

Thermal Performance Analysis of a Large-Scale Water Pit Heat Storage

Meng Gao, Jianhua Fan*, Simon Furbo, Dengjia Wang, and Yanfeng Liu

Abstract—Solar thermal application is a practical approach to achieving carbon neutrality. Large-scale water pit heat storage (PTES) is a crucial component in ensuring the stability of large-scale solar thermal plants. Based on the model of Type 1535-1301, this paper performs a 2D simulation investigation of the long-term thermal performance of PTES using Trnsys. The accuracy of this model was verified by comparison with measured data from the solar plant in Dronninglund, Denmark. The results show that the average error between the model and the actual measurements is only 3%. The determination coefficients R^2 for temperature and energy are more significant than 0.98. In addition, this can find that the PTES average temperature decreases from 24°C to 12°C before the 80th day due to heat losses. During the charging period from the 80th to 250th day, the PTES average temperature increases to 68°C. The PTES formed a temperature stratification with 85°C at the top and 40°C at the bottom. The sloping soil temperature boundary expands and shows a non-uniform stratification of 70-10°C with 5 m thickness. The average temperature of the PTES gradually decreases to 16°C during the discharge period after the 250th day. The storage efficiency is as high as 90.1% because PTES is used for long-term and short-term energy storage. This paper reveals the dynamic thermal process of PTES throughout the year to provide a reference for designers.

Keywords— Water pit heat storage, Trnsys, Thermal performance, Simulation model

I. INTRODUCTION

SIGNIFICANT CLIMATE CHANGE and energy crises have emerged worldwide in recent years. It indicates that the transition of the industry to sustainability is urgent. Developing renewable energy sources such as solar energy is one of the important ways to promote this process [1]. In city heating, reducing the proportion of fossil energy by using renewable energy has become a trend in many countries. Large-scale solar district heating (SDH) systems will effectively increase system efficiency and significantly reduce total costs [2]. In addition, system operation management and peak regulation will be more convenient. However, solar energy fluctuates considerably

with time, and heat storage focuses on improving system stability.

Heat storage is divided into short-term and long-term according to heat capacity. Short-term heat storage, such as heat storage tanks, is small and easy to install. Still, the disadvantage is that the small capacity tank can only be used to regulate short-term supply and demand imbalances. It has been widely used in distributed solar heating projects and is suitable for buildings in remote areas away from the heating network [3]. The advantage of long-term heat storage (also known as seasonal heat storage), such as water pit heat storage (over 500 m³), is that the large capacity can regulate seasonal energy fluctuations. The disadvantage is the significant initial investment. This equipment is used in district heating and is often buried underground [4]. The reason is that if the heat storage is exposed to air, a large amount of insulation must be applied to reduce heat loss. Conversely, the soil is less affected by climate and can be used as a thermal storage layer to replace insulation [5]. Only the top of heat storage, which is in contact with the ambient, must be insulated.

There are four types of long-term, large-scale heat storage using water as the medium: tank thermal energy storage (TTES), pit thermal energy storage (PTES), borehole thermal energy storage (BTES), and aquifer thermal energy storage (ATES) [6]. The TTES is a large heat storage tank buried in the soil, which can achieve high heat storage capacity. The BTES is a device that buries dozens of long pipes into the ground, which can better utilize the heat storage function of the soil. The ATES uses underground water to store heat and only requires an inlet, outlet pipes, and a pumping machine to implement storage. PTES is water-filled and sealed equipment into a soil or stone pit compared to the above three technologies. Its heat storage efficiency is followed by TTES, its cost is just higher than ATES, and PTES also demands a large building area [7].

The application of thermal storage in different categories should integrate regional geographic, economic, and technical conditions. Therefore, the system needs to be designed optimally by simulation calculations

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[8]. The accuracy of any component in the system determines the deviation of the total simulation. Excessive variations lead to misjudgments in equipment selection, economic calculations, and recovery cycles. It is not conducive to the correct estimation of costs and benefits by manufacturers and users, thus hindering the development of renewable energy [9].

To deal with this problem, many researchers have investigated and built many available models for solar collectors, pipe losses, control components, etc. There are few numerical models for PTES, and most systems studied use conventional tank models with structural parameter corrections. Pan *et al.* [10] modified and experimentally validated Type 342, adapted to PTES calculations by axisymmetric cylindrical water tank model through coordinate transformation. The results showed that the difference between the calculated and measured charging and discharging energies was less than 5% and that the heat loss at the bottom and sides of the water pit accounted for only 32.3% of the total heat loss. Raab *et al.* [11] validated the XST model using a Hanoverian solar district heating system. They constrained the XST model to a two-dimensional symmetric cylindrical shape. The simulation results showed a maximum deviation of 3.7 K between the calculated and measured temperatures of the water pit, indicating a good model fit. Dahash *et al.* [12] developed a 3D model for a symmetric PTES with surrounding soil areas using COMSOL Multiphysics. The deviations of annual charge energy, discharge energy, internal energy, and heat loss were less than 0.5% compared to the field measurements, indicating the reliability of the new model.

