETRT) combined DTRT principles with linear heat source systems, with Zhang's [20] copper-mesh composite heating cables. The marking a significant engineering advancement, though the approach remains constrained by copper's temperature-dependent resistance and subsurface heterogeneity. Parallel research efforts have explored alternative sensor-based solutions, exemplified by Zhang's comprehensive 26 sensor array deployment [21] and Zhao's multi-depth measurement system, fig. 4 [22], which offer improved stratigraphic resolution but introduce new challenges including fluid interference and complex installation requirements. After prolonged operation of the heat pump, soil heat accumulation becomes a significant negative impact on reducing the system's COP [23]. Wang and Han [24, 25] developed control models suitable for multi-energy coupled heat pump systems, which mitigates the issue of soil heat accumulation.These successive innovations demonstrate an ongoing trajectory toward more precise, comprehensive thermal characterization methodologies in geothermal applications.

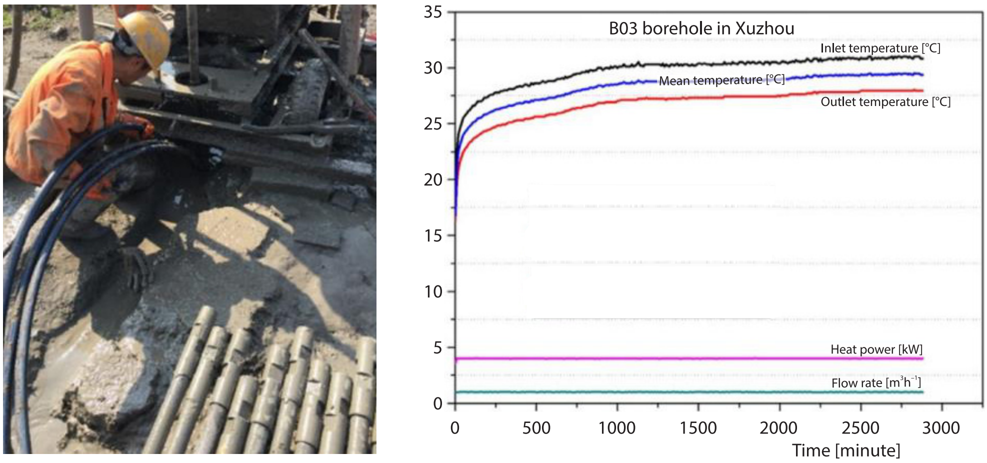

Figure 4. The TRTS method construction process and temperature real-time monitoring feedback [22]

While fiber optic-based DTRT enables multidimensional acquisition of formation thermal parameters, its current application faces bottlenecks including insufficient case studies and lack of standardized protocols. Therefore, in-depth investigation of fluid-geothermal temperature evolution patterns during DTRT could provide theoretical foundations for establishing standardized testing frameworks, holding significant practical value for advancing efficient shallow geothermal energy exploitation. The characteristics and advantages of the four test methods are listed in tab. 1.

Artificial neural network in geothermal energy development

The ANN emulate biological neural systems to construct computational architectures capable of parallel processing, non-linear mapping, and adaptive learning through weight adjustment algorithms (supervised/unsupervised) and activation functions [26, 27]. Their topological structures enable complex pattern recognition and data-driven inference via training, driving significant advances in geothermal resource assessment [28, 29], fig. 5.

