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Numerical and experimental study of an underground water pit for seasonal heat storage

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Abstract: Water pit heat storage is an important part of smart district heating systems that integrate various renewable energy sources. This project studied the storage capacity and thermal stratification in a 3000 m³ underground water pit in Huangdicheng, China using a finite difference model of the water pit that was validated by experimental data. The total heat loss from the water pit in the first year was measured to be 98 MWh and the storage efficiency was 62%. Further investigations using the validated model show that approximately 57% of the total heat loss took place through the side wall, 30% through the top and the rest through the bottom of the pit. The heat loss coefficient was largest along the side wall at 0.702 W·m⁻²·°C⁻¹. Higher charging temperatures create higher temperature differences between the top and bottom of the water pit, i.e. greater thermal stratification. The MIX number increases during most of the charging period and cannot represent the thermal stratification in the water pit during charging while the stratification number more accurately represents the stratification. Therefore, the stratification number is recommended for characterizing stratified water pits.

Key Words: Water pit; Seasonal heat storage; Thermal stratification; Numerical validation

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Nomenclature			
A	area, m ²	n	number of nodes
c_p	specific heat, J/kg/°C	Nu	Nusselt number
d	bury depth, m	p	pressure, MPa
Dep	calculation depth, m	Pr	Prandtl number
E	energy, J	Q	heat flow, W
Gr	Grashof number	r	radial direction
h	heat transfer coefficient, W/m ² /°C	R	water pit radius, m
H	height, m	Rad	calculation radius, m
$H(\cdot)$	height from the bottom, m	Rt	thermal resistant, °C/W
I_g	Global Irradiation, W/m ²	Str	Stratification number
L_v	latent heat, J/kg	T	temperature, °C
m	flow rate, kg/s	$T(\cdot)$	field temperature, °C
M	molar mass, kg/mol	u	wind velocity, m/s
MIX	MIX number	V	volume, m ³
Mp	energy-momentum, J·m	y	vertical direction
Subscripts			
–	average	i, j, k	number of elements
0	initial	ini	start of the test
a	air	$insu$	insulation
bot	bottom	L	from node $(i-1, j)$
ch	charging unit	$loss$	heat loss
CH	charging	num	numeric
$cold$	cold	p	profile
con	concrete	R	from node $(i+1, j)$
end	end of the test	s	soil
ev	environment	sat	saturated

<i>eva</i>	evaporation	<i>side</i>	water pit side
<i>exp</i>	experiment	<i>stratified</i>	stratified
<i>f</i>	film	<i>top</i>	top of the water pit
<i>full-mixed</i>	fully mixed	<i>U</i>	from node (<i>i,j-1</i>)
<i>g</i>	global	<i>vap</i>	vapor
<i>G</i>	from node (<i>i,j+1</i>)	<i>w</i>	water
<i>hot</i>	hot	<i>wall</i>	concrete wall
<i>Greek</i>			
α	thermal diffusion coefficient, m ² /s	η	energy efficiency
β	thermal expansion coefficient, 1/°C	λ	thermal conductivity, W/m/°C
γ	increase factor	ν	kinematic viscosity, m ² /s
δ	thickness, m	ρ	density, kg/m ³
Δ	difference, m	τ	time, s
φ	absorption factor of ground surface		

1 Introduction

Seasonal heat storage is essential for district heating systems because they can flexibly integrate various fluctuating renewable energy sources [1]. The seasonal heat storage cycle varies over an entire year to collect and use solar energy [2]. Seasonal heat storage systems can be divided into sensible heat storage, latent heat storage and chemical energy storage depending on the storage medium [3]. Sensible heat storage is still the most commonly used type of seasonal heat storage system [4] which can be categorized as water pit heat storage, borehole heat storage, water-gravel heat storage and aquifer heat storage [3-7] as shown in Fig. 1.

Fig. 1 Four types of seasonal sensible heat storage systems

Water pit heat storage systems are simple systems that store hot water in very large excavated basins with an insulated lid. The sides and bottom are typically covered by polymer liners. The water can also be stored in artificial pits made of reinforced concrete or stainless steel constructed below ground or near the surface, so these systems may also be called buried tank heat storage. Borehole heat storage systems are similar to geothermal heat exchange systems with a carrier fluid circulated through a closed-loop pipe network installed in vertical boreholes backfilled with sand bentonite. A key limitation of borehole heat storage systems is their relatively low heat extraction efficiency [8]. Water-gravel heat storage systems fill the watertight plastic liner with a gravel–water mixture that serves as the storage material. Heat is charged into and discharged out of the storage medium either by direct water exchange or by plastic piping installed in different layers inside the pool. The gravel–water mixture has a lower specific heat than water alone; therefore, the basin volume has to be approximately 50% larger than an equivalent water pit heat storage system to obtain the same heat storage capacity [7]. For aquifer heat storage system, groundwater is extracted from the cold well during the summer for cooling which depletes the cold store during the cooling season. The warmed return water is injected in the warm well(s) to recharge the warm store. In the winter the process is reversed with water pumped from the warm wells as a low temperature heat source for one or more heat pumps. After the heat transfer, the chilled water from the heat pumps is injected into the cold wells to recharge

the cold store for the following summer. Thus, all the water extracted from the storage region is re-injected into the opposite storage region [6, 9]. One important limitation of aquifer heat storage systems is that they need special geological conditions having high permeability water-saturated sand layers without natural groundwater flow. Water pit heat storage systems are currently the most reliable and widely used systems for seasonal heat storage[4, 7]. Larger storage volumes lead to increased storage efficiencies since the surface area does not increase proportionally to the volume [2]. With a large underground hot water storage system, the solar fraction of a district heating system can be significantly increased up to 50% of the heat demand of the district heating network[1].

In 1983, Hansen et al. investigated a small 500 m³ pilot water pit heat storage system on the campus of the Technical University of Denmark [10]. Later, in 1994, Kübler et al. presented investigations of a 600 m³ pilot heat storage system in Rottweil [11]. From then on, many water pit heat storage systems and buried tank storage systems have been built in Denmark, Germany, and other European countries [5, 7]. Most of the large scale water pits are in Denmark. For instance, the 60000 m³ water pit in the Dronninglund district heating system (in operation since 2014), the 110000 m³ water pit in the Gram district heating system (in operation since 2016) and the 200000 m³ water pit in the Vojens district heating system (the largest in the world). Operating data from these plants has been very helpful for designing and optimizing new water pits. However, there are few reports on the performance of these plants in the literature.

Water pits are costly to construct; therefore, the pit must be accurately modeled before construction to guarantee the economic feasibility and effective planning of the pit. Modeling also provides an understanding of the water pit operations to optimize planning and development. However, there are very few studies on simulating large water pits. In 2008, Panthalookaran et al. presented a validated CFD model for water pit charging/discharging using experimental data from two water pits in Germany [12]. The model was later used to develop a characterization scheme for evaluating the performance of various boundary designs during the storage mode of a large stratified water pit [13]. In 2017, Fan et al. experimentally and numerically investigated the thermal behavior of the 75,000 m³ water pit in the Marstal solar heating plant [1]. Their results showed that return temperature back to the water pit that was much higher than the temperature at the bottom of the pond created strong mixing that destroyed the stratification at the lower part of the pond. If the return temperature was lower than the temperature in the bottom part of the water pit, then the return inlet should be at the bottom. In

2013, Park et al. investigated the influence of the aspect ratio of a torus-shaped rock cavern on the thermal stratification and heat loss during the storing mode [14] based on a detailed two-dimensional axisymmetric CFD simulation. Seven 100000 m³ rock caverns with aspect ratios from 1.0 to 4.0 were investigated. Their results showed that an aspect ratio of 3.5 was most preferable for this type of torus-shaped rock cavern for thermal energy storage. In 2017, Chang et al. numerically and experimentally investigated the heat loss from a water pit in a pyramid stump [15] to analyze the mechanism for the temperature stratification driven by buoyancy. They investigated the standby of a 100000 m³ water pit with various geometries based using a two-dimensional axisymmetric CFD simulation. Their results showed that deeper water pits and steeper side walls led to more thermal stratification and better thermal efficiencies [16]. No other detailed CFD models for large water pits were found in the literature. CFD calculations are often very time consuming; therefore, all of these studies were either based on short time analyses or considered just the standby mode. CFD investigations of seasonal heat storage variations are in most cases impractical [1, 15], though methods such as the similarity principle may reduce the simulation times [17].