However, traditional water tank models are unsuitable for underground heat storage calculations [10]. The cylindrical model fundamentally differs from the inverted truncated pyramid in temperature stratification. The 3D model has too long a computational cycle to be used for long-term optimization. Finer gradient meshes on the flow-solid boundary are needed to simulate convection calculations.

Therefore, developing high-accuracy large-scale heat storage models is an urgent challenge. The technical difficulty lies in the coupled heat transfer-flow analysis and the realization of long-term simulations with short calculation time. This paper carries out long-term calculations of the novel PTES hybrid model (Type1535-1301) through Trnsys simulations. The predicted results are evaluated compared with the measured data of the Doninglund solar collector plant in 2015-2017.

II. METHODOLOGY

This section describes the specific expression of structural coordinate transformation and meshing in Type 1535-1301. The finite difference method is used to solve the energy equation in this model.

A. Physical model

The shape of PTES is generally an inverted truncated pyramid designed to economize excavation cost and shell material. The soil on the sidewalls will not settle and collapse due to gravity, and only a waterproof liner is required. The ground is a vast insulation layer to reduce heat loss and provide additional heat storage. The temperature distribution of PTES shows a heat buoyancy trend with height [13]. The hot water inlet is at the top, the cold water inlet is at the bottom, and the middle inlet is used for flexible adjustment. In the short term, PTES is charged on sunny afternoons and discharged at night. In the long term, PTES is charged in the summer and discharged in the winter. The simulation model needs to be built with suitable assumptions and meshes according to the actual situation.

1) Assumptions

Renewable energy densities fluctuate, and it isn't easy to manually calculate energy gains with a constant standard. Before project construction, simulations are usually used for year-round performance prediction and economic optimization. Therefore, the year-round computation time of the model must be kept within acceptable boundaries and generally should not exceed 30 minutes. The model needs to be built to reduce the computational load by making the following assumptions.

- a. PTES has no significant temperature difference in the horizontal direction and, therefore, can be simplified to a one-dimensional. The temperature distribution of the far-side soil and the soil near the heat source is different. However, the horizontal direction is uniformly affected by PTES diffusion heat transfer so that the soil model can be simplified to two-dimensional cylindrical coordinates. Correspondingly, the physical model of the water pit is transformed from an inverted truncated pyramid to an inverted truncated cone.
- b. The soil is assumed to be dry, and the PTES is assumed to be ideally stratified without considering flow. The momentum equation and mass equation in the computational domain can be neglected. Thus, the model considers only the heat conduction in the energy equation.
- c. The soil is assumed to be all isotropic materials, and its heat transfer with the water pit is homogeneous in the horizontal direction. Therefore, the overall model can be simplified to central axis symmetry.

2) Grid scheme

The Type 1535-1301 combines a soil model and a PTES model. The soil model grid is generated based on the number of water pit stratifications. PTES is a one-dimensional isovolumetric division, with (j) denoting its nodes. Figure 1 illustrates that the grid nodes are generated in two directions, radial *r* direction, and vertical *z* direction.

There are two ways to divide the soil field in the vertical z-direction, and (k) denotes the nodes in this direction. One is encrypted above and below the baseline of the water pit grid division interface, and the other is a dimensionally asymptotic grid. This grid division allows a more accurate heat transfer simulation at temperature stratification intersections. In addition, the grid near the PTES is refined, while the grid near the bottom soil boundary is coarsened. The grid nodes in the radial r direction are indicated by (i). The delineation is like (k), where the grid at the boundary between the soil and the top insulation becomes increasingly dense, and the grid at the far-field soil becomes progressively coarser.

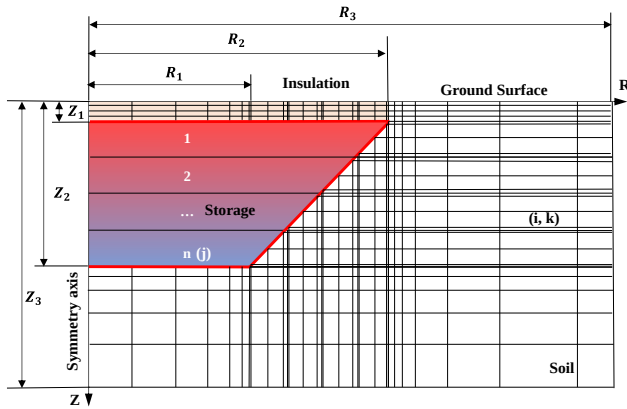


Fig. 1. The simulation mesh scheme of Type 1535-1301.

