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Performance Investigation of a Ground-Coupled Warehouse Cooling System with an Underground Thermal Energy Storage Tank.

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ABSTRACT

Thermal performance parameters for a ground-coupled warehouse cooling system with an underground Thermal Energy Storage (TES) tank are investigated in this study. The system comprises a warehouse, a cooling unit, and an underground TES tank. A MATLAB program was created to evaluate the system's performance on an hourly basis, considering various design parameters and operational conditions. To solve the hourly heat transfer to the surrounding TES tank, the similarity transformation and Duhamel's superposition principle are employed. The results indicate that the volume of the TES tank and the type of earth surrounding it are critical factors affecting the system's performance. Among the tested surrounding materials (granite, limestone, and clay earth types), granite exhibits the highest system performance. The results also reveal that the water temperature in the TES tank reaches a maximum of 25.33 °C in July, significantly below the maximum ambient air temperature of 45.67 °C, resulting in a higher COP of 3.42. This performance is achieved with a TES tank volume of 600 m^3, a Carnot efficiency of 40%, and using granite as the earth type. Moreover, the system demonstrates periodic operation starting from the 9th year onwards, continuing for 15 years of operation. These improvements lead to significant energy savings and reduced environmental effects.

Keywords:

Potato cooling, warehouse, TES tank; COP, energy analysis.

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1. INTRODUCTION

An increase in population density in the world requires an increase in the provision of food. The essential types of food that people need must be healthy, edible, and available at all times during the year. Among these basic foods that people need are potatoes, which