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Review

Insulated top cover of a large-scale water pit for heat storage: A structure, materials, and performance review

Mingfei He[1,2], Akbar Halimov[3], Mingting Wu[1,2,*], Huanhuan Wang[1,2], Jingyun Li[4], Lijiao Gong[1,2], Lixin Zhang[1,2], and Cong Wang[1,2,*]

[1] School of Energy and Materials, Shihezi University, No. 221 Beisi Road, Shihezi, Xinjiang 832000, China
[2] Institute of Bingtuan Energy Development Research, Shihezi University, No. 221 Beisi Road, Shihezi, Xinjiang 832000, China
[3] Physical-Technical Institute, Uzbekistan Academy of Sciences, Tashkent 100084, Uzbekistan
[4] Xinjiang Tianfu New Energy Industry Innovation Research Co., LTD, No. 2-H, Beiyi East Road, Shihezi, Xinjiang 832099, China

* **Correspondence:** Email: cw2023@shzu.edu.cn, wumingting1995@163.com.

Abstract: Among the many clean heating technologies with solar energy as the main energy source, a water pit for solar seasonal heat storage and heating technology has been actively promoted by many countries due to its reliable technology and mature engineering applications. The insulated top cover is the most important, critical, and expensive component of the water pit for solar heat storage. In this paper, the structural design, material application, and evaluation methods of an insulated top cover were reviewed based on scientific references and practical projects. First, the whole type and split type structure forms of the insulated top cover were summarized, and the applicable scenes of different structural forms were pointed out. Second, the performance analysis of impermeable materials and insulation materials of the insulated top cover was carried out, and the performance characteristics of the corresponding materials as well as the problems to be solved were pointed out. Finally, the performance evaluation method of the insulated top cover was comprehensively analyzed, and it was pointed out that there is still a lack of scientific and efficient evaluation parameters and monitoring methods for an insulated top cover in line with engineering practice. The purpose of this paper was to provide reference for the scientific research and engineering application of a water pit for solar seasonal heat storage and heating technology.

Keywords: seasonal heat storage; water pit; insulated top cover; structural form; insulation materials; impermeable materials; evaluation parameter; solar energy; clean heating

1. Introduction

Since the onset of industrialization, massive fossil fuel consumption has led to a continuous increase in carbon dioxide emissions. This, in turn, has caused numerous environmental problems, including rising global temperatures, melting glaciers, and rising sea levels, posing unprecedented threats and challenges to the environment essential for human survival. The 2023 Annual Progress Report on Global Carbon Neutrality states that 151 countries around the world have proposed carbon neutrality targets, with 90% of them setting the year for achieving carbon neutrality as 2050 and beyond, covering 92% of GDP, 89% of the population, and 88% of emissions [1–3]. Figure 1 illustrates the annual carbon dioxide emissions of selected countries and compares their “carbon peak and carbon neutral” goals, underscoring the global commitment to energy conservation, emission reduction, and sustainable development.

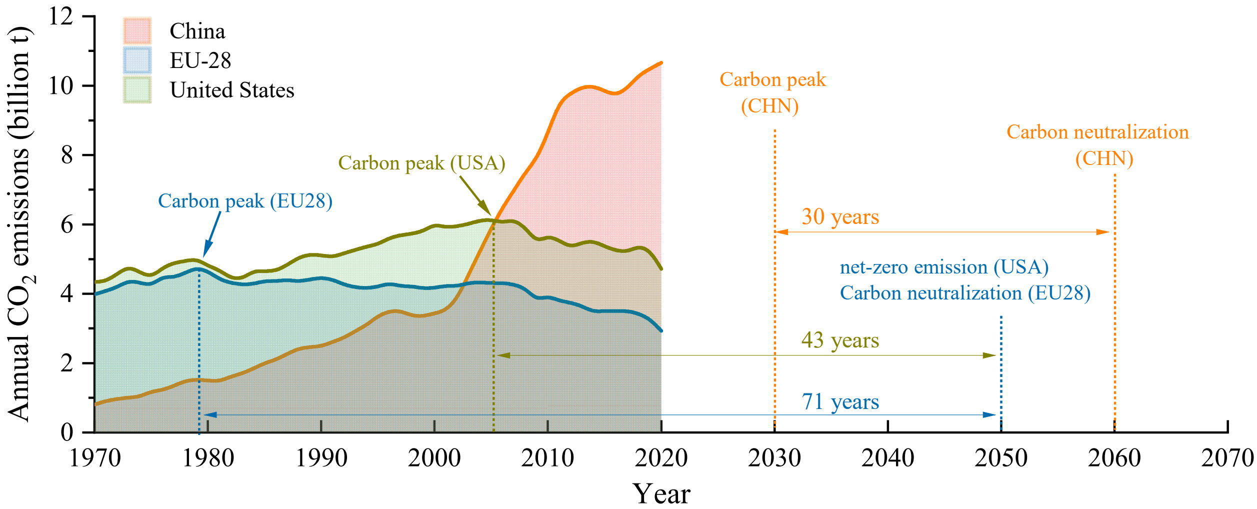


Figure 1. Annual CO_2 emissions from fossil fuels and the targets of the carbon peak and neutralization [4,5].

As of January 2025, fossil energy from coal and natural gas will continue to be the main types of energy consumed globally. In Europe and the United States, the building sector accounts for about 40% of energy consumption and 36%~38% of CO_2 emissions [3]. Space heating and domestic hot water demand in the built environment account for about 40% of energy consumption in mid- and high-latitude countries [6]. In China, heating energy consumption is about 220 million tons of standard coal, accounting for 19.2% of the national building energy consumption [7–9]. Evidently, fossil fuels continue to dominate domestic heating in cold-climate countries, presenting a significant challenge to global energy conservation and emission reduction initiatives [10,11]. Therefore, countries around the world are actively exploring clean or renewable energy sources to replace fossil fuels for clean residential heating.