B. Mathematical description

1) Heat transfer coefficient

Since there is no insulation between the water pit and the soil, the heat transfer coefficient is determined based on water-side convection and soil-side conduction. Forced convection is negligible in mass storage compared to the effect of natural convection [14]. The heat transfer coefficients for the sides and bottom are given by Equation (1). Where A is the heat transfer area, h is the convection coefficient, δ is the wall thickness, and λ is the thermal conductivity. The thermal resistance of multiple materials is calculated using the sum of δ/λ .

$$U = \frac{A_{\text{mea}}}{A_{\text{sim}}} \cdot \frac{1}{\frac{1}{\bar{h}} + \sum \frac{\delta}{\bar{\lambda}}} \quad (1)$$

The natural convection coefficient of the sloped wall can be calculated by equation (2), which is the heat transfer coefficient of the wall of the waterproof liner [15]. The D in the formula is the equivalent diameter of the wall. Where H is the wall length, g is the acceleration of gravity, and β is the thermal diffusion coefficient. ΔT is the temperature difference between the hot water and the waterproof liner, ν is the kinematic viscosity, and Pr is the Prandtl number.

$$h = \frac{0.6 \cdot \lambda}{H} \cdot \left(\frac{g \cdot \beta \cdot \Delta T \cdot D^3}{64 \cdot \nu^2} \cdot Pr \right)^{\frac{1}{3}} \quad (2)$$

2) Energy equation

The energy equation is expressed in equation (3), which contains the energy change term on the left side, the diffusion term, and the heat source term on the right side. Difference calculations are performed using Taylor expansion for the discrete equations.

$$\frac{\partial(\rho C_p T)}{\partial t} = \nabla(\lambda \nabla T) + S_T \quad (3)$$

where ρ is the density, C_p is the constant pressure specific heat capacity, and t is the time step. The lack of a momentum equation means that no additional flow inlet or outlet is required. The inlet can be used as an external heat source S_T into the energy equation, as shown in equation (4). This allows flow switching by controlling only the dipole control.

$$S_T = \begin{cases} V_{in} \rho_w C_p (T_{in} - T_j), & \text{with inlet flow} \\ 0, & \text{without inlet flow} \end{cases} \quad (4)$$

3) Boundary conditions

The boundary conditions have different expressions according to the border characteristics. The fluid-solid coupling boundary needs to follow the third boundary conditions. The distant soil follows the Dirichlet boundary conditions. Solid heat transfer boundaries follow Neumann boundary conditions. The expressions and ranges of the differential equations at the boundary are shown in Eqs. (5)-(9). where T_{∞} is the ambient temperature, T_{far} and T_{deep} are the far-field and depth soil temperatures, respectively, determined by the region's climate. The subscript s represents the soil node, the subscript ins is the insulation node, and the subscript w is the water pit node. $\mathbf{n}$ is the node transmission vector.

For $k = 0$,

$$-\lambda \frac{\partial T}{\partial r} = h(T - T_\infty) \quad (5)$$

For $i = R_3$ or $k = Z_3$,

$$\begin{cases} T = T_{far} , & i = R_2 \\ T = T_{deep}, & k = Z_3 \end{cases} \quad (6)$$

For $i = R_2$ and $k = (0, Z_1)$,

$$-\lambda_s \left(\frac{\partial T_s}{\partial n} \right)_s = \frac{T_{ins} - T_s}{\frac{\delta_{ins}}{\lambda_{ins}} + \frac{\delta_s}{\lambda_s}} = \lambda_{ins} \left(\frac{\partial T_{ins}}{\partial n} \right)_{ins} \quad (7)$$

For $i = (R_1, R_2)$ and $k = (Z_1, Z_2)$,

$$-\lambda_s \left(\frac{\partial T_s}{\partial n} \right)_s = (T_w - T_s) \left(\frac{\lambda_s}{\delta_s} + h \right) = \lambda_w \left(\frac{\partial T_w}{\partial n} \right)_w \quad (8)$$

For $k = Z_1$ and $i = (0, R_2)$,

$$-\lambda_{ins} \left(\frac{\partial T_{ins}}{\partial n} \right)_{ins} = (T_w - T_{ins}) \left(\frac{\lambda_{ins}}{\delta_{ins}} + h \right) = \lambda_w \left(\frac{\partial T_w}{\partial n} \right)_w \quad (9)$$

4) Performance evaluations

Equation (10) shows the charging and discharging calculations for each time step [16]. Positive values represent the discharge energy and negative values represent the charging energy. where *out* represents the physical parameters of the outlet and *in* represents the inlet.