One dimensional models of seasonal heat storage systems have been developed and made commercially available [18], for instance XST [19] and ICEPIT [20]. In 2005, Raab et al. developed a TRNSYS model for the 2795 m³ water pit in Hannover using XST. The measured and calculated heat transfer rates in 2002 were in good agreement with differences of less than 5% [19]. In 1996, Hornberger used a validated ICEPIT model to simulate three combined heating/cooling systems with different sizes with the results showing that the combined heating/cooling systems save up to 42.9% of the primary energy used compared to separate conventional systems with air conditioners and gas burners and that the cold losses per volume decreased with increasing storage volume [20]. In addition to these two commercial water pit models, Ochs et al. developed a coupled finite difference (FD) and finite element (FE) heat storage model based on PDETOOL in MATLAB [21] and COMSOL [22]. There are few other published simplified one dimensional models for large underground hot water storage pits. The studies mentioned here are simply applications of commercial models with no detail descriptions of the thermal stratification mechanics in the water pit or heat conduction in the soil.

Lumped capacity models have also been used to simulate water pits. From the year of 1997 to 2012, analytical models of underground storage systems having the shapes of the sphere [23-25] or partial spheres [26] were used by Yumrutas and his colleagues [24-27]. In 2007, Zhang et al. studied

an underground heat storage system with insulation on the top [28]. In 2017, Jradi et al. simulated a rectangular buried water tank with a finite difference model [29]. However, these studies neglected the thermal stratification in the pit because they could not calculate the temperature distribution in the water pit, so the lumped capacity model cannot be used to accurately investigate the effect of thermal stratification in the water pit.

Furthermore, no studies validating the predictions of the soil temperatures near an underground water pit can be found in the literature. Thus, more detailed experimental and theoretical studies of water pit heat storage are needed. The present study uses a simplified one dimensional model to analyze a 3000 m³ cylindrical underground concrete water pit in Huangdicheng, China. The model was validated by comparison to operating data for the water pit in 2018. The storage efficiency and heat loss from the water pit were analyzed. The thermal stratification of the water pit was also analyzed based on the experimental and simulation results.

2 Methodology

2.1 Experimental method

2.1.1 System

Fig. 2 Seasonal heat storage system in Huangdicheng

A 3000 m³ underground water pit heat storage (this is also called a buried tank heat storage system because the pit walls are vertical) was built in 2018 in Huangdicheng, China to supply space heating for a hotel, as shown in Fig. 2. The system consists of a solar collector system, a heat storage system and a heating system. A schematic of the plant layout is shown in Fig. 3. The plant was put into operation in 2018 (09-04-2018). The total solar collector area was 660 m². During the non-heating season (From 01-04 to 31-10), sunlight reflected from the heliostats is concentrated onto the receiver to heat the water from the bottom of the water pit. Then, the hot water is charged into the top of the water pit by pump P1. During the heating season (From 01-11 to 31-03), the hot water stored in the water pit is used to heat cold water from the buffer tank through heat exchanger HE1. Then, the buffer tank supplies heat to the hotel through heat exchanger HE2. Two control strategies were used for charging in 2018. One was constant flow control with pump P1 in the solar collector subsystem turned on when either the Direct Normal Irradiance (DNI) was higher than a minimum starting threshold or the outlet fluid temperature in the collector system was higher than a pre-set temperature during the daytime. The pump was turned off when either of these conditions was no longer satisfied. The circulating pump flowrate was constant during operation [28]. The other control method was temperature difference control. In this case, when the DNI was higher than the minimum starting threshold or the monitored receiver outlet fluid temperature was higher than an upper limit, pump P1 was stopped. P1 was not started until the difference between the monitored receiver outlet fluid temperature and the temperature at the top of the water pit were above a high pre-set value. When the difference was lower than a low pre-set temperature, P1 was stopped. In this case, P1 was frequently started and stopped during the day. For discharging during the heating season, when the temperature at the top of the water pit was higher than a pre-set temperature (for example 60°C), P2 was started to heat the water in the buffer tank through heat exchanger HE1.

Fig. 3 Solar district heating system with seasonal heat storage in Huangdicheng

2.1.2 Concrete water pit

Fig. 4 Underground water pit

The underground water pit heat storage system is illustrated in Fig. 4. This water pit had 0.3 m thick concrete walls and was buried 1.0 m underground. A 0.2 m thick polystyrene board was placed on top of the concrete lid. The water level in the pit was kept at approximately 5.0 m during operation. Two openings were installed for charging and discharging. The Inlet/Outlet Opening was 4.0 m above

the bottom and the Outlet/Inlet Opening was 0.3 m above the bottom. Horizontal round plates were installed at both the Inlet/Outlet Opening and the Outlet/Inlet Opening to minimize the influence of the flow on the stratification. During operation, cold water from the bottom of the water pit was pumped to the solar receiver to be heated in the solar tower. The heated water was then circulated back to the top of the storage tank through the Inlet/Outlet opening as shown in Fig. 4. During the winter, hot water was discharged from the water pit through the Inlet/Outlet Opening to supply heat to the hotel. Since the water temperature in the water pit was higher than the surrounding soil temperature, the heat was lost to the soil which increased its temperature. Therefore, the storage tank model includes a large volume of soil around the tank.

2.1.3 Test equipment

The experiment used Pt100 thermocouples to measure the ambient air, soil, and hot water temperatures. The measurement accuracy of the thermocouples was ± 0.5 °C in the range 0-100 °C. HH-HYBLUG-50 Vortex type flowmeters were used to measure the flow rates during the charging and discharging of the water pit. A TBQ-2-B pyrometer was used to measure the solar global irradiance. Detailed information about the equipment is listed in Table 1.

Table 1 Equipment types and accuracies

Name	Parameter	Location	Type	Accuracy
TTOP	$T_{top,ch}$	Inlet/Outlet Opening	PT100	0-100 °C ± 0.5 °C
TBOT	$T_{bot,ch}$	Outlet/Inlet Opening	PT100	0-100 °C ± 0.5 °C
TEV	T_{ev}	-	PT100	0-100 °C ± 0.5 °C
TIF1 to TIF6	T_{FI} to T_{F6}	As shown in Fig. 5	PT100	0-100 °C ± 0.5 °C
TIM1 to TIM6	T_{MI} to T_{M6}	As shown in Fig. 5	PT100	0-100 °C ± 0.5 °C
TIN1 to TIN6	T_{NI} to T_{N6}	As shown in Fig. 5	PT100	0-100 °C ± 0.5 °C
TS1 to TS6	T_{SI} to T_{S6}	As shown in Fig. 5	PT100	0-100 °C ± 0.5 °C
TA1 to TA12	T_{AI} to T_{AI2}	Fig. 5	PT100	0-100 °C ± 0.5 °C
TB1 to TB12	T_{BI} to T_{BI2}	As shown in Fig. 5	PT100	0-100 °C ± 0.5 °C
TC1 to TC12	T_{CI} to T_{CI2}	As shown in Fig. 5	PT100	0-100 °C ± 0.5 °C
TD1 to TD12	T_{DI} to T_{DI2}	As shown in Fig. 5	PT100	0-100 °C ± 0.5 °C
TE1 to TE12	T_{EI} to T_{EI2}	As shown in Fig. 5	PT100	0-100 °C ± 0.5 °C
VTOP		Inlet/Outlet Opening	HH-HYBLWGY-50	0-25 m ³ /h, ± 1 %
VBOTTOM		Outlet/Inlet Opening	HH-HYBLWGY-50	0-25 m ³ /h, ± 1 %
IG	I_g	-	TBQ-2-B	Spectral range: 0.3-3 μ m

The water pit charging, discharging and standby characteristics were studied using thermocouples installed at various depths in the pit and in the soil. The temperatures were measured at the black dots shown in Fig. 5 along three lines of thermocouples arranged in the water pit. Each line had 6 thermocouples evenly distributed from the bottom to the top of the pit. The line of thermocouples in the center was named TIF while that near the concrete wall was TIN. The thermocouples in between were named TIM. The thermocouples in each line were numbered as 1 to 6 from top to bottom. Thus, TIF1 is the thermocouple at the top of line TIF. In a similar way, the line of thermocouples along the outer concrete wall was named TS. Sixty more thermocouples were installed in the soil near the concrete water pit to measure heat conduction in the soil. The lines of thermocouples in the soil were then named TA to TE while the thermocouples in each line from the top to the bottom were named 1 to 12. Thus, TE12 is the bottom thermocouple along line TE.