Solar energy resources are abundant, clean, and widely distributed. Therefore, countries around the world are actively exploring clean heating methods that use solar energy as the main source of energy [12–14]. While solar energy offers numerous advantages, it is also characterized by low energy density, intermittency, and significant seasonal variations in irradiance. The temporal and spatial mismatch between solar energy resources and load demand has constrained the development and application of solar clean heating technology. Among the many solar-supported clean heating technologies, water pits for solar seasonal heat storage and heating technology have been actively promoted by many countries due to their reliable technology and mature engineering applications. As shown in Figure 2, the central idea of the water pit for solar seasonal heat storage and heating technology is to store the abundant solar energy resources in the form of heat energy in the water pit in the non-heating season for use in the heating season. This technology realizes the transfer of solar energy resources in time and space [15].

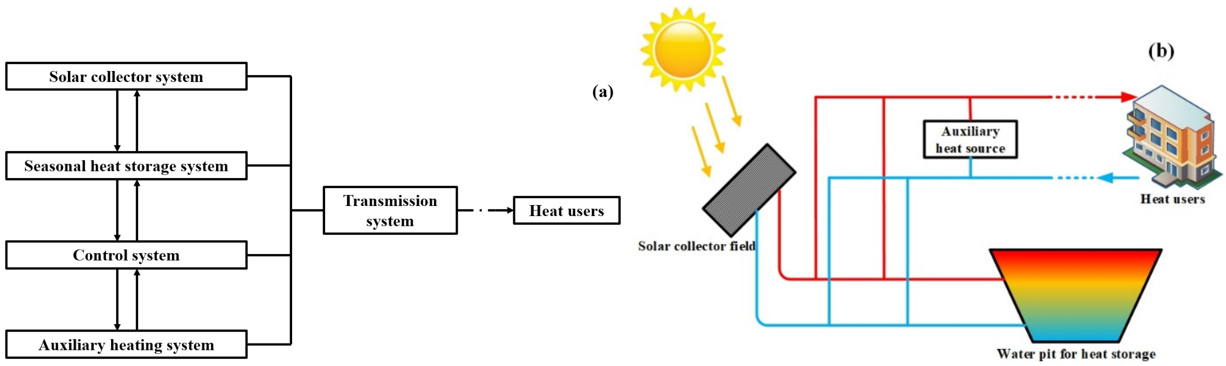


Figure 2. Typical water pit for solar thermal storage and heating technology principle and system schema. (a) Technical principal schematic. (b) System schematic [15].

Current research on water pit solar seasonal heat storage and heating technology primarily focuses on several key areas: the solar collector sub-system [16–22], seasonal heat storage sub-system [23–26], control sub-system [27,28], auxiliary heat supply sub-system [29–33], heat transfer sub-system [34,35], and heat-using end-loads. Additionally, whole-system operation strategies and energy balance are actively investigated [36–43].

As shown in Figure 3, in this paper, the structural design, material application, and evaluation methods of an insulated top cover are reviewed based on scientific references and practical projects. First, the whole type and split type structure forms of the insulated top cover are summarized, and the applicable scenes of different structural forms are pointed out. Second, the performance analysis of impermeable materials and insulation materials of the insulated top cover is carried out, and the performance characteristics of the corresponding materials as well as the problems to be solved are pointed out. Finally, the performance evaluation method of the insulated top cover is comprehensively analyzed, and it is pointed out that there is still a lack of scientific and efficient evaluation parameters and monitoring methods for the insulated top cover in line with engineering practice. The purpose of this paper is to provide reference for the scientific research and engineering application of water pits for solar seasonal heat storage and heating technology.

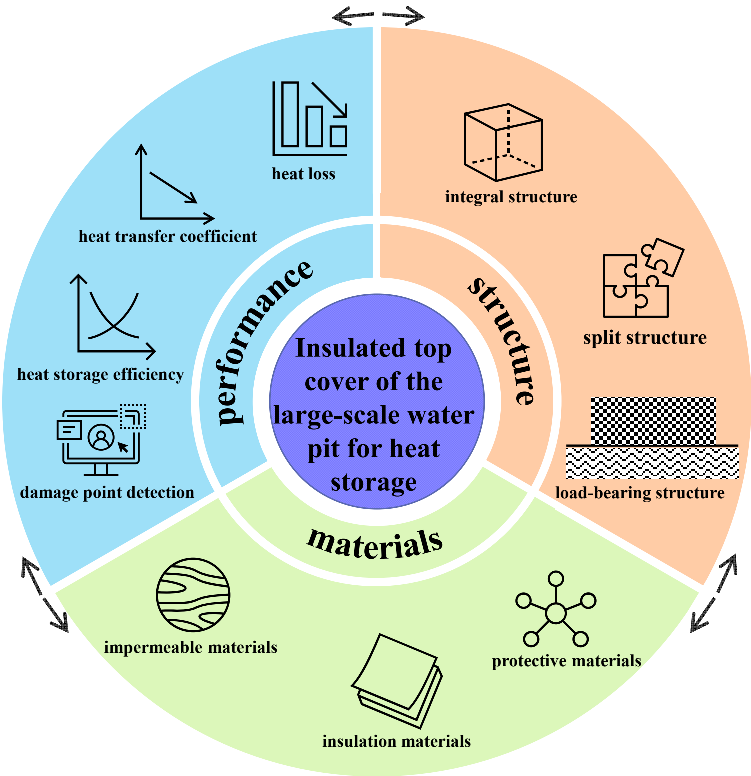


Figure 3. Key technologies for the top cover.

2. Insulated top cover of a water pit for heat storage

The insulated top cover is the most important, critical, and expensive component of the water pit. As illustrated in Figure 4, an analysis of the heat storage principle reveals that while the surrounding soil provides some insulation to the sides and bottom of the water pit, an insulated top cover is essential for effective heat retention; without it, the water pit cannot effectively store heat. The better the thermal insulation effect of the top cover, the higher the heat storage efficiency of the water pit, and the more obvious the temperature stratification of the water pit. From the experience of engineering practice, the top cover structure is complex, difficult to construct, and costly. The structure, materials, and performance evaluation methods of the top cover are areas of significant interest in both scientific research and engineering practice. While scientific research often necessitates engineering validation, the long cycle times of solar seasonal heat storage projects and the proprietary nature of large-scale top cover engineering by commercial entities mean that publicly available, top cover-specific references are relatively scarce. This paper focuses on representative large-scale water pits and their insulated top covers. As shown in Table 1, this paper lists the relevant parameters of the top cover of some water pits in the world based on relevant references and engineering project reports. These parameters will be applied in later analysis.