$$Q_{ch/dis} = \rho_w C_p \Delta \tau (V_{out} T_{out} - V_{in} T_{in}) \quad (10)$$

The energy change of the heat storage is represented by equation (11), *N* is the total number of water pit nodes, *V_j* is the node volume, *T_{j,now}* is the node temperature at the current time, *T_{j,start}* is the initial node temperature, and equation (11) indicates the energy content when *T_{j,start}* is 0.

$$Q_{change} = \sum_{j=1}^N \rho_w C_p V_j \cdot (T_{j,now} - T_{j,start}) \quad (11)$$

The average temperature is calculated using equation (12), considering the relationship between volume and energy, and *V_i* is the total volume of the water pit.

$$\bar{T} = \frac{\sum_{j=1}^N T_j V_j}{V_i} \quad (12)$$

The energy efficiency is expressed in equation (13), which is the ratio of discharge and store to energy input and reflects the effective utilization of energy by PTES.

$$\eta_{sto} = \frac{Q_{dis} + Q_{change}}{Q_{ch}} \quad (13)$$

The coefficient of determination *R*² is used to measure the accuracy of the model. This coefficient is a quantitative measure of the degree of variance in the data. Thus, it is possible to see how much of the variance in the data is captured (or predicted) by the modelled data. Where *y* denotes experimental data and *f* represents simulated data in equation (14).

$$R^2 = 1 - \frac{\sum_i (y_i - f_i)^2}{\sum_i (y_i - \bar{y})^2} \quad (14)$$

C. Operation inputs

The TRNSYS simulation requires reasonable parameters and input settings. Table I lists the parameter conditions needed for this study. This paper's calculation time and comparison results cover the years 2015-2017 for Donninglund, Denmark. The time step in this paper is

consistent with the experimental data collection time of 10 minutes to facilitate comparison. The minimum grid size is 0.05 m, and the total number of grids is 52,851. The thickness and thermal conductivity of the insulation material PE foam are given [17]. The soil properties are shown based on studies and reports of geological exploration. The initial conditions of PTES and the surrounding soil strongly influence the thermal properties of PTES. The Trnsys verification model for Type1535 and Type1301 coupling diagram is shown in Figure 2. In this model, only soils with uniform temperatures are allowed to be set.

TABLE I
PARAMETERS INPUTS FOR SIMULATION

Symbol	Parameter	Unit	Value
-	Calculated years	-	3 years
<i>t</i>	Time step	s	600
<i>V</i>	Volume	m ³	60,000
<i>H</i>	Storage height	m	16
<i>θ</i>	Slope angle	°	24
<i>R</i> ₁	Top diameter	m	45
<i>R</i> ₂	Zone length	m	200
<i>Z</i> ₃	Zone depth	m	40
<i>δ</i> _{ins}	Insulation thickness	m	0.24
<i>λ</i> _{ins}	Insulation conductivity	W/(m·K)	0.046
<i>λ</i> _s	Soil conductivity	W/(m·K)	1.44
<i>ρ</i> _s	Soil density	kg/m ³	2000
<i>C_p</i>	Soil specific heat	kJ/kg·K	0.84
<i>T</i> _s	Initial soil temperature	K	10.8
<i>T</i> _w	Initial water temperature	K	measured
-	Minimum node size	m	0.05

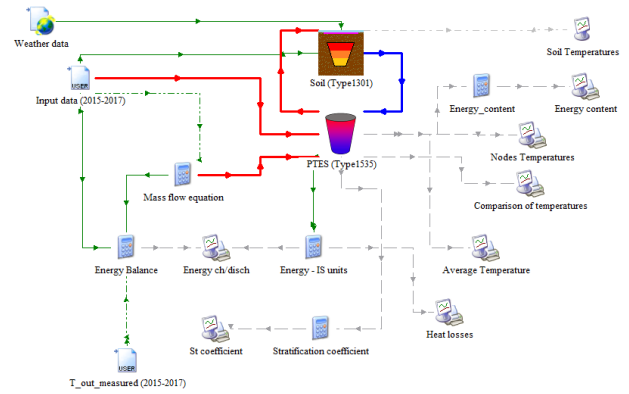


Fig. 2. The Trnsys verification diagram of Type 1535-1301.

The experimental measurement locations within the water pit differ from the grid, so the initial simulation data are experimentally interpolated and averaged. The results from early 2015 were taken as the initial conditions. The initial storage temperatures ranged from 15°C to 55°C from the bottom to the top, with an average soil temperature of 10.8°C. Meteorological data, solar plant flows, and temperatures are real-time inputs to the model.