Table 1. Comparison of characteristics of TRT, DTRT, ETRT and TRTS

Characteristic	TRT	DTRT	ETRT	TRTS
Spatial resolution	No vertical resolution	High	Ultra	Medium
Cost	Low	Medium high	High	Medium
Accuracy	Medium	High	High theory, limited practice	Medium high
Key technology	Inlet and outlet water temperature monitoring+ heat conduction model inversion	DTS + vertical heat transfer model	Built in copper wire heat source + integrated optical fiber temperature measurement	Multi depth temperature sensor array
Acquisition of formation information	Thermal conductivity only	Layered thermal conductivity + temperature profile	Accurate inversion of in-situ geotechnical thermal properties	Stratification of formation thermal conductivity + characteristics of initial geothermal field
Key advantages	Portable equipment + standardized operation	Reveal the dynamics of vertical heat exchange + support multi flow/ heat injection testing	Active heat control + distributed temperature measurement integration	Wireless/wired flexible deployment + direct point measurement
Engineering applicability	Widely used in conventional geothermal exploration	Complex data analysis required, applicable to scientific research/ fine projects	Insufficient engineering verification in the experimental stage	Suitable for layered research, but the installation is complex
Degree of standardization	High (commonly used internationally, but parameters are not unified)	Low (lack of standard protocol)	Very low (emerging technology)	Medium (various but not standardized methods)

With the maturity and large-scale application of advanced technologies such as DTRT, ETRT, and TRTS, technical standardization is imminent, and the standardization project needs to make collaborative breakthroughs in three aspects: technical optimization, agreement unification and engineering verification.

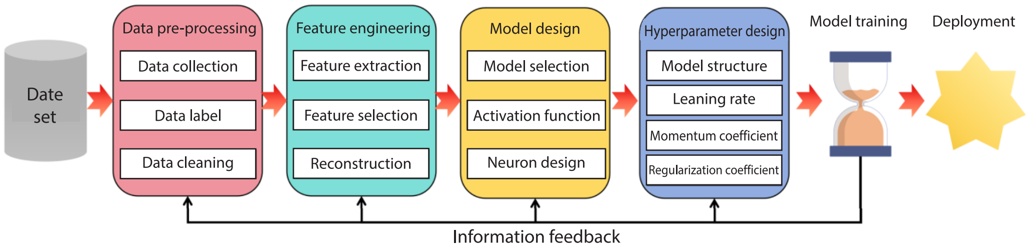

Figure 5. Development process of ANN model

The ANN demonstrate comprehensive applications across geothermal energy development, from resource exploration productivity prediction. They effectively handle complex geological datasets (fracture networks, permeability fields, *etc.*) for resource assessment and modelling, as evidenced by Holmes' play fairway analysis [30], Saibi's magnetic-gravity inversion [31], and Haby's Egypt geothermal mapping, fig. 6 [32]. In enhanced geothermal systems, ANN enables seismic risk management through Shan's stress field inversion (M3 threshold prediction) [33] and Maity's fracture network characterization [34]. Reservoir modelling benefits from Fusun's hydrogeochemical prediction [35], Afandi's shallow geothermal validation [36], and Feng's ANN-HMM hybrid for porosity prediction [37]. For production optimization, Xue's ANN-DE integration achieved 36000 × efficiency gains in LCOE-based forecasting [38], while Bassam developed precise wellbore pressure models [39], showcasing ANN's transformative potential in geothermal energy.

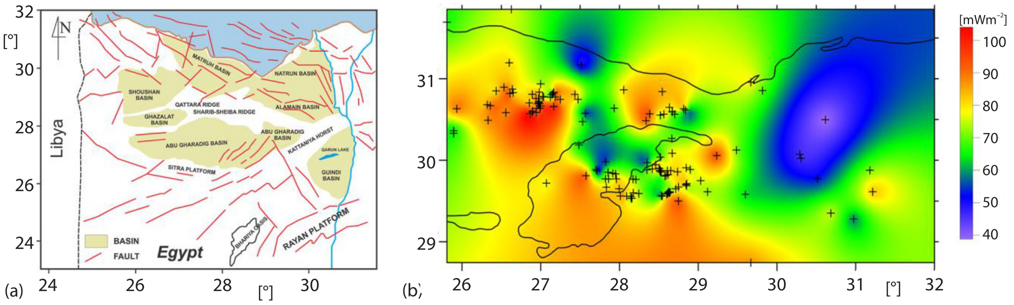

Figure 6. Geographical structure of Northwest Egypt (a) and heat flow diagram combining temperature gradient and thermal conductivity (b) [32]