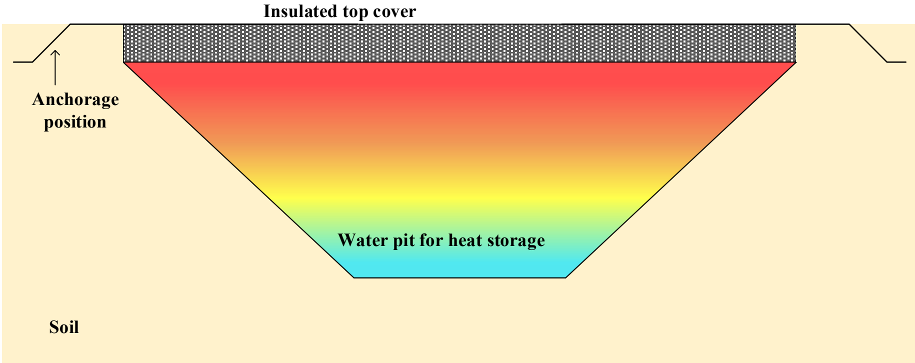


Figure 4. Schematic section of the water pit for heat storage.

Table 1. Parameters related to the top cover of the water pit [44].

Name of project	Year of construction	Area of the top cover (m^2)	Type of structure of the top cover	Impermeable materials for the top cover	Insulation materials for the top cover
Lambohov	1980	1750	Sandwich structure	Butyl rubber	Clay pellet
Stuttgart	1985	835	Sandwich structure	HDPE geomembrane	Gravel, clay, volcanic pebbles
Julich	1996	/	Sandwich structure	Double-layer polypropylene film	Rock wool
Augsburg	1996	/	/	HDPE geomembrane	Extruded polystyrene
Steinfurt	1999	1305	Sandwich structure	Double-layer polypropylene film	Expanded glass granules
Chemnitz	2000	3375	/	HDPE geomembrane	Extruded polystyrene
Eggenstein	2008	1964	Sandwich structure	HDPE-Al composite film	Expanded glass granules
Herlev	1991	1630	/	EPDM rubber	Organosilicon
Ottrupgård	1995	1400	Modular structure	EPDM rubber	Organosilicon
Marstal	2012	20800	Split structure	HDPE geomembrane	Nomalen (Danish)
Langkazi	2018	3364	Sandwich structure	HDPE geomembrane	Rubber plastic insulation foam
Yanjing 1	2019	420	Split load-bearing structure	HDPE geomembrane	Extruded polystyrene + soil
Yanjing 2	2019	420	Sandwich structure	HDPE geomembrane	Rubber plastic insulation foam
Phase I of Huangdicheng	2017	560	Integral structure	Concrete	Extruded polystyrene + soil
Phase II of Huangdicheng	2021	1020	Integral structure	Stainless steels	Extruded polystyrene + wood chips
Phase III of Huangdicheng	2023	8976	Split load-bearing structure	HDPE geomembrane	Extruded polystyrene + soil

Note: "/" means no accurate data available.

3. Structure of the insulated top cover

According to a large number of references and engineering projects, this paper summarizes the structural forms of insulated top covers into two types: integral structure and split structure.

3.1. Insulated top cover of integral structure

An integral insulated top cover is defined as a single, undivided unit. Most of the top covers in the previous references and engineering practice are of integral structure, which can be categorized into a flexible material insulation top cover, rigid material insulation top cover, and bulk material insulation top cover according to the type of insulation material. Flexible material insulation top cover insulation often uses polystyrene insulation wool, polyurethane insulation wool, rock wool, fiberglass insulation wool, and other flexible insulation materials. The rigid material insulation top cover generally refers to the top cover of a reinforced concrete structure, or early large buried water tanks used on the steel lid to take thermal insulation measures to form a thermal insulation top cover. There are also cases where thin aluminum or metal sheets are used as the impermeable layer and rigid insulation materials such as polyurethane rigid foam or polyisocyanurate foam are used as the insulation cover. Bulk materials such as vermiculite granules, clay granules, ceramic granules, wood chips, and other bulk materials are often used for the insulation of the bulk material insulation top cover [45,46].

The most common type of integral top cover is the "sandwich" structure. In Figure 5, a typical structure is shown, from top to bottom: top impermeable layer, insulation layer, bottom impermeable layer. As shown in Figure 6, the Marstal water pit for heat storage, Dronninglund water pit for heat storage, and Langkazi water pit for heat storage all use this form of insulated top cover [44,47–49].

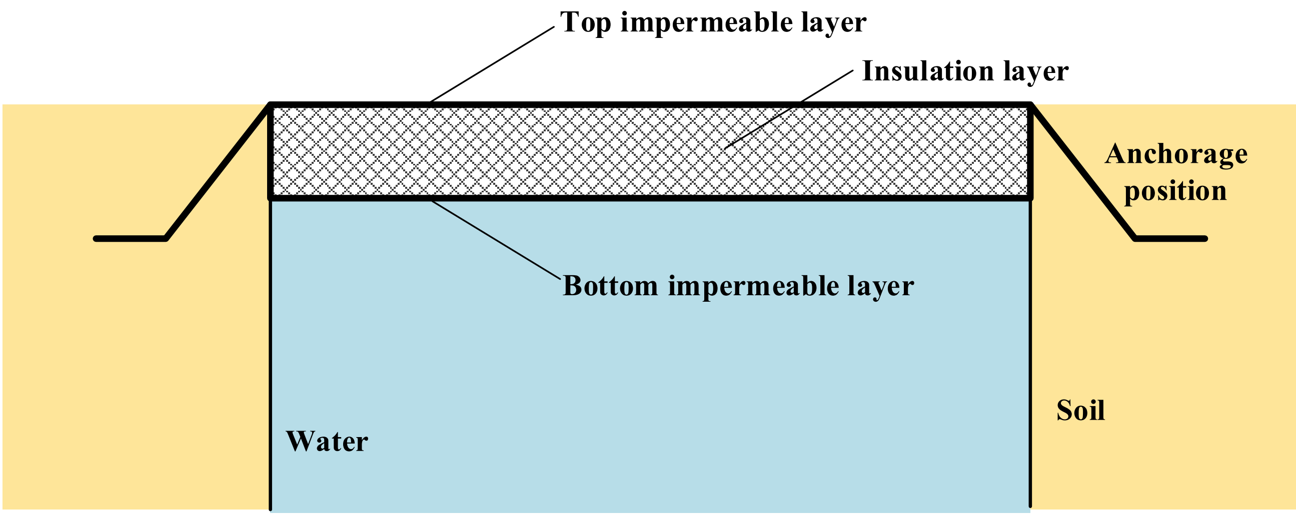


Figure 5. Schematic of a typical sandwich structure top cover.