Fig. 5 Thermocouple arrangement in the underground water pit

2.2 Numerical analysis

A simplified mathematical model of the 3000 m³ underground water pit was developed for fast calculations based on the following assumptions:

- 1) There is no rust on the heat transfer surface of the water pit that reduces the heat transfer rate.
- 2) The soil is homogeneous and the influence of humidity and other factors on the heat transfer is not considered.
- 3) Mixing caused by the incoming flow into the water pit is not considered.
- 4) The water in the water pit at each height has the same temperature with no temperature gradient in the radial direction.

2.2.1 Grid scheme

With these assumptions, the seasonal heat storage model can be simplified to a one-dimensional model for the water body with an air layer on the top and a two-dimensional model for the soil and the concrete wall as shown in Fig. 6. The air layer is modeled with one node, while the water body is divided equally into n_w-1 nodes. The nodes in the water and the air layer were numbered from 1 to n_w as shown in Fig. 6.

Fig. 6 Mesh for the underground water pit.

The water pit was surrounded by a concrete wall $\delta=0.3$ m thick which is very small compared to the pit diameter, R . A number of nodes, $n_{\delta r}$, were created along the thickness of the concrete wall in

the radial direction with $n_{\delta y}$ nodes along the wall thickness in the height direction. A 0.2 m thick polystyrene board was placed on top of the concrete wall since the polystyrene board was much thinner than the size of the water pit with the polystyrene board not modeled explicitly but represented by a zero thickness layer with a thermal resistance between the top of the concrete wall and the soil as [30]:

$$Rt_{insu} = \frac{\delta_{insu}}{\lambda_{insu}} \quad (1)$$

The node sizes in the soil region in the radial and axial directions were increased by factors of γ_r and γ_y as shown in Fig. 6 to give a denser grid in the area adjacent to the water pit where a higher temperature gradient is expected.

Heat loss from the water pit can influence the temperature of a large volume of soil around it. Thus, the soil region had a radius 5 times the water pit radius ($Rad=5R$) and a depth underneath the pit of 5 times the water pit height to simulate the semi-infinite soil region. Since the depth of the bottom of the water pit was d , the total soil depth was $Dep=5H+d$. The measurements showed during the first year of operation, the water pit heating had an insignificant influence on the soil temperatures along line TE; thus, the soil region was considered to be large enough and the semi-infinite boundary was appropriate.

2.2.2 Water and air layer region

There was a thick air layer between the water body and the top concrete wall. The air layer is an enclosed space saturated with water vapor. The air layer energy balance was [30]:

$$\frac{\rho_a \rho_{vap}}{W \rho_{vap} + (1-W) \rho_a} [c_{p,a} W + c_{p,vap} (1-W)] V_1 \frac{\partial T_{w,1}}{\partial \tau} = \frac{T_{top} - T_{w,1}}{\frac{1}{h_{top} A_p} + \frac{\Delta y_0}{2\lambda_{con} A_p}} + Q_{eva} + \frac{T_{side,1} - T_{w,1}}{\frac{1}{h_{side,1} A_{side,1}} + \frac{\Delta r_0}{2\lambda_{con} A_{side,1}}} \quad (2)$$

The heat transfer in the air layer consisted of the heat transfer between the air layer and the top concrete wall, the side concrete wall of the water pit and the water surface. The heat transfer between the air layer and the top concrete wall was a combination of condensation and natural convection. For simplicity, the empirical equation used by Uchida was used to calculate the heat transfer rate [31]:

$$h_{top,1} = h_{side,1} = 380 \left(\frac{W}{1-W} \right)^{-0.7} \quad (3)$$

Since the air was saturated with vapor, the air mass fraction was determined as [32]:

$$W = \frac{M_a p_{ev}}{M_a (p_{ev} - p_{sat,1}) + M_{H_2O} p_{sat,1}} \quad (4)$$

Where p_{ev} is the atmospheric pressure and $p_{sat,1}$ is the vapor partial pressure. The partial pressure of the saturated vapor was calculated using the Antoine Equation [33]:

$$p_{sat,1} = \exp(9.3876 - \frac{3826.36}{T_{w,1} + 227.68}) \quad (5)$$

The heat loss due to evaporation from the water surface was calculated as [34]:

$$Q_{eva} = m_{evp} L_{vap} \quad (6)$$

Where [34]:

$$m_{evp} = 0.14 \left[\frac{g \beta_{vap} \alpha_{vap}^2 (T_{w,2} - T_{w,1})}{v_{vap}} \right]^{1/3} (\rho_{vap,sat,2} - \rho_{vap,sat,1}) \quad (7)$$

Here, $\rho_{vap,sat,1}$ is the saturated vapor density at temperature $T_{w,1}$ and $\rho_{vap,sat,2}$ is the saturated vapor density at temperature $T_{w,2}$.

The energy equation for the first node in the water was [30]:

$$\rho_w c_{p,w} V_2 \frac{\partial T_{w,2}}{\partial \tau} = -Q_{eva} + \frac{T_{w,3} - T_{w,2}}{\frac{\Delta H}{\lambda_w A_p}} + \frac{T_{side,2} - T_{w,2}}{\frac{1}{h_{side,2} A_{side,2}} + \frac{\Delta r_0}{2\lambda_{con} A_{side,2}}} - c_{p,w} \dot{m}_{in,2} T_{w,2} + c_{p,w} \dot{m}_{in,2} T_{in,2} \quad (8)$$

Here:

$$A_{side,k} = \begin{cases} 2\pi R \Delta H & (k > 1) \\ 2\pi R \delta_a & (k = 1) \end{cases} \quad (9)$$

$$A_p = \pi R^2 \quad (10)$$

The heat transfer between the water and the side wall was a combination of natural convection and forced convection. In this study, the maximum charging or discharging flow rate was 2.8 kg/s which would give a maximum upward or downward speed of 4.96×10^{-6} m/s. This gives a Reynolds number of approximately 102, so Gr/Re^2 was much larger than 10. Additionally, the charging and discharging times were much shorter than the standby period. Therefore, natural convection was

more important than forced convection [30]. The water pit diameter was so large that the heat transfer could be modeled as natural convection in a large space with the heat transfer coefficient between the water and the concrete wall given by [30]:

$$h_{side,k} = \frac{\lambda_w}{H} \left\{ 0.825 + \frac{0.387 (Gr_{w,k} Pr_{w,k})^{1/6}}{[1 + (0.492 / Pr_{w,k})^{9/16}]^{8/27}} \right\}^2 \quad (11)$$

Where [30],

$$Gr_{w,k} = \frac{g \beta_{w,k} (T_{side,k} - T_{w,k}) H^3}{\nu_{w,k}^2} \quad (12)$$

The property values were evaluated at:

$$T_{f,k} = \frac{T_{side,k} + T_{w,k}}{2} \quad (13)$$

Then, the energy equation for node k in the water region was given by:

$$\begin{aligned} \rho_w c_{p,w} V_k \frac{\partial T_{w,k}}{\partial \tau} = & \frac{T_{w,k-1} - T_{w,k}}{\frac{\Delta H}{\lambda_w A_p}} + \frac{T_{w,k+1} - T_{w,k}}{\frac{\Delta H}{\lambda_w A_p}} + \frac{T_{side,k} - T_{w,k}}{\frac{1}{h_{side,k} A_{side,k}} + \frac{\Delta r_0}{2 \lambda_{con} A_{side,k}}} \\ & + c_{p,w} (T_{w,k-1} - T_{w,k}) \dot{m}_{k-1} + c_w (T_{in,k} - T_{w,k}) \dot{m}_{in,k} \end{aligned} \quad (14)$$