III. RESULTS AND DISCUSSIONS

A. Temperature comparison

The deviation from the long-term simulation of Type 1535-1301 can be seen by comparing it with the measured temperature and energy. Figure 3 shows how the temperature and energy content changed between 2015-2017. It would be too cluttered to compare the test results for all heights. Because temperature stratifies with height, the top and bottom temperatures can be chosen as the upper and lower limits of the temperature interval. The middle temperature is selected at the equivalent volume to show each layer's fluctuation better. As shown in the figure, the simulated and experimental deviations are more pronounced in the middle. It is due to weak mixing

format chosen for the simulation, which causes discrete errors at each iteration. Although the values are corrected with the inputs, there is still a computational delay. The maximum temperature deviation of each layer is 16.3°C , and the average deviation is merely 1.7°C .

The middle part of Figure 3 illustrates the trend of decreasing, increasing, and reducing energy content during the year. As a result, we can determine the approximate charging and discharging periods. The periods are not simply charging or discharging. PTES is always in discharging and is only charged during sunny days. Therefore, the charging and discharging periods proposed in this paper are only a broad concept for understanding seasonal heat storage. The lower part of Figure 3 demonstrates that the variation trend of the

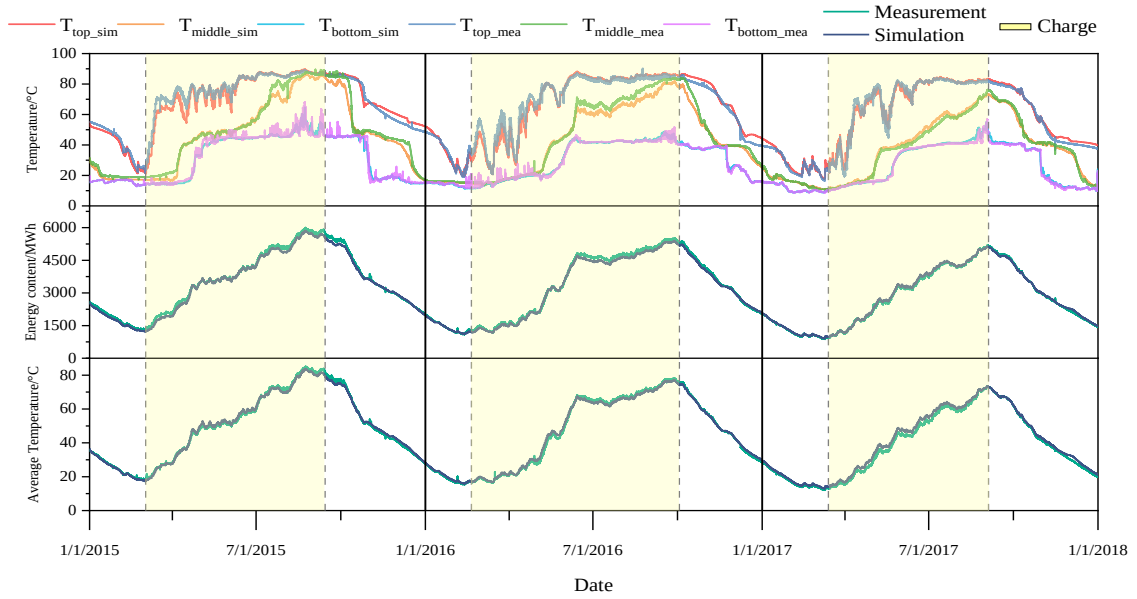


Fig. 3. Comparison of temperature and energy content in 2015-2017

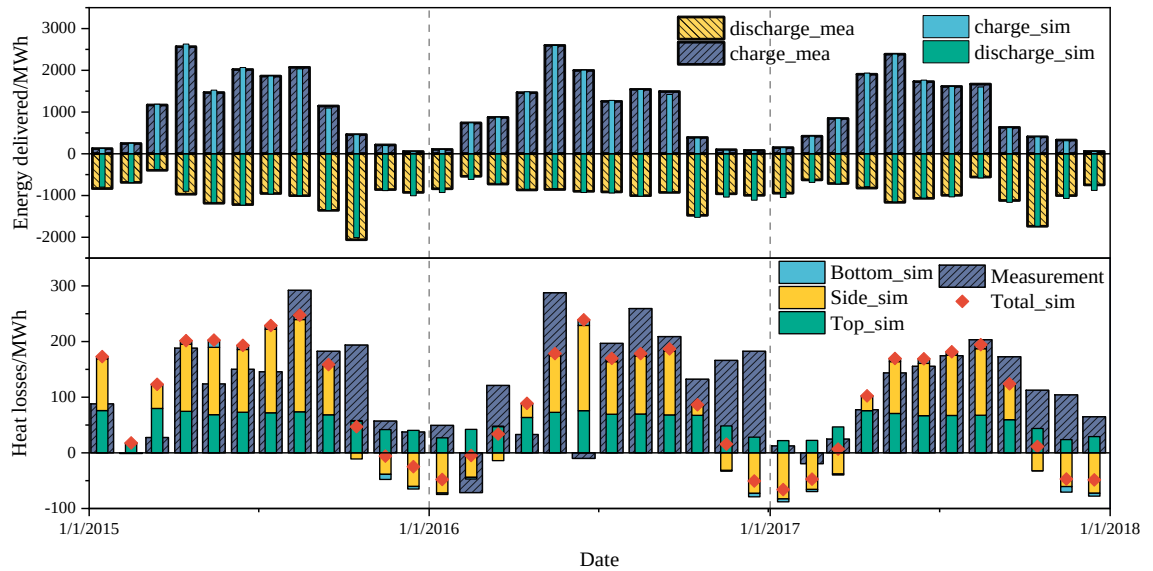


Fig. 4. Monthly energy delivery and heat losses

in the middle, which cannot be calculated, especially in the moments of large temperature gradients such as May-August. In addition, the simulations make it more difficult to predict the periods with a large rate of temperature change. It is because of the forward differential time

average temperature is consistent with the energy content, and the deviation does not exceed 5°C . The maximum deviation of the energy content is 296 MWh, and the average is 73 MWh, but the top rate is only 11%.

In summary, the model is in good overall agreement for the temperature calculation but with large local deviations. The energy content is superimposed by the internal energy of the calculated domains in each layer and, therefore, is only temperature dependent. This model difference cannot be ignored if the operation requires flexible water extraction along the height. The model achieves a good prediction function if the water is taken at a fixed level.

B. Energy delivery and heat losses