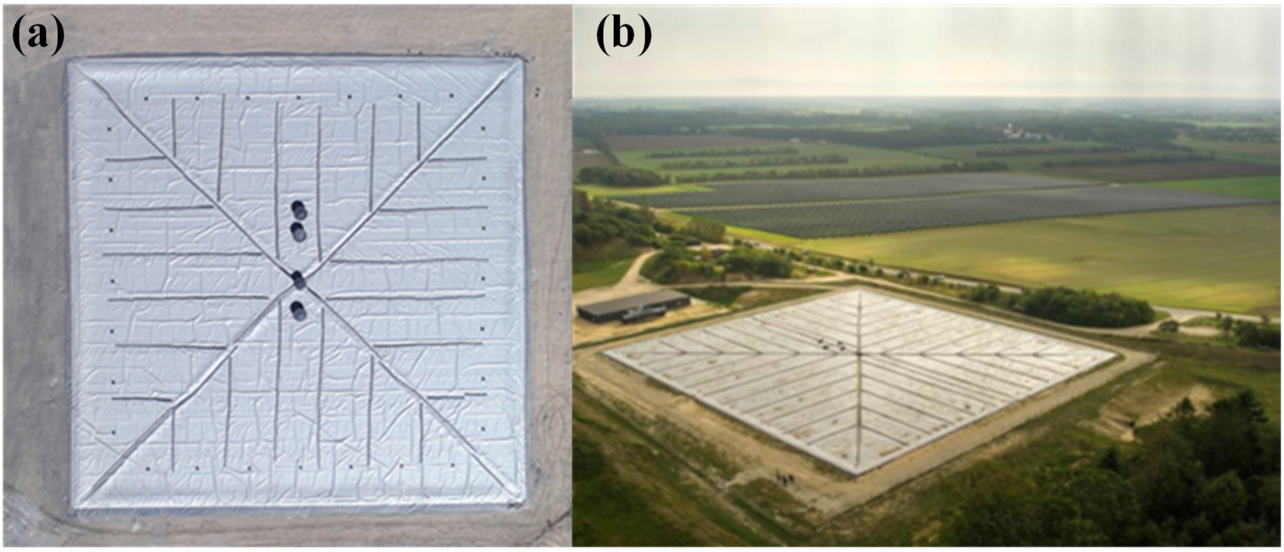


Figure 6. Aerial view of the water pit. (a) Langkazi water pit for heat storage. (b) Dronninglund water pit for heat storage [44,47–49].

A sandwich-structured top cover allows the entire assembly to float on the water, with the edge of the seepage control layer extending to an anchoring trench for fixation. The top cover floats directly on the water surface due to buoyancy. Consequently, if leakage occurs within the water pit, the falling water level can cause the cover to sag. This places concentrated force on the anchoring positions around the pit, potentially leading to rupture of the top cover at these points in severe cases. Such a rupture would then allow water to soak the thermal insulation layer, causing it to fail. On the other hand, damage to the top cover of the bottom of the impermeable layer or the top of the impermeable layer will lead to failure of the top cover of the insulation layer of water immersion. While these problems have occurred in related projects, locating damage to the bottom impermeable layer is difficult because the top cover is an integral unit or the top impermeable layer, it is difficult to repair, and the maintenance cost is high. Furthermore, the construction process for a sandwich-structure top cover is complex. To ensure the insulation material remains dry, construction must avoid rainy weather, posing a significant challenge for large-area top covers requiring long construction cycles.

As shown in Figures 6 and 7, due to the large area of the top cover, a lot of rainwater will be gathered on the top cover during heavy rainfall, so the sandwich-structural top cover will generally be designed with a corresponding counterweight pipe to guide the rainwater to converge in the center of the top cover, and then the rainwater will be discharged through the water pump. It is important to note that the thermal insulation layer inside the top cover will form a thermal bridge under the action of the counterweight pipe, which will affect the thermal insulation effect of the top cover.

Figure 7. The top cover weighted pipe guides rainwater to collect and drain away.

As shown in Figure 8, in order to vent the water vapor inside the water pit, the sandwich-structural top cover had to be designed and installed with vent holes. Under normal circumstances, the heat loss caused by the vent hole is negligible. However, since the vent hole passes directly through the top cover, substandard construction techniques often lead to leakage in the top cover at the location of the vent hole, which in turn leads to a decline in the thermal insulation performance of the top cover or even failure.

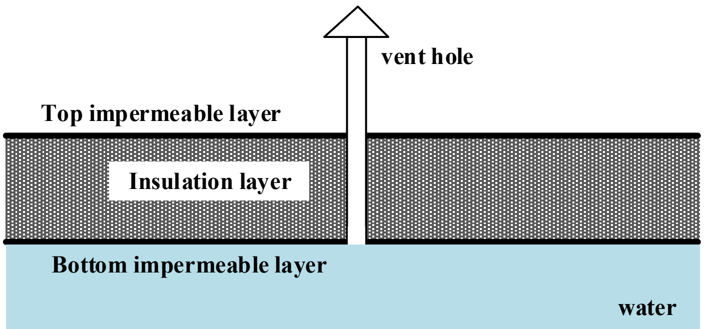


Figure 8. Schematic of the top cover vent hole.

Shown in Figure 9 is a typical rigid material top cover, generally designed and constructed in conjunction with the water pit, laying the thermal insulation layer and impermeable layer on the concrete surface [8]. In such a structure, the steel reinforcement within the top cover creates numerous thermal bridges, leading to suboptimal insulation performance. Additionally, this design presents construction challenges, high costs, and maintenance difficulties.

Figure 9. Reinforced concrete construction of the water pit and top cover.