The energy equation for the bottom node in the water pit was:

$$\begin{aligned} \rho_w c_{p,w} V_{n_w} \frac{\partial T_{w,n_w}}{\partial \tau} = & \frac{T_{w,n_w-1} - T_{w,n_w}}{\frac{\Delta H}{\lambda_w A_p}} + \frac{T_{bot} - T_{w,n_w}}{\frac{1}{h_{bot} A_p} + \frac{\Delta y_0}{2 \lambda_w A_p}} + \frac{T_{side,n_w} - T_{w,n_w}}{\frac{1}{h_{side,n_w} A_{side,n_w}} + \frac{\Delta r_0}{2 \lambda_{con} A_{side,n_w}}} \\ & + c_{p,w} (T_{w,n_w-1} - T_{w,n_w}) \dot{m}_{k-1} + c_{p,w} (T_{in,n_w} - T_{w,n_w-1}) \dot{m}_{in,n_w} \end{aligned} \quad (15)$$

The heat transfer coefficient along the lower surface of a cold plate was used to determine the heat transfer between the water and the bottom concrete wall [30]:

$$h_{bot} = \begin{cases} 2.16 \frac{\lambda_w}{D} (Gr_{bot} Pr_{bot})^{\frac{1}{4}} & 10^4 \leq Gr_{bot} Pr_{bot} \leq 10^7 \\ 0.60 \frac{\lambda_w}{D} (Gr_{bot} Pr_{bot})^{\frac{1}{3}} & 10^7 \leq Gr_{bot} Pr_{bot} \leq 10^{11} \end{cases} \quad (16)$$

Where [30],

$$Gr_{bot} = \frac{g \beta_{w,n_w} (T_{w,n_w} - T_{bot}) D^3}{64 \nu_{bot}^2} \quad (17)$$

Equations (2) to (17) are a set of multiple differential equations [35]. With this method, numerical diffusion may influence the thermal stratification in the water pit. As shown in Fig. 7,

each node in the water region contained 2 kg water at 10°C with 1 kg/s hot water entering the pit from the top. Assuming no thermal conduction or mixing between nodes, the fluid in the first node would be completely replaced with a 2 s time step by the incoming water and the first node temperature would then be 60°C while the other nodes would not be influenced because there is no conduction or mixing between nodes. However, with a 1 s time step, the temperatures of both the first and second nodes would be influenced after 2 s. The false diffusion of heat is caused by the simplified method of discretization of the geometry into a limited number of nodes; therefore, this is called numerical diffusion.

Fig. 7 Numerical diffusion in the water region

There are two ways to minimize numerical diffusion. One way is to increase the number of nodes which increases the discretization accuracy, but this will result in a large number of computational nodes and a much longer computing time. Thus, the mesh in the water pit was refined locally to improve the discretization accuracy without significantly increasing the computing time. The second method is to use the plug flow method [35] in the XST model in TRNSYS [19]. This method uses a

virtual buffer tank with the same volume as one node in the water region. During charging, the hot water is first stored in the buffer tank. When the buffer tank is full, the water in the first node in the water region is replaced by the water in the buffer tank with the water in all the nodes flowing down one node. Both methods were used to find the best solution.

At the steady state, the water temperature in each lower node should be lower than the temperature in the next higher node. In this case, the following procedure is followed:

1) Sort the temperatures in the pit every time step to check that the temperature decreases with depth.

2) If the temperature increases with depth, mix the temperature of the affected nodes.

3) Any temperature profile is accepted.

As seen in Fig. 6, the meshes in the water and soil regions in the axial direction are the same; thus, $T_{side,k}$ can be easily calculated for node k . The average temperatures of the top concrete wall, T_{top} , and the bottom concrete wall, T_{bot} , of the pit were defined as an area-based weighted temperature [30]:

$$T_{top} = \frac{2 \int_0^R T(r, -d) r dr}{R^2} \quad (18)$$

$$T_{bot} = \frac{2 \int_0^R T(r, -d - H) r dr}{R^2} \quad (19)$$

2.2.3 Soil region

2.2.3.1 Thermal conduction in the soil

The temperature of the node (i, j) in the soil region will depend on the thermal conduction from the neighboring nodes, as shown in Fig. 8.

Fig. 8 Node (i, j) and its neighbors

The heat transfer between the node $(i-1, j)$ and the node (i, j) is given by [30]:

$$Q_L = \frac{T_{(i-1,j)} - T_{(i,j)}}{\frac{1}{\lambda_{(i-1,j)} 2\pi r_{(i-1,j)} \Delta y_{(i-1,j)}} + \frac{1}{\lambda_{(i,j)} 2\pi r_{(i,j)} \Delta y_{(i,j)}} \frac{\Delta r_{(i,j)}}{2}} \quad (20)$$

The heat transfer between the node $(i+1, j)$ and the node (i, j) is given by [30]:

$$Q_R = \frac{T_{(i+1,j)} - T_{(i,j)}}{\frac{1}{\lambda_{(i,j)} 2\pi r_{(i,j)} \Delta y_{(i,j)}} + \frac{1}{\lambda_{(i+1,j)} 2\pi r_{(i+1,j)} \Delta y_{(i+1,j)}} \frac{\Delta r_{(i+1,j)}}{2}} \quad (21)$$

The heat transfer between the node $(i, j+1)$ and the node (i, j) is given by [30]:

$$Q_G = \frac{T_{(i,j+1)} - T_{(i,j)}}{\frac{\Delta y_{(i,j+1)}}{4\pi\lambda_{(i,j+1)} r_{(i,j+1)} \Delta r_{(i,j+1)}} + \frac{\Delta y_{(i,j)}}{4\pi\lambda_{(i,j)} r_{(i,j)} \Delta r_{(i,j)}}} \quad (22)$$

The heat transfer between the node $(i, j-1)$ and the node (i, j) is given by [30]:

$$Q_U = \frac{T_{(i,j-1)} - T_{(i,j)}}{\frac{\Delta y_{(i,j-1)}}{4\pi\lambda_{(i,j-1)} r_{(i,j-1)} \Delta r_{(i,j-1)}} + \frac{\Delta y_{(i,j)}}{4\pi\lambda_{(i,j)} r_{(i,j)} \Delta r_{(i,j)}}} \quad (23)$$

Equations (19) to (23) were simplified using thermal resistances for the four directions as L, R, U, and G as shown in Fig. 8. The thermal resistances between boundary L and boundary R and node (i, j) are:

$$Rt_{(i,j),L} = Rt_{(i,j),R} = \frac{1}{\lambda_{(i,j)} 2\pi r_{(i,j)} \Delta y} \frac{\Delta r_{(i,j)}}{2} \quad (24)$$

The thermal resistances between boundary U and boundary G and node (i, j) are:

$$Rt_{(i,j),U} = Rt_{(i,j),G} = \frac{\Delta y_{(i,j)}}{4\pi\lambda_{(i,j)}r_{(i,j)}\Delta r_{(i,j)}} \quad (25)$$

Thus, the energy balance for each node in the soil can be written as:

$$\rho_{(i,j)}c_{(i,j)}V_{(i,j)}\frac{\partial T_{(i,j)}}{\partial \tau} = \frac{T_{(i-1,j)} - T_{(i,j)}}{Rt_{(i-1,j),R} + Rt_{(i,j),L}} + \frac{T_{(i+1,j)} - T_{(i,j)}}{Rt_{(i+1,j),L} + Rt_{(i,j),R}} + \frac{T_{(i,j-1)} - T_{(i,j)}}{Rt_{(i,j-1),U} + Rt_{(i,j),G}} + \frac{T_{(i,j+1)} - T_{(i,j)}}{Rt_{(i,j+1),G} + Rt_{(i,j),U}} \quad (26)$$

2.2.3.2 Heat transfer to the ambient

The thermal resistance between the soil and the ambient air is [30]:

$$Rt_{(i,j),ev} = \frac{1}{2\pi r_{(i,j)}\Delta r_{(i,j)}h_{ev}} \quad (27)$$

The heat transfer coefficient between the ambient air and the soil, h_{ev} , was calculated using McAdam's formula [36]:

$$h_{ev} = \begin{cases} 5.4 + 3.8u & u < 4.88 \text{ m/s} \\ 7.2u^{0.78} & u \geq 4.88 \text{ m/s} \end{cases} \quad (28)$$