Energy transfer involves charging and discharging energy. Since the solar radiation intensity varies significantly with the month, it is feasible to use the month as a unit for the energy summary. Figure 4 indicates the energy variation for 36 months from 2015-2017. The above figure shows that the periods with more energy charging are concentrated in the spring and summer months from March to September. Besides the factor of solar radiation intensity, Denmark has more cloudy days in autumn and winter. It is observed that the energy discharge in autumn and winter is similar to that in summer, except for September and October. It is because the temperature of the water pit decreases after October, and the energy output decreases. Most of the heat is provided by biomass and natural gas. It illustrates the current PTES is still limited to regulate across seasons and should be considered for capacity expansion or additional energy input. The simulation and the actual measurement are in good agreement, and the maximum deviation of charging energy is 69MWh, not more than 10%. The maximum deviation of energy discharge is 131MWh, which does not exceed 20%.

The below figure shows the heat loss variation. The simulation obtains the heat loss by PTES wall node heat transfer calculation. The actual measurement is to calculate the heat loss by energy balance. The difference in calculation methods will inevitably have an impact on the results. Moreover, the accumulation of water and soil seepage on rainy days will also cause additional heat loss.

These are uncertainties not considered in the model and are hard to predict. The heat loss is about 10% of the energy transfer, and the resulting energy deviation is less than 5%. Although the energy impact of heat loss, in this case, is small, other cases of long-term heat storage with heat loss over 20% are at risk of larger deviations. These deviations are concentrated in the treatment of rainfall and subsurface soil seepage.

C. Energy efficiency and deviation determination

Table II provides an annual summary of the determination coefficient and energy efficiency. A slight variation in charging energy throughout the year with a slightly higher discharge can be observed. There is a deviation of 31%-39% in heat loss from 2016-2017. The stored internal energy is lower by 1130 MWh in three years. The project was preheated for six months when it was built in 2014, resulting in higher initial energy in 2015. However, the soil preheating was not completed, making the difference between charging, and discharging energy

TABLE II
YEARLY ENERGY AND EFFICIENCY

Years	Parameter	Measurement	Simulation
2015	Charge energy/MWh	13,400	13,475
	Discharge energy/MWh	12,500	12,405
	Storage change/MWh	-570	-598
	Heat losses/MWh	1,480	1,563
	Energy efficiency	89.0%	87.6%
2016	Charge energy/MWh	12,600	12,582
	Discharge energy/MWh	11,000	11,432
	Storage change/MWh	50	136
	Heat losses/MWh	1,550	1,074
	Energy efficiency	88.0%	91.9%
2017	Charge energy/MWh	12,100	12,103
	Discharge energy/MWh	11,500	11,926
	Storage change/MWh	-610	-601
	Heat losses/MWh	1,220	750
	Energy efficiency	90.0%	93.6%
Total	R ² of temperature		0.984
	R ² of energy		0.982