A typical bulk material insulated top cover is shown in Figure 10, which is used in the world's largest water pit for heat storage in Vojens, Denmark, with a volume of about 200,000 m^3 [50,51]. It is also a sandwich-structure top cover, but the difference is that the insulation is often made of expanded vermiculite granules, clay granules, ceramic granules, wood chips, and other bulk materials. The main advantage of this type of top cover is that these bulk insulation materials are inexpensive.

Figure 10. A typical bulk material insulated top cover [50,51].

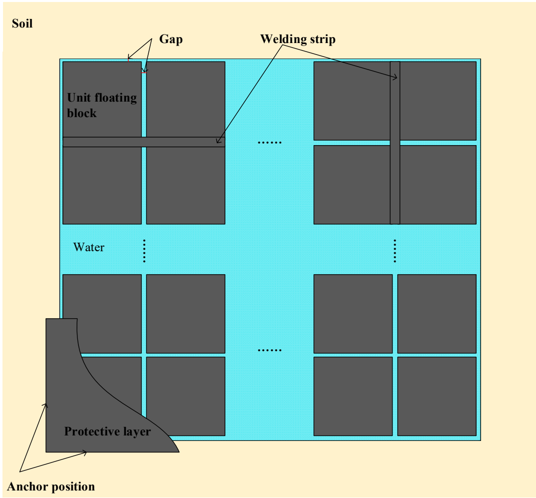
Overall, while integral insulated top covers offer good thermal insulation performance, their construction is difficult, and operation and maintenance costs are high.

3.2. Insulated top cover of split structure

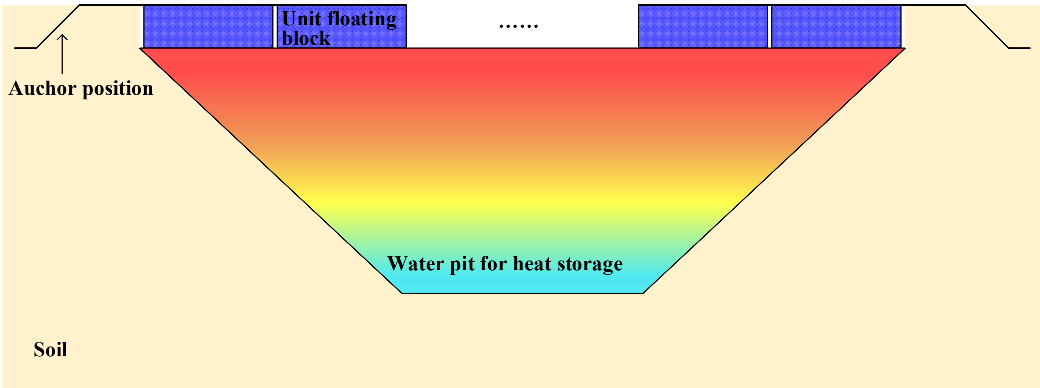
A split-structure insulated top cover refers to a large insulated cover formed by joining multiple smaller insulated sections using a specific connection method. As shown in Figure 11, the Institute of Electrical Engineering of Chinese Academy of Sciences (IEECAS) first designed the split-structure insulated top cover on the Yanjing-1 water pit for heat storage experimental platform of the Yanqing solar thermal power generation experimental base. The size of the split unit float is 5.2 × 1.2 × 0.5 m. The unit float is made of extruded polystyrene foam board wrapped with HDPE geomembrane. The HDPE geomembrane was used to weld the unit floats together to form the entire insulated roof. This water pit for heat storage experimental platform continues to be in operation today.

Figure 11. The split-structure insulated top cover of the Yanjing-1 water pit.

Based on the work of the Yanjing-1, the IEECAS has also explored the technology of a load-bearing split insulated top cover, with the aim of further expanding the integrated application of water pit for heat storage. For Phase III of the Huangdicheng solar seasonal heat storage and heating project, IEECAS designed a split load-bearing insulated top cover to avoid altering the land's designated use. As shown in Figure 12, the project designed split unit floats with thermal insulation and load-bearing capacity, and then connected multiple unit floats to form an integral top cover. The top cover floats directly on the water surface, and the surface of the top cover can bear a certain amount of load. The total area of the top cover is 8976 m^2. The insulation material of the top cover is extruded polystyrene foam board with a compressive strength of 298.68 kPa. The impermeable material of the top cover is HDPE geomembrane with a tensile strength of 16.7 MPa. The draft depth of the top cover without load is 8.2 mm, and the ultimate load is 6512.39 kg, which can realize a load of 231.8 kg/m^2 (safety load).



(a) Vertical view



(b) Cutaway view

(c) Engineering construction process

Figure 12. Load-bearing split insulated top cover of Huangdicheng Phase III.

Based on practical project experience, the advantages of the split load-bearing insulated top cover include the following:

(1) The top cover can provide load-bearing capacity while maintaining satisfactory thermal performance. The former sandwich-structure top cover is not load-bearing and the cost is high, which leads to difficulties in the promotion and application of large-scale water pits in cities and towns. On the other hand, the large area of the top cover is difficult to use twice, resulting in a waste of resources. The split load-bearing insulated top cover is load-bearing under the premise of thermal performance, and can lay photovoltaic panels or plant crops above the top cover. This technology promotes the comprehensive utilization of the top cover and broadens the application scope of the water pit.

(2) The selection range for top cover materials is expanded. Compared to integral top covers, split top covers offer wider compatibility with various impermeable and insulation materials.

(3) Convenient construction. The simple and stable structure of the split unit float has higher reliability and stability. Split unit floats are easy to produce, their production efficiency can be further improved, and costs are reduced when combined with industrial automation technology. Sandwich-structural top covers are greatly affected by the weather during the production and installation process, and wet and precipitous weather cause great difficulties to the construction process of sandwich-structural top covers. Split unit floats can be factory-produced, making their production efficiency independent of weather conditions. The assembly and welding process of the split top covers are virtually unaffected by the weather. In addition, the sandwich top cover can only be constructed after the water pit has been completed and filled with water, whereas the split top cover can be constructed at the same time as the water pit, which further enhances the efficiency of the project.

(4) Simple and low-cost operation and maintenance. Split unit floats do not have a significant impact on the top cover as a whole in the event of a breakage, and the entire top cover will not fail due to the failure of a unit float. Upon discovering a failed split unit float, targeted repair or replacement can be performed. This maintenance process does not affect the normal operation of the water pit, and the associated time, material, labor, and other costs are extremely low. But with the sandwich-structure top cover, if a breakage occurs, it could lead to the overall performance failure of the top cover. If the breakage point is difficult to locate, maintenance of the water pit cannot happen normally, and there could be high maintenance costs.

It should be noted that split insulated top covers have drawbacks, as gaps will inevitably exist between the individual unit floats. These gaps can lead to increased heat loss from the water pit, a problem requiring future attention.

4. Materials of the insulated top cover

The top cover generally involves impermeable materials and thermal insulation. The lower surface of the top cover is in direct contact with water (or water vapor), the temperature of the water is generally between 40~90 °C, and it undergoes a long cycle of hot and cold cycles. The upper surface of the top cover is generally in direct contact with the environment, with years of wind and sun exposure subjecting it to, hot and cold shock. Therefore, impermeable materials should focus on the following performance parameters:

(1) Seepage resistance performance. The impermeable material should have excellent seepage resistance, and its sealing and isolation can effectively block the infiltration and leakage of water (water vapor) and prevent the insulation material from soaking in water.

(2) Physical stability. Excellent physical stability is crucial for the impermeable material to ensure the top cover maintains a stable shape and performance when subjected to external forces such as stretching, puncture, load bearing, and thermal shocks, thereby preventing breakage.

(3) Chemical stability. The impermeable material should be chemically stable to prevent corrosion.

(4) Flexibility. The impermeable material should be flexible enough to accommodate a special-shaped top cover, while being easy to transport and construct.

(5) Aging resistance. The impermeable material should be resistant to ultraviolet light, oxidation, and other factors in the natural environment to ensure its stability and service life.

Insulation materials are wrapped by impermeable materials and should focus on the following performance parameters:

(1) Thermal conductivity. The lower the thermal conductivity, the better the insulation.

(2) Water absorption. The water absorption of the insulation material should be as low as possible to prevent it from affecting its insulating properties.

(3) Physical stability. Insulation materials should maintain shape and structural stability to prevent deformation or rupture when undergoing long cycles of temperature changes in the top cover or under external forces.

(4) Chemical Stability. Insulation materials should not corrode or dissolve during use. Comprehensive consideration should also be given to its weathering resistance, such as resistance to freezing and thawing, exposure, weathering, and degradation resistance.

(5) Fire rating. Insulation materials should have a high fire resistance rating to prevent fire accidents.

It is difficult to find near-perfect materials, so it is important to define the main performance parameters during the design of the water pit for heat storage as well as the top cover.

4.1. Impermeable materials for the insulated top cover

As shown in Figure 13, a stainless steel thin plate or thin aluminum plate was used as the impermeable layer of the top cover in some early projects [45,46], while reinforced concrete was also used in some small projects [8,52]. However, later, it was no longer used because of poor impact resistance, high thermal conductivity, serious oxidation and corrosion, high cost, and high construction difficulty.

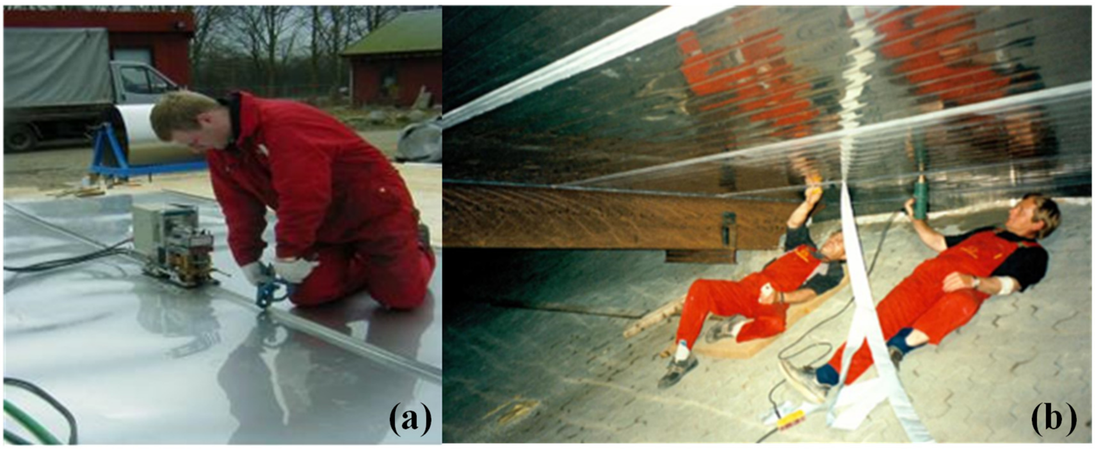


Figure 13. Metal impermeable layer. (a) Impermeable layer of a stainless-steel thin plate. (b) Impermeable layer of a thin aluminum plate.

As shown in Table 2, this paper summarizes some of the impermeable materials used in the water pit and top cover through a large number of references and engineering research, and summarizes the relevant properties.

Table 2. Summary of common impermeable materials for the water pit and top cover.

Classifications	Materials	Thermal conductivity (W/(m•K)	Advantages	Disadvantages
Polymer film	High density polyethylene	0.44	Good toughness; Ease of construction; Less degradation; Corrosion resistance; Low thermal conductivity; Low price	Complex temperature resistance; Poor strength
	polypropylene	0.11		
	polyethylene	0.4		
	Low density polyethylene	0.33		
	Polyvinyl chloride	0.14~0.17		
Rubber	EPDM rubber	0.2~0.5	Good temperature resistance; Low price;	Requires special adhesive;
Sheet metal	Stainless steels	14~23	High temperature resistance; High strength; High weather resistance	High thermal conductivity; High price; Some risk of corrosion; Requires special welding equipment
	Aluminum	237		

With the progress of related technology, the later top cover impermeable layer materials are mostly made of polymer film, common high-density polyethylene film, linear low-density polyethylene film, polyvinyl chloride film, polymer modified asphalt waterproofing roll-roofing, neoprene rubber, and so on [53]. To enhance the comprehensive performance of polymer films, additives such as stabilizers, plasticizers, anti-aging agents, and fungicides are often incorporated, primarily to further improve their key performance parameters [54–56].