In the application of ANN in geothermal energy development, the high precision prediction model has excellent performance in key parameters such as reservoir temperature, porosity distribution and shallow temperature and humidity, which can directly support engineering decision-making. Resource assessment and economic optimization models have good reliability, while geophysical inversion and seismic risk prediction need to be combined with physical interpretation due to data complexity. The fracture characterization and wellbore pressure drop model meet the engineering practical standards, but it is suggested to further improve the accuracy through hybrid algorithm. The ANN has significant advantages in physical property prediction and economic optimization. For high noise data, it is necessary to build a physical constraint framework to reduce uncertainty.

The ANN has demonstrated high precision prediction advantages in the geothermal field, especially in scenarios such as reservoir temperature, porosity distribution, and economic index optimization, achieving engineering decision level reliability. However, its large-scale application still faces bottlenecks. Insufficient in-situ monitoring of deep parameters, such as fracture permeability, leads to inversion models relying on high noise interpolation data. Key decisions such as resource assessment and earthquake risk prediction have reduced interdisciplinary collaboration efficiency due to model interpretability. The accuracy of region specific models significantly deteriorates when promoted across basins. Current research is seeking solutions through embedding conservation equations in physical information neural networks, enhancing feature interpretability through attention mechanisms, and implementing cross site knowledge transfer through federated learning. However, industrial applications still need to overcome the challenge of balancing training data costs and cross scale modelling accuracy.

Research on heat transfer model of ground source heat pumps

The GSHP, as sustainable energy technologies, regulate building thermal loads through coupled heat exchange with soil, groundwater, or surface water bodies (lakes/rivers), with technical configurations categorized into ground-coupled (CGHP), groundwater-source (GWHP), and surface-water-source (SWHP) systems based on thermal source differentiation [40]. The GWHP and SWHP predominantly employ open-loop configurations that risk water quality contamination, aquifer level fluctuations, and potential geological-environmental impacts through water extraction/reinjection processes. In contrast, CGHP (*i.e.*, closed-loop ground-coupled systems) operates via sealed circulation of heat transfer fluids (water/antifreeze solutions) driven by heat pump units, physically isolating the circulating medium from geological formations to prevent environmental disturbances. A complete CGHP system comprises three core components: subsurface GHE network, heat pump, and indoor devices [41], with system architecture.

The GHE are classified into horizontal (H-GHE) and vertical (V-GHE) configurations based on installation methods [42]. Horizontal systems typically deploy parallel pipe arrays in shallow trenches at 1-2 m depth [43], yet exhibit compromised thermal performance due to surface temperature fluctuations and require extensive land occupation [44]. Vertical systems achieve efficient heat transfer through closed-loop plastic pipes, single/double *U*-tube, *W*-shape, spiral, or coaxial casings [45], installed in boreholes, with typical structural parameters [46]. Borehole annuli are backfilled with high thermal conductivity grouting materials to ensure low thermal resistance at pipe-soil interfaces [47]. Vertical systems demonstrate broad applicability without dependence on specific hydrogeological conditions (via fluid-formational isolation) and enable cost reduction through repurposing of abandoned oil wells [48]. Compared to open-loop alternatives, these systems exhibit superior environmental compatibility and enhanced thermal stability.

The analytical solution model and numerical model [49] are mainly used in GSHP:

– Analytical solution model

The analytical solution is a model to simplify the proces by assuming some conditions, and then make some modifications to the theoretical calculation results. Representative classical analytical solution models include infinite line source model (ILSM) [50], infinite cylinder source model (ICSM) [51], finite line source model (FLSM) [52], and finite column source model (FCSM)and other heat transfer models.