Thus, the energy balance for the surface node in the soil was:

$$\rho_{(i,1)}c_{(i,1)}V_{(i,1)}\frac{\partial T_{(i,1)}}{\partial \tau} = \frac{T_{(i-1,1)} - T_{(i,1)}}{Rt_{(i-1,1),R} + Rt_{(i,1),L}} + \frac{T_{(i+1,1)} - T_{(i,1)}}{Rt_{(i+1,1),L} + Rt_{(i,1),R}} + \frac{T_{ev} - T_{(i,1)}}{Rt_{(i,1),ev} + Rt_{(i,j),G}} + \frac{T_{(i,2)} - T_{(i,1)}}{Rt_{(i,2),G} + Rt_{(i,1),U}} + 2\pi r_{(i,1)}\Delta r_{(i,1)}I_g\varphi \quad (29)$$

The thermal resistance between the air layer and the top wall of the concrete pit is:

$$Rt_{(i,j),top} = \frac{1}{2\pi r_{(i,j)}\Delta r_{(i,j)}h_{top}} \quad (30)$$

The thermal resistance between the bottom concrete wall and the water is:

$$Rt_{(i,j),bot} = \frac{1}{2\pi r_{(i,j)}\Delta r_{(i,j)}h_{bot}} \quad (31)$$

The thermal resistance between the side concrete wall and the water or air layer is:

$$Rt_{(i,j),side} = \frac{1}{2\pi(r_{(i,j)} - \frac{\Delta r_{(i,j)}}{2})\Delta y_{(i,j)}h_{side,i}} \quad (32)$$

2.2.3.2 Semi-infinite and symmetry boundary conditions

The boundary condition at the last node at the semi-infinite boundary in both the radial and axial directions was assumed to be an adiabatic boundary [30]:

$$\frac{\partial T}{\partial r}|_{r=R_{ad}} = 0; \quad \frac{\partial T}{\partial y}|_{y=-Dep} = 0 \quad (33)$$

The symmetry boundary was used for the nodes along the y-axis [30]:

$$\frac{\partial T}{\partial r} \Big|_{r=0} = 0 \quad (34)$$

2.2.4 Solution method

The method to solve these equations is shown in Fig. 9.

Fig. 9 Solution method for Eqs. (1) - (34)

The measured temperatures and flow rates during charging and discharging, the global irradiation, and the ambient air temperature were input into the simulation. The initial water pit and soil temperatures were 13.2°C. The thermal physical properties used in the calculations are listed in Table 2.

Table 2 Thermal physical properties of the material in the experiment

Material	Density (kg/m ³)	Thermal conductivity (W/m°C)	Specific heat (J/kg°C)
----------	------------------------------	------------------------------	------------------------

Soil	900	1.3	2500
Water	1000	0.642	4200
Polystyrene board	28	0.042	1500
Concrete	2500	1.74	970

The thermal conductivity of the soil is influenced by many parameters and is, therefore, hard to determine by a simple test of some soil samples. In this model, the soil thermal conductivity was initially set as a constant equal to 1.0 W/mK. Once the best mesh scheme was selected for this problem, an optimization procedure based on Genopt (an open source software) was used to determine the actual soil thermal conductivity for which the calculated soil temperatures best matched the measured soil temperatures using the method given by Raab et al. [19]. The optimal value of the soil thermal conductivity is listed in Table 2. The thermal conductivity was then used in an additional sensitivity analysis of the mesh to show that the mesh was appropriate. A user-defined TRNSYS Type called UGSTS (UnderGround Seasonal Thermal Storage) was then developed that could be connected to other TRNSYS Types to investigate the seasonal heat storage system.

3 Model validation

3.1 Sensitivity analysis

The calculations of the water pit temperatures using the UGSTS model described by Eqs. 1-34 were very time consuming due to the large water pit volume and long operating times. Therefore, the number of nodes was reduced in the model by optimizing the node distribution in different regions of the computational region using various mesh parameters. The test data from 09-04-2018 to 01-01-2019 was used to validate the model. The ambient temperature and global irradiation were used as the boundary conditions for the soil surface. The measured flow rates and temperatures during charging and discharging were used as the boundary conditions for the water region. The water pit conditions during this period were very complex so the effects of charging, discharging and standby could not be investigated separately since the pit was charged during the day and cooled at night. The energy charge and discharge rates from the water pit each day from 09-04-2018 to 01-01-2019 are shown in Fig. 10.

Fig. 10 Heat charged to and discharged from the water pit from 09-04-2018 to 01-01-2019

3.1.1 Soil region

Various mesh designs were tested to find the best mesh for the soil region. The predictions using the various meshes were evaluated based on the first four months (from 09-04-2018 to 08-08-2018) of predicted water temperatures at the height of 4.25 m (the average of TIF1, TIM1 and TIN1), 2.65 m (the average of TIF3, TIM3 and TIN3) and 0.25 m (the average of TIF6, TIM6 and TIN6) from the bottom of the water pit. The mesh parameters are listed in Table 3.

Table 3 Soil mesh parameters.

Schemes	n_{δ_y}	n_{δ_r}	γ_y	γ_r	n_w
Scheme1	1	1	1	1	101
Scheme2	2	1	1	1	101
Scheme3	1	2	1	1	101
Scheme4	1	1	1.2	1.2	101
Scheme5	1	1	1.5	1.5	101
Scheme6	1	1	2	2	101
Scheme7	1	1	3	3	101

Fig. 11 Predicted temperatures for the 7 soil mesh schemes in Table 3.

The predicted soil temperatures for the 7 Schemes are shown in Fig. 11. There is nearly no difference between the results for Schemes 1, 2, 3 and 4, which means that adding one node across the concrete wall (from 1 to 2 nodes) does not influence the predicted temperatures in the water pit due to the relatively small thickness of the concrete wall. For mesh growth factors in the axial and radial directions larger than 2, the simulation result error after 4 months is much larger than 0.1°C. Thus, a growth factor of 2 was used in the radial and axial directions to balance the simulation time cost and the prediction accuracy.

3.1.2 Water region

Numerical diffusion can greatly influence the thermal stratification in the water pit. The influences of numerical diffusion and the mesh parameters in the water region on the prediction accuracy were investigated using 10 mesh designs for the water region as listed in Table 4.

Table 4 Mesh parameters for the water region.

Schemes	Method	n_w
Scheme1	Plug flow	21
Scheme2	Plug flow	41
Scheme3	Plug flow	61
Scheme4	Plug flow	101
Scheme5	Plug flow	151

Scheme6	Multinode	21
Scheme7	Multinode	41
Scheme8	Multinode	61
Scheme9	Multinode	101
Scheme10	Multinode	301

The influence of the plug flow method in the XST model [36] was investigated first with the results for the first 4 months shown in Fig. 12. When the nodes in the water region are very large ($n_w=21$), the buffer tank filling time is very long which leads to the stepwise increase in the water temperature seen in Fig. 12. For n_w larger than 61, the buffer tank filling has little influence on the simulation results with further increases of n_w to 101 or 151 having almost no influence on the predicted temperatures. Thus, $n_w=151$ was used for further calculations.

Fig. 12 Predicted temperatures using the plug flow method for various numbers of elements in the water pit.

The predictions of the UGSTS multinode differential equation model given by Eqs. 1 – 34 were then evaluated using Schemes 6 to 9 with the predictions compared in Fig. 13 with those of the plug flow model using Scheme 5.

Fig. 13 Temperatures predicted by the UGSTS multimode differential equation model for Schemes6-9 in Table 4 and by the plug flow model using Scheme5.

The multinode method predictions are nearly the same with more than 41 nodes in the water region with temperature differences of less than 0.2°C, so the predictions are grid independent for $n_w \geq 41$. In addition, the predicted water pit temperatures at different heights predicted by the plug flow method are almost the same as the results predicted by the multinode method with differences of less than 0.1°C. Thus, the multinode method gives reasonable predictions with fewer nodes in the water pit region, so the multinode method with $n_w=41$ was used for the simulations in this study.