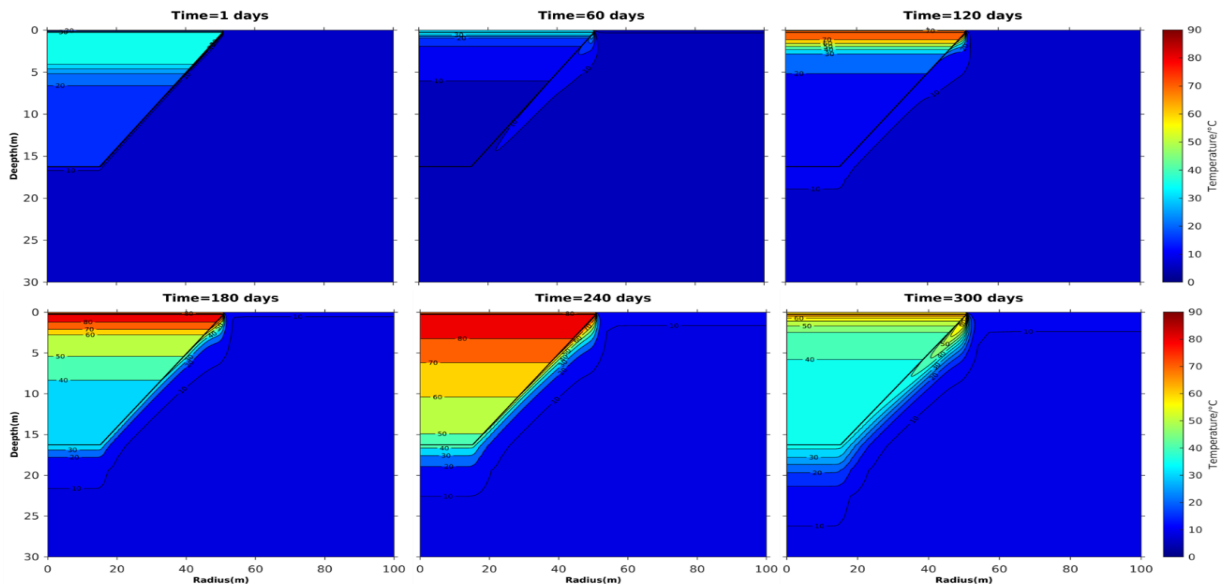


Fig. 5. Annual temperature contour of storage and soil region in 2017

less than the heat loss. The energy efficiency of this project has remained high at around 90% for three years. The reason is that the PTES is used for both short-term and long-term heat storage and is in a constant state of heat. This operation mode may serve as a reference for improving the efficiency of large-scale heat storage. The R^2 for temperature and energy always considers the RMS of all nodes. More than 98% of the measured variance is captured accurately by the simulation, and the model accuracy is high.

D. Water and soil temperature

The PTES and soil temperature variations throughout the year are shown in Fig. 5. The storage temperature decreases continuously to 12°C in the first two months due to low radiation intensity. The temperature started to rise back up to 35°C after the charging period in March. The top is filled with 70°C hot water, and heat is gradually transferred downwards. Thus, it is evident that the 20°C low-temperature zone gradually becomes a 45°C medium to high-temperature zone due to heating from 120th to 240th day. The PTES shows a gradual temperature distribution of 85°C at the top and currently 40°C at the bottom. The thermal diffusion of the soil is slower than the storage, so the thickness of the temperature gradient zone reaches a relative maximum of 10 m on the 300th day. After September, the PTES temperature decreases to 40°C due to a significant increase in heat supply. The soil serves as a temperature compensation to delay the decrease of the storage temperature.

E. Influence of the storage discretization

The node number (N) represents the number of one-dimensional meshes in the PTES, which can be used to study the relationship between meshes and calculation accuracy. Its physical expression can be seen in Fig. 1, represented by a symbol (j). The selection of node number and correlation diffuser location is provided in Table III.

TABLE III
STORAGE DISCRETIZATION AND DIFFUSER'S LOCATION

Nodes number N	Volume per node (m ³)	Top diffuser location	Middle diffuser location	Bottom diffuser location
15	4000	Node 1	Node 8	Node 15
20	3000	Node 2	Node 11	Node 20
32	1875	Node 3	Node 17	Node 32
50	1200	Node 4	Node 27	Node 50
75	800	Node 5	Node 40	Node 75
100	600	Node 7	Node 53	Node 100

The PTES temperature variation is most pronounced in the height region of the diffuser. Therefore, it is necessary to compare only the node temperature evolution at 15.5 m, 11.2 m, and 0.5 m to reflect the overall temperature characteristics. Fig. 6 presents a comparison of the measured temperature for different nodes number. The results show that the agreement between the various heights for the measured is quite different. The coupling of numerical diffusion and mixing effects renders the analysis extremely difficult, but some practical consequences can be obtained. The top temperature deviation displays different results over time. The higher node number has a rapid response to temperature changes, and this response has both positive and negative effects. The advantage is the better agreement above 50 layers in the period of large temperature fluctuations from April to June. The disadvantage is that the deviation is smaller below 20 layers during the small fluctuations framed in the figure. The middle and bottom temperature deviations coincide best at large node numbers most of the time. The opposite happens at some times. Perhaps the mixing effect is more significant than the numerical diffusion correction.