Table 3. Comparison of characteristics and applicability of analytical solution model

Model	ILSM	ICSM	FLSM	FCSM	Others
Theoretical assumption	Infinite heat source, homogeneous medium, radial heat transfer dominant	Constant radius cylindrical heat source, infinite homogeneous medium	Finite length heat source, semi infinite homogeneous medium, constant temperature boundary	3D cylindrical heat source, Green's function solution, homogeneous property parameters	Extended assumptions such as multi-layer media/seepage coupling/anisotropy
Accuracy	Low	Medium	Medium high	High	High
Efficiency	☆☆☆☆☆	☆☆☆☆	☆☆☆	☆☆	☆☆
Aquifer adaptability	Completely ignoring the impact of groundwater	Only static homogeneous aquifer	Suitable for weakly permeable layers	Can be extended to layered aquifers	Exclusive optimization of layered aquifers
Limitation	Unable to simulate short-term heat transfer; ignore vertical heat flow	The G-function is computationally complex, simplify empirical formulas	Ignore drilling size, the temperature prediction in the middle section is systematically overestimated	Complex calculation (including Bessel function/error function integration); need numerical assistance	Theoretical complexity; parameter sensitivity (such as Bernier model requiring dynamic load aggregation)
Typical application scenarios	Initial design estimation; long term performance prediction	Steady-state analysis of conventional borehole heat exchanger	Mid deep geothermal system; accurate temperature field simulation	Short term thermal response testing; Non-steady-state process analysis	Complex geological conditions, system optimization design

– Numerical solution model

The numerical solution lists the differential equations of heat transfer process, discretizes them on the basis of the energy balance equation and boundary condition control, and obtains the temperature distribution and calculated the heat exchanger. Generally, this kind of model can more accurately represent the geometry than the analytical solution model. Numerical method is primarily through open-source or commercial platforms that can multithread data and offer solutions to PDE for variables, including COMSOL Multiphysics, TOUGREACT, FEFLOW, TRYSNS and other to establish the numerical model. Among them, 1-D numerical model includes: equivalent diameter pipe model; 2-D numerical models include: EWS model, MISOS model, CaRW model, TRCM model, *etc*; 3-D numerical models include: 3-D-TRCM model, STRCM model*, etc.* However, the current indoor experiments are difficult to achieve similar experiments due to site constraints, and current research exhibits significant limitations: laboratory experiments are constrained by spatial scale restrictions that prevent full-scale simulations, while most numerical and analytical models lack empirical validation against actual temperature evolution parameters and frequently neglect critical boundary conditions such as geothermal gradients and seepage field interactions.

Therefore, considering the complexity of heat transfer process in practical engineering, it is required to establish a 3-D model heat exchange system under complex conditions in combination with various actual conditions such as rock and soil stratification, seepage, ground temperature gradient, and temperature change, so as to more accurately simulate its performance and impact on the environment.

Conclusions

This paper presents a comprehensive overview of geothermal energy utilization, tracing its historical development and examining contemporary applications across different countries based on resource grades. It provides a detailed analysis of TRT technologies for buried pipes, including their technical characteristics and practical applications, while demonstrating how artificial intelligence has significantly improved predictive capabilities beyond traditional TRT limitations. The research further explores advancements in heat transfer modelling through both analytical and numerical methods.

Despite these technological developments, shallow geothermal energy implementation faces substantial challenges including geological variability, high capital costs, complex maintenance requirements, and environmental concerns such as groundwater contamination. These barriers are further compounded by inconsistent policy support and regional climate variations. To address these issues, the study proposes an integrated approach combining technical standardization through DTRT ISO specifications (with fracture permeability thresholds >1 mD and thermal breakthrough durations >20 years), innovative financial mechanisms like cost-sharing funds and green bond subsidies, and system-level solutions exemplified by China's successful hybrid geothermal-PV-phase change storage system that achieved a 41% cost reduction. The proposed framework also incorporates AI-enhanced river-source heat pump technology that has demonstrated significant operational improvements, reducing flood-related downtime by 87%. This multi-faceted strategy aims to create a sustainable pathway for large-scale shallow geothermal energy adoption.

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