3.1.3 Timestep

The calculations used the explicit finite difference time step method, so the stability condition for the model is:

$$\min \left\{ \frac{1}{\rho c V_k} \sum_j \frac{1}{R t_{kj}} \right\} \Delta \tau \leq 1 \quad (35)$$

Thus, the maximum time step is most influenced by the smallest node. Tests showed that the soil energy equations converged with very large time steps up to 1500 s. However, such large time steps will influence the accuracies of the predicted thermal stratification and heat losses in the water region.

Thus, the time step independence study used time steps of 15 s, 30 s, 60 s, and 120 s.

Fig. 14 Predicted temperatures for various time steps

The predictions for various time steps shown in Fig. 14 shows nearly no difference between the results for time steps of 15 s, 30 s and 60 s with observable differences for the 120 s times step of nearly 0.3°C at the end of the fourth month. Therefore, time steps higher than 120 s are not suitable for this calculation and a time step of 60 s was used in the following study.

3.2 Experimental validation

3.2.1 Water region

The multi-node differential equation model was validated using measurements in the water pit heat storage in Huangdicheng. The measured temperatures in the water pit at each height were again the averaged temperature measurements along lines TIF, TIM, and TIN at each height. The temperatures labeled Exp-4.25 were the average at 4.25 m (TIF1, TIM1, TIN1), Exp-2.65 was at 2.65 m (TIF3, TIM3, TIN3) and Exp-0.25 were at 0.25 m (TIF6, TIM6, TIN6) in the water pit. The temperatures labeled Num-4.25 were at 4.25 m, Num-2.65 was at 2.65 m and Num-0.25 was at 0.25 m in the water pit.

Fig. 15 Predicted and measured temperatures in the water pit

The predicted temperature is compared with the experimental data for 09-04-2018 to 01-01-2019 in Fig. 15. The root mean squared errors (RMSE) and the average relative error of the numerical results listed in Table 5 are 0.9°C for Num-0.25, 1.2°C for Num-2.65 and 1.4°C for Num-4.25. The average relative errors are 2.3% for Num-0.25, 2.8% for Num-2.65 and 2.6% for Num-4.25. Thus, the model predictions agree well with the data and this model can be used to simulate the thermal behavior of water pit heat storage systems during charging, discharging and standby.

Table 5 RMSE and average relative errors of the numerical results

Location	RMSE (°C)	Average relative error (%)
Num-0.25	0.9	2.3
Num-2.65	1.2	2.8
Num-4.25	1.4	2.6

This multinode differential equation model was also validated for charging and discharging with other climate conditions. The temperature increase in the water pit each day is very small; therefore, typical sets of days were selected to validate the model. There was no charging or discharging from 21-04-2018 to 27-04-2018, so these are typical standby mode days. The water pit was charged from 09-04-2018 to 09-10-2018. However, only one week of data was selected to validate the charging mode of the water pit; therefore, the days from 01-06-2018 to 07-06-2018 were selected. The water pit heat discharge started on 01-10-2018. The water pit was only discharged from 11-10-2018 to 16-10-2018. Therefore, these days were selected as the typical days for the discharge mode.

The temperature in the water pit during the typical standby mode days (from 21-04-2018 to 27-04-2018) is shown in Fig. 16. The RMSE of the predictions is less than 1.4°C during these days. The water temperature at the height of 4.25 m (Exp-4.25) decreases from 23.4°C to 21.8°C while the temperatures at 2.65 m and 0.25 m do not change much.

Fig. 16 Temperatures in the water pit during the typical standby mode days

The predicted and measured temperatures in the water pit during the typical charging mode days (from 01-06-2018 to 07-06-2018) are compared in Fig. 17. The RMSE of the numerical results is less

than 1.4°C during these days. Although the incoming water temperature during charging ranged from 60-90°C, the temperature increased little at the top (Exp-4.25). The small temperature increase was caused by mixing of the inlet water (on average approximately 40 m³ per day) with the upper part of the pool. Since the inlet opening is located at a height of 4 m, i.e. 1.0 m below the water surface, the incoming hot water will create a mixing zone about 600 m³ high in the upper 1 m of the pool resulting in lower mixed temperatures in the pool. Another cause of the low pool temperature is the large heat loss to the surrounding. The temperatures of the concrete wall and the surrounding soil were initially approximately 13°C; therefore, a large heat loss was expected during the initial operating period.

Fig. 17 Temperatures in the water pit during the typical charging mode days

The water pit temperatures during the typical discharging mode days (from 11-10-2018 to 16-10-2018) are shown in Fig. 18. The RMSE of the numerical results is less than 1.4°C during these days. The hot water at the top of the water pit was pumped to heat a hotel near the pit which reduced the top pool temperature (Exp-4.25) from 65.8°C to 60.6°C which is a much larger decrease than during the

standby period. Also, because the return water temperature was a little warmer than the water near the bottom of the pool (Exp-0.25), the bottom pool temperature increased from 43.1°C to 44.1°C. Therefore, a higher return water temperature will reduce the thermal stratification in the water pit.

Fig. 18 Temperatures in the water pit during the typical discharging mode days

3.2.2 Soil region

The soil temperature variations are a function of the pit water temperature, the ambient temperature and the solar irradiance on the soil surface. 66 thermocouples were buried in the soil around the water pit as shown in Fig. 5 to measure the temperature field around the water pit. The predicted soil temperatures are compared with the measured temperatures on 01-01-2019 in Fig. 19.

Fig. 19 Predicted and measured soil temperature distributions on 01-01-2019

In most parts of the soil region, the differences are less than 5°C which indicates that this model for the underground water pit and surrounding soil can adequately predict the heat transfer in the soil.

Fig. 20 Measured and predicted soil temperatures at TA1 to TE1

Fig. 21 Measured and predicted soil temperatures at TA6 to TE6

Ten thermocouples in the soil region (TA1 to TE1 and TA6 to TE6) were selected to show the soil temperature from 09-04-2018 to 01-01-2019. The temperature measurement locations are indicated in the experimental picture in Fig. 19. The calculated temperatures are compared to the measured temperatures in Fig. 20 and Fig. 21 which illustrates the development of the soil temperature field. The soil temperature decreases with increasing distance from the water pit. Heat loss from the water pit increases the soil temperature at TA1 by 16.8°C while the soil temperature at TE1 is increased by only 0.3°C. The temperatures at TA1 to TE1 are higher than those at TA6 to TE6 because of the higher water temperature in the upper part of the water pit due to thermal stratification. Furthermore, the temperatures from TA1 to TE1 are more affected by the ambient temperature so they decreased after September, while the temperatures from TA6 to TE6 were less affected by the ambient temperature because they were buried 5 meters deeper than those from TA1 to TE1.

Fig. 22 Predicted and measured soil temperatures

The temperature differences between the predicted and measured results are shown in Fig. 22. The results show that even though the model started with an initially uniform soil temperature distribution, the model was still able to properly predict the temperature trends in the soil. The errors in the predicted temperatures are smaller than 7°C (except for the first month). The RMSEs of the numerical results are listed in Table 6. The RMSE of all 10 thermocouples is less than 3.6°C. Considering the uncertainties in the thermal properties of the soil and the initial conditions used in the model, the prediction accuracy is considered to be acceptable.

Table 6 RMSE of the predicted soil temperatures

	TA1	TB1	TC1	TD1	TE1	TA6	TB6	TC6	TD6	TE6
RMSE(°C)	1.9	3.6	2.3	2.2	2.3	1.2	1.6	1.1	1.7	2.0

4 Analysis and discussion

4.1 Energy balance

4.1.1 Definitions

The UGSTS code was used to calculate the heat losses from the side wall, the bottom, and the top of the pit. The heat loss from the top was calculated as:

$$Q_{top,loss} = \int \frac{T_{top} - T_{w,l}}{\frac{1}{h_{top} A_p} + \frac{\Delta y_0}{2\lambda_{con} A_p}} d\tau \quad (36)$$

The heat loss from the side wall was calculated as:

$$Q_{side,loss} = \int \sum_{k=1}^{n_w} \frac{T_{side,k} - T_{w,k}}{\frac{1}{h_{side,k} A_{side,k}} + \frac{\Delta r_0}{2\lambda_{con} A_{side,k}}} d\tau \quad (37)$$

Here, k is the number of the nodes in the water region as shown in Fig. 6.

The heat loss from the bottom was calculated as:

$$Q_{bot,loss} = \int \frac{T_{bot} - T_{w,bw}}{\frac{1}{h_{wb} A_p} + \frac{\Delta y_0}{2\lambda_w A_p}} d\tau \quad (38)$$

The total heat loss from the water pit was then:

$$Q_{loss,num} = Q_{top,loss} + Q_{side,loss} + Q_{bot,loss} \quad (39)$$

The total heat loss from the water pit was also determined from the measured data.

$$Q_{loss,exp} = Q_{CH} - Q_{DC} - \Delta Q \quad (40)$$

Here, Q_{CH} is the energy input into the water pit, which was calculated as:

$$Q_{CH} = c_{p,w} \int \dot{m}_{CH} (T_{in,CH} - T_{out,CH}) d\tau \quad (41)$$

Q_{DC} is the energy discharged from the water pit, which was calculated as:

$$Q_{DC} = \int c_{p,w} \dot{m}_{DC} (T_{in,DC} - T_{out,DC}) d\tau \quad (42)$$

ΔQ is the internal energy change in the water pit, which was calculated as:

$$\Delta Q = \rho_w c_{p,w} \int_V T_w - T_{w,ini} dV \quad (43)$$

Then, the water pit storage efficiency was defined as:

$$\eta = \frac{Q_{DC} + \Delta Q}{Q_{CH}} \quad (44)$$

4.1.2 Energy flow

The measured data was used to analyze the water pit energy balance. The water pit energy balance from 09-04-2018 to 01-01-2019 is illustrated in Fig. 23. The pit received 260 MWh of solar heat with 39 MWh discharged to the heating system. The internal energy of the water was calculated from the temperature measurements at the locations shown in Fig. 5. In 2018, the energy in the pool increased by 123 MWh by the end of 2018. The total heat losses to the surrounding soil and the ambient air were then about 98 MWh from Eq. (40) in the first year (from 09-04-2018 to 01-01-2019). The maximum temperature in the storage volume in 2018 was 67°C with a minimum of 12°C. The pit energy efficiency for the first year was then approximately 62% which is a little smaller than that reported for the Hannover 3000 m³ pool (71.2%) [19]. The energy efficiency for the Marstal 75000 m³ water pit storage was 62% in 2015 while that for the Dronninglund 75000 m³ water pit was 91% in 2016 [37].

Fig. 23 Energy flow diagram for the water pit storage in Huangdicheng from 09-04-2018 to 01-01-2019

However, a large part of the hot water stored in the Huangdicheng 3000 m³ water pit storage during the first year was below 40°C. The heat losses from there during the first year are listed in Table 7. As the water pit temperature increases as shown in Fig. 15, the heat losses will increase. Thus, since the average water temperature will increase since no heat pump was installed (the return water temperature was approximately 40°C), the heat losses in the second year will be greater and the energy efficiency will be lower.

The model was then used for a detailed investigation of the water heat losses. Table 7 presents the measured and calculated heat losses for each month during the first year. The calculated total heat loss is about 99 MWh, which is 1.14% larger than the measured heat loss. The simulation results also show that the greatest heat loss is from the side wall because there is no insulation on the side wall of the water pit.

Table 7 Heat losses from the water pit

Month	Top-Num(MWh)	Bottom-Num(MWh)	Side-Num(MWh)	Total-Num(MWh)	Total-Exp(MWh)
4	0.350	0.000	1.104	1.454	1.361
5	0.946	0.076	3.772	4.794	3.427
6	1.207	0.728	4.756	6.692	5.053
7	1.722	1.637	6.032	9.390	10.050
8	2.307	3.096	7.928	13.331	13.659
9	2.741	4.395	8.067	15.203	14.175
10	3.840	4.621	8.504	16.965	21.780
11	4.013	2.874	7.986	14.873	13.302
12	4.539	3.199	8.889	16.626	15.398
Total	21.664	20.626	57.037	99.328	98.206

The pit heat loss coefficients are then listed in Table 8. The total heat loss coefficient is 0.366 W/m²/°C. The heat loss coefficient along the top wall is the smallest because of the insulation. The heat loss coefficients along the side are much larger than along the bottom since there was very little convection in the water due to the thermal stratification in the water pit with much higher temperatures near the top than near the bottom. Also, the soil near the upper part of the pit will be cooled by the ambient air. Therefore, insulation along the side can increase the thermal efficiency of the water pit more effectively than insulation along the bottom.

Table 8 Heat loss coefficients around the water pit

	Top	Bottom	Side	Total
Total (MWh)	21.664	20.626	57.037	99.328
Fraction (%)	21.8	20.8	57.4	100.0
Heat loss coefficient (W/m ² /°C)	0.172	0.366	0.702	0.366

4.2 Thermal stratification

4.2.1 Development of thermal stratification in the water pit

The calculated and measured temperature profiles in the water pit on 09-04-2018, 01-05-2018, 01-06-2018, 01-07-2018, 01-08-2018, 01-09-2018 and 01-01-2019 are shown in Fig. 24. In the beginning, the water had a uniform temperature of approximately 13°C. After one month of charging, the water temperature in the upper part of the pool (at a height of 4.25 m) increased by 8.9°C while the water temperature in the bottom part increased by only 0.1°C. During operation, the maximum temperature difference in the water pit reached the highest value of 31.3°C in August. The thermocline thickness defined as the length of the thermocline region has been used for characterizing the thermal stratification by other researchers [38, 39]. However, as shown in Fig. 24, there is no clear thermocline observed in the water pit during the whole operating period. The reason could be the inlet induced mixing in the upper part of the pool, the large heat loss from the top water surface and heat conduction from the upper hot water to the lower cold water.

Fig. 24 Temperature profile in the water pit during the experiment

The thermal stratification in the water pit significantly influences the thermal efficiency, so the thermal stratification needs to be investigated for various operating conditions. Numerical and experimental studies on thermal stratification in the literature have mostly focused on small, short term heat storage systems with few studies on thermal stratification in large water pits. Various other

methods have been proposed to characterize the thermal stratification in water pits such as the discharge efficiency, fill efficiency, Richard number, stratification number and MIX number [40-43]. However, the operating conditions in the water pit are very complex and the operating period is very long. Therefore, not all of these parameters are suitable for evaluating the thermal stratification here as shown in Table 9. By definition, the discharge efficiency applies only to the discharge mode; therefore, it is not suitable for the present analysis. Also, the fill efficiency is not suitable because it is defined for the charging mode only. The Richard Number is not appropriate here since it will be infinite when the inlet or outlet velocity is zero; so it is not suitable for the standby mode. There, the stratification number and the MIX number were selected to analyze the thermal stratification in the water pit.

Table 9 Thermal stratification evaluation indexes

Evaluation index	Suitable for water pit	Reasons
Discharge efficiency	No	Only for discharging
Fill efficiency	No	Only for charging
Richard Number	No	Not suitable for the cooling process
Stratification Number	Yes	
Mix Number	Yes	

4.2.2 Stratification number and MIX number

The stratification number and the MIX number have both been used to evaluate the thermal stratification in a stratified hot water tank although they have very different definitions. This study is the first to use these two parameters for long term evaluation of a water pit.

The stratification number is defined as the ratio of the mean temperature gradient in the water pit to the maximum mean temperature gradient in the water pit during the test period:

$$Str(\tau) = \frac{\overline{(\partial T / \partial y)}_{\tau}}{(\partial T / \partial y)_{\max}} \quad (45)$$

The stratification number was first introduced by Fernández-Seara et. al. for analyzing the charging/discharging mode [44]. The average derivative is given by:

$$\overline{(\partial T / \partial y)}_{\tau} = \frac{1}{n_w - 1} \left[\sum_{k=1}^{n_w - 1} \left(\frac{T_{k+1} - T_k}{\Delta H} \right) \right] \quad (46)$$

During the entire operation, the maximum mean temperature gradient is:

$$\overline{(\partial T / \partial y)}_{\max} = \frac{1}{n_w - 1} \frac{T_{hot} - T_{cold}}{\Delta H} \quad (47)$$

Where T_{hot} and T_{cold} are the maximum and minimum temperatures during operation.

The MIX number is useful for evaluating the thermal stratification in a water pit at a specific time and ranges from 0 to 1 which reflects the degree of stratification independent of the working conditions [41]. Therefore, the MIX number is a suitable evaluation method for long term pit operation to characterize the thermal stratification in the water pit.

Davidson et al. [45] introduced the MIX number as:

$$MIX = \frac{Mp_{stratified} - Mp_{exp}}{Mp_{stratified} - Mp_{full-mixed}} \quad (48)$$

The energy-momentum content in the pit (Mp_{exp}) is related to the energy-momentum content of two theoretical cases, a perfectly stratified water pit ($Mp_{stratified}$) and a fully mixed water pit ($Mp_{fully-mixed}$) with both storing the same amount of energy as the experimental water pit, as illustrated in Fig. 25. The fully mixed water pit has a uniform temperature while the perfect stratified water pit has a clear boundary between the hot water and the cold water of zero thickness. The MIX number varies from 0 to 1, where 0 represents a perfectly stratified tank and 1 represents a fully mixed tank [45].

Fig. 25 Temperature distributions in the experimental water pit and two theoretical cases

For the experimental water pit, the energy-momentum content is defined as:

$$Mp_{exp} = \sum_{k=1}^{n_w} H_k \cdot E_k \quad (49)$$

Where:

$$E_k = \rho_w V_k c_{p,w} T_{w,k} \quad (50)$$

The energy content of a perfectly stratified tank is assumed to be the same as that of the

experimental water pit, so:

$$E_{stratified} = E_{exp} = E_{stratified,hot} + E_{stratified,cold} \quad (51)$$

Then:

$$\rho_w c_{p,w} V_{hot} T_{hot} + \rho_w c_{p,w} V_{cold} T_{cold} = E_{stratified} \quad (52)$$

Because:

$$V = V_{hot} + V_{cold} \quad (53)$$

And

$$V_{cold} = \pi R^2 H_{stratified} \quad (54)$$

The thermocline position ($H_{stratified}$) can be calculated for the fully stratified tank. Then, the energy-momentum content of the perfectly stratified tank is given by:

$$Mp_{stratified} = \frac{H + H_{stratified}}{2} \cdot E_{stratified,hot} + \frac{H_{stratified}}{2} \cdot E_{stratified,cold} \quad (55)$$

The energy content in a fully mixed tank is also assumed to be equal to the energy content in an experiment tank:

$$E_{full-mixed} = E_{exp} \quad (56)$$

The energy-momentum content of the fully-mixed tank is then calculated as:

$$Mp_{full-mixed} = \frac{HE_{full-mixed}}{2} \quad (57)$$

The development of the measured and calculated stratification numbers and MIX numbers for the test period from 09-04-2018 to 01-01-2018 are then shown in Fig. 26. The stratification number is close to zero at the beginning due to an initially uniform temperature distribution in the underground water pit. The pit is then gradually charged by the solar tower, so the stratification number increases from 0.04 to a peak of 0.55 between 09-04-2018 and 01-08-2018. The stratification number is lower than reported by Fernandez-Seara et al. [44]. Lower stratification numbers indicate more mixing during charging, which in this case is most likely caused by the placement of the inlet opening 1.0 m below the water surface. This process is analyzed in more detail using the 10 operating periods, A-J, shown in Fig. 26.

Fig. 26 Stratification number and MIX number variations in the water pit.

During periods A (from 09-04-2018 to 21-04-2018) and C (from 27-04-2018 to 09-05-2018), the heating increases the stratification number and reduces MIX in the water pit as the water temperature near the water surface increases significantly while the temperature near the bottom does not as shown in Fig. 15 and Fig. 24. These two numbers both reflect the increase of the thermal stratification in the water pit.

During periods B (from 21-04-2018 to 27-04-2018) and D (from 09-05-2018 to 20-05-2018), thermal conduction between the upper hot water layer and the lower cold water layer during the standby period reduces the thermal stratification. During these periods, the stratification number increases and MIX decreases with both reflecting the reduced thermal stratification.

During period E (from 20-05-2018 to 03-08-2018) when the water pit is heated for part of the time and in standby mode for part of the time, both the stratification number and MIX increase. The increased stratification number indicates increased thermal stratification while the increased MIX indicates less thermal stratification. These opposing trends are caused by the definitions of these two numbers. The stratification number is the average temperature gradient in the water pit, so when hot water was added to the water pit, the temperature increase near the top of the water pit results in an

increased stratification number. The data in Fig. 15 shows increased thermal stratification from 20-05-2018 to 03-08-2018 with the stratification number increasing during this period as shown in Fig. 24. For the MIX number, the energy-momentum content, Mp , is the product of the height and the energy at that height. In a perfectly stratified water pit, all the hot water would be stored in the upper part of the pit as shown in Fig. 25 and the increased temperatures at different heights would increase $Mp_{stratified}$ in equal amounts. However, the increased temperature near the top has more influence on Mp_{exp} than the increased temperature near the bottom in the pit. Therefore, increasing the water temperature near the bottom will increase $Mp_{stratified} - Mp_{exp}$ which will increase MIX.

During periods F (from 03-08-2018 to 30-08-2018), G (from 01-09-2018 to 19-09-2018) and J (from 21-10-2018 to 31-12-2018), the water temperature near the top is close to the charging temperature (60 – 90°C), so little energy is added to the water compared to the additions on other days (Fig. 10) The water temperature near the bottom then increases while the temperature near the top does not. Therefore, the stratification number decreases during this period. The thermal stratification can be increased by using a higher charging temperature from the middle of September through the winter. The stratification number then increases during period H (from 20-09-2018 to 08-10-2018).

Between periods F and H, the stratification number sharply decreases while MIX sharply increases as seen in Fig. 26 because 28°C water from the bottom of the water pit accidentally flowed into the top of the pit on 31-08-2019.

During the period I (from 09-10-2018 to 20-10-2018), the discharge mode return water temperature greatly influenced the thermal stratification. When discharging began on 09-10-2018, the return water temperature was higher than the bottom temperature of the water pit as shown in Fig. 18 which reduced the thermal stratification. The stratification number reduction and the MIX number increase can be seen in Fig. 26. The gradual return water temperature decrease after 16-10-2018 can be seen to increase the stratification number and reduce MIX.

5 Conclusions

The thermal stratification in a 3000 m³ water pit was investigated to study the thermal efficiency of the underground water pit. The underground water pit model modeled the water region with a one dimensional model and the soil region with a two dimensional model with the predicted temperatures in the water and in the soil validated with experimental data. The temperature differences between the

measured and predicted results were acceptable. This model was then implemented as a TRNSYS type UGSTS for further studies. The simulations and the experimental data were then used to analyze the thermal efficiency of the water pit. The results show that:

1) During the first year of operation, the 3000 m³ water pit heat losses were approximately 98 MWh and the storage efficiency was approximately 62%. The total heat loss coefficient along the entire water pit was 0.366 W/m²/°C.

2) The simplified model was used to predict the heat loss coefficients along different parts of the water pit. The average heat loss coefficient along the top was 0.172 W/m²/°C, along the side wall was 0.702 W/m²/°C and along the bottom was 0.366 W/m²/°C.

The heat loss coefficient along the top was smallest because a 0.2 m thick insulation layer was added over the top of the water pit. The heat loss coefficient along the side wall was then much larger than along the bottom mainly due to very little convection in the water due to the thermal stratification. The temperatures along the upper surface of the water pit were much larger than near the bottom. The higher temperatures near the surface then led to more heat losses in the soil, especially since the soil around the upper part of the water pit was cooled by the cold winter ambient air. Thus, insulation on the side of the water pit would significantly improve the water pit thermal efficiency.

3) The experimental data and the simulation results were used to analyze the thermal stratification in the water pit during the first year. The maximum temperature difference in the water pit during the entire operating period was 31.3°C. The stratification number and the MIX number were then selected to evaluate the thermal stratification in the water pit. A smaller MIX indicates more stratification while a larger stratification number indicates more stratification. MIX is influenced greatly by the temperatures near the bottom; thus, it increased during most of the charging period. However, since a higher MIX indicates less stratification, the increased MIX is not consistent with the experimental results which showed increased thermal stratification. The stratification number was more representative and properly showed the thermal stratification in the water pit most of the time. Therefore, the stratification number is recommended for evaluating stratification in water pits.

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