IV. CONCLUSION

This paper presents a Trnsys simulation study of large-scale water pit heat storage and validates it with measured

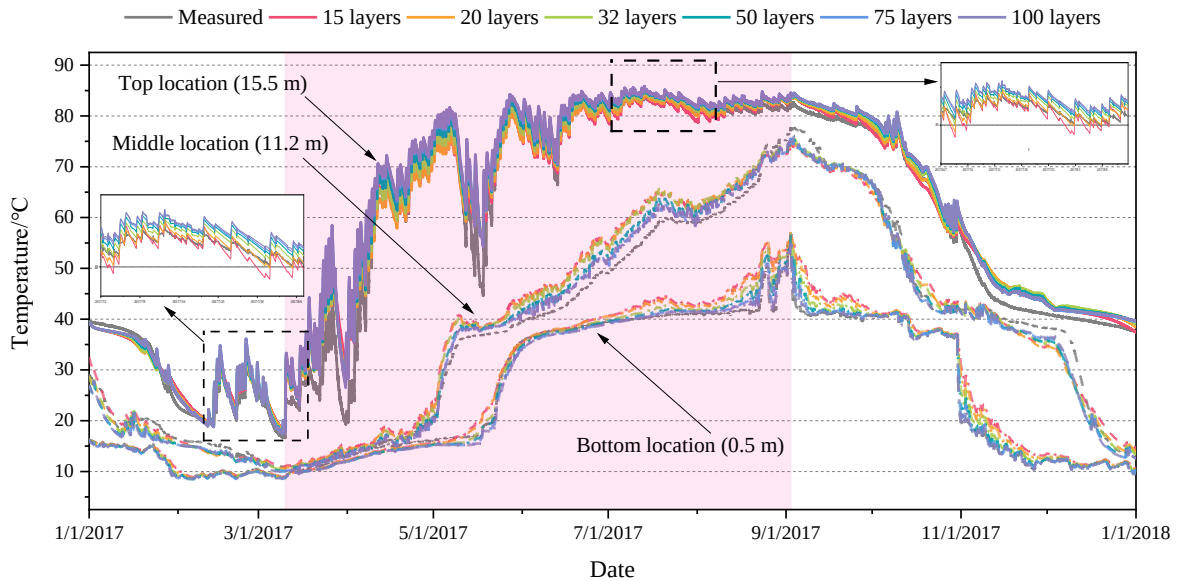


Fig. 6. Annual temperature variation inside storage with different nodes number in 2017

data from a solar district heating plant. The accuracy of Type 1535-1301 is evaluated quantitatively by a three-year round-robin test. In addition, parametric investigations are performed for different numbers of storage nodes. The following conclusions were obtained:

- a. The average temperature deviation is 1.7°C, and the maximum temperature difference is 16.3°C. The maximum variation of charging energy is 69 MWh, and the maximum deviation of discharging energy does not exceed 20%. The monthly heat loss has a significant deviation and shows an opposite trend. It indicates that this model has high calculation accuracy for energy delivery but low calculation accuracy for partial temperature and heat loss.
- b. PTES had a total charge of 38,100 MWh and discharge of 34,980 MWh from 2015-2017, with an internal energy reduction of 1,130 MWh and a heat loss of 4,260 MWh. For an average annual heat demand of 36,000 MWh, PTES can deploy 32% of the heat and receive over 80% of the thermal energy from solar plants.
- c. The more minor the numerical diffusion when simulation nodes number is higher, but the accuracy of temperature mixing calculation may be lower. The temperature is best predicted at 100 layers most time. However, the 20 layers of discretization have smaller deviations at the top when the temperature is highest or smallest. Therefore, node volume changes will affect the node temperatures and may cause abnormal heat transfer velocities.

In summary, large-scale water pit heat storage is ideally suited for district heating systems with renewable energy, such as solar energy. It can effectively improve the energy fraction and energy efficiency. Type 1535-1301 model is suitable for long-term simulation of energy. However, problems such as large heat loss and partial temperature deviation must balance the accuracy and calculation time for further optimization.

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