In 1984, the first International Geomembrane Conference named HDPE film with additives as HDPE geomembrane, which is mainly used in seepage control projects such as large reservoirs, dams, and landfills [57–59]. As the HDPE geomembrane has excellent seepage resistance and mechanical strength, and has high flexibility and tensile properties, in the role of an additive, it also shows high aging resistance, heat resistance, and other characteristics. Drawing on the experience of a variety of seepage control projects, later top covers and water pits mostly use the HDPE geomembrane as the seepage control layer material, as shown in Figure 14, which shows the common types of HDPE geomembranes.

Figure 14. Several common types of HDPE geomembranes. (a) Glossy geomembrane. (b) Rough surface geomembrane. (c) Pillar point geomembrane.

Usually, the permeability coefficient is used to evaluate the seepage control performance of the geomembrane, and the permeability coefficient of the geomembrane is usually between 10^{-11}~10^{-12} cm/s [60–62]. The vertical permeability test is usually used to test the permeability coefficient of the geomembrane. The vertical permeability test is typically employed because the small thickness of the geomembrane, along with very small permeability channels and seepage velocities, results in laminar water flow. Therefore, Darcy's law, as applied in geotechnics, is considered applicable for determining the permeability of geomembranes [63]. Because of insufficient research on the micro-microstructure of geomembranes, their permeability mechanism is still unclear, and their evaluation parameters are limited to a certain extent. Ozsu et al. proposed a test method for the apparent hydraulic conductivity of geomembranes [64]. Giorni et al. concluded that the primary mechanism of water transport is a function of the hydrophobic behavior of the geomembrane, not the pressure gradient, and that Darcy's law fails to describe the geomembrane infiltration mechanism [65]. Aminabhavi et al. concluded that the diffusive transport of liquids in geomembranes depends on the temperature and concentration of the liquid [66]. Hu Liwen et al. observed the microstructure of geomembranes under tension using an electron microscope, and concluded that the way water passes through the geomembrane in the case of small elongation is diffusive transport [67]. Zhang Guangwei et al. used a flexible wall permeability meter to measure the permeability through a geomembrane in a certain period of time under different permeability pressures, and the results showed that the permeability exhibited three kinds of trends in the pressure range of 0.1~0.6 MPa. It was believed that the inhomogeneity of the geomembrane's physical properties and the morphology of the permeability channel were the main factors affecting the seepage control [68]. Although the above studies have achieved some results on the permeability properties of geomembranes, most of the permeability characterization studies originate from the analysis of macro-test results. Zhang Xianlei et al. constructed an infiltration flow-porosity mathematical model by using the vertical permeability test data of geomembranes under multiple sets of infiltration pressures and the porosity obtained based on low-field nuclear magnetic resonance (NMR) technology, and explored the applicability of evaluating the vertical permeability performance of the geomembranes by porosity in combination with the pore space and pore diameter dynamic distributions [69].

Overall, the geomembrane seepage control mechanism is not clear enough and deserves to be further explored with a focus on maintaining excellent seepage control performance under long cycles of high and low temperature cycling.

4.2. Insulation materials for the top cover

Reasonable selection of insulation materials directly affects the thermal performance and cost of the top cover, which in turn affects the thermal efficiency and economy of the water pit for heat storage. Therefore, the insulation material should be selected according to the design requirements of the top cover and the reality of various factors. Mastal's SUNSTORE-3 and SUNSTORE-4 water pits and the top cover of the Dronninglund water pit in Denmark are insulated with "Nomalen" (Danish), a chemically cross-linked polyethylene foam with a closed cell structure. The base material is low-density polystyrene, but the chemical cross-linking makes it more heat-resistant than ordinary low-density polystyrene. According to the supplier concerned, the material can operate at temperatures of up to 95 ℃ [46,49,70]. Polyurethane/polyisocyanurate foam was used for the top cover of the water pit in Ottrupgaard, Denmark, and the project experience has shown that special attention needs to be paid to the waterproofing treatment of this material [46]. As shown in Figure 15, the top cover of the Vojens and Gram water pits utilize an insulation material called "Leca" (Danish, a type of expanded vermiculite), which is similar to expanded vermiculite or clay particles [46,71]. However, due to the inherent mobility of these particles and their susceptibility to weather changes and temperature shocks, the insulation layer within the top cover may not maintain a fixed position. This can compromise the uniformity and flatness of the top cover, thereby adversely affecting its thermal performance. The top cover of China Huangdicheng Phase I used polystyrene board as the insulation material [8]. The top cover of the Yanjing-2 water pit used rubber-plastic insulation wool as the insulation material [47]. In this paper, the insulation materials used on the top cover are summarized as shown in Table 3 based on relevant references and project experience.

Figure 15. Leca (Danish, a type of expanded vermiculite) insulation material [46,71].

5. Evaluation methods for top cover performance

Through comprehensive related references and engineering experience, the heat transfer coefficient and the heat loss of the top cover are commonly used to evaluate the thermal performance of the top cover.

Fan Jianhua et al. installed a heat flow meter on the top cover of the Marstal water pit to measure the heat loss at the installation point, and the experimental results showed that the heat flow density of the top cover was in the range of 22~34 W/m^2 [72]. This method is only a single-point measurement at the fixed position of the top cover, and it is difficult to accurately measure the heat loss of the entire top cover. For example, the measurement is unable to measure the additional heat loss caused by periodic ventilation, thermal bridging of access holes, thermal bridging of counterweight tubes, and various joints on the top cover. In addition, it is not possible to measure the additional heat loss caused by the deterioration of insulation performance due to the deformation of insulation materials observed in some places on the top cover.

In order to further accurately characterize the thermal performance of the top cover, Bai Yakai et al. from IEECAS established a numerical model of the water pit and verified the correctness of the numerical model with experimental data, which showed that the heat loss of the top cover of the Huangdicheng phase I water pit in 2018 was 21.664 MWh, which accounted for 21.8% of the total heat loss of the water pit, and the coefficient of heat loss of the top cover was 0.172 W/(m^2•K) [8]. Engineering experience with the Ottrupgard water pit predicts heat loss from the top cover to be 24 MWh/year, which is 28.2% of the total heat loss from the water pit [46]. Other researchers have studied the heat transfer process and mechanism of the top cover of the Yanjing-2 water pit through finite element modeling, and the comprehensive heat transfer coefficient of the top cover was shown to be as low as 0.186 W/(m^2•K) [21,47].

Table 3. Comparison of the performance of common insulation materials for the top cover and water pit.

Materials	Particle size (mm)	Thermal conductivity (W/(m•K))	Density (kg/m³)	Advantages	Disadvantages
Expanded glass granules	2~16	0.07~0.08	140~200	Easy to construct; High temperature resistant	Poor hydrophobicity
Expanded clay particles	1~8	0.08~0.1	270~300	High strength; Low price	Poor hydrophobicity
Foam glass gravel	10~50	0.06~0.09	150~195	Dimensional stability; Easy to construct	Wide gap
Polyurethane/polyurethane granules	3~20	0.02~0.03	80	High temperature resistant	High price
Nomalen	3~10	0.06~0.09	28	High thermal stability; High temperature resistance; High moisture resistance	Difficulties in operation and maintenance
Leca (A type of expanded vermiculite)	2~15	0.05~0.1	20~35	High temperature resistance; High moisture resistance; Easy construction; Many applications	Difficulties in operation and maintenance
Mineral wool	Sheet	0.03~0.05	160	Low thermal conductivity; Easy construction	Poor hydrophobicity; Difficult to dry when damp
Expanded polystyrene	Sheet	0.03~0.04	15~40	Low thermal conductivity	High price; Fragile when absorbing water
Perlite	1~10	0.05~0.09	90	High temperature resistance	Difficult construction
Shell products	Irregularly	0.10~0.15	1071	Low price	High density; High thermal conductivity; Difficulty in operation and maintenance

As shown in Figure 16, during the operation and maintenance process of a large-scale top cover, Ioannis Sifnaios et al. used a drone equipped with a conventional camera and an infrared thermal camera to simultaneously photograph the top cover, and the photographs taken were spliced together to restore the full picture of the top cover through image processing technology. By comparing the temperature differences on the thermal infrared images, it can help to determine whether there is any leakage in the top cover [73]. This method was used to monitor the top covers of Dronninglund, Marstal, Gram, Toftlund, and Vojens water pits and successfully identified breakage points on the top covers.

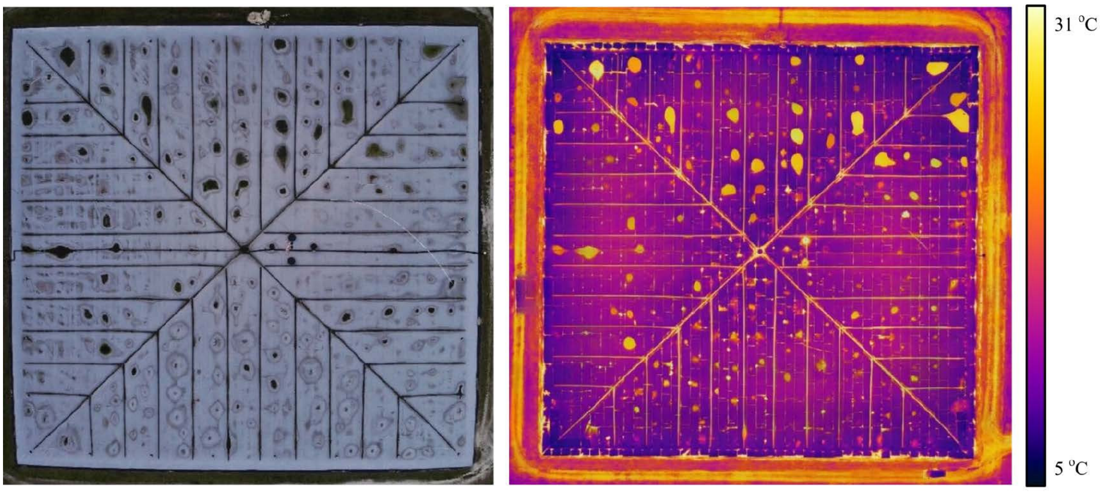


Figure 16. Comparison of real and thermal infrared images of the top cover [73].

In summary, a lack of uniform parameters for evaluating top cover performance persists. Further investigation is needed into modeling the heat loss mechanisms of the top cover and developing effective heat loss monitoring techniques.

6. Conclusions and prospects

In this paper, the structural design, material application, and evaluation methods of insulated top covers are reviewed based on scientific references and practical projects. The conclusions are as follows:

(1) An integral top cover has better heat preservation effect, but its construction and operation maintenance is difficult; this is suitable for a small-size (<500 m^2) top cover. A split top cover is simple to process and easy to assemble; this is suitable for a large-scale (>500 m^2) top cover.

(2) The HDPE geomembrane remains a relatively reliable seepage control material; however, its physicochemical properties and long-term reliability warrant further in-depth research. The selection of insulation materials should be based on a synthesis of thermal performance requirements and cost considerations.

(3) The comprehensive heat transfer coefficient and heat loss of the top cover are currently the main evaluation parameters of the thermal performance of the top cover. Load-bearing top covers can further broaden the application scenarios for water pits, positively impacting seasonal heat storage and heating technology.

(4) Long-cycle monitoring techniques for top cover performance urgently require exploration. Furthermore, operation and maintenance methods for top covers need further optimization and cost reduction.

For future research directions, it is necessary to further optimize the top cover structure and design a simpler and more reliable top cover structure. The seepage prevention mechanism of the top cover impermeable material should be emphasized. It is also necessary to optimize the performance evaluation parameters and evaluation methods of the top cover.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

The authors declare no conflicts of interest.

Author contributions

Mingfei He: Conceptualization, Methodology, Data curation, Writing—original draft, Funding acquisition; Akbar Halimov: Data curation, Investigation, Validation, Writing—review & editing; Mingting Wu: Data curation, Investigation, Validation, Visualization, Writing—review & editing; Huanhuan Wang: Data curation, Investigation, Validation, Writing—review & editing, Funding acquisition; Jingyun Li: Data curation, Investigation, Validation, Writing—review & editing; Lijiao Gong: Data curation, Investigation, Validation, Writing—review & editing; Lixin Zhang: Data curation, Investigation, Validation, Writing – review & editing; Cong Wang: Project administration, Resources, Visualization, Writing – review & editing, Funding acquisition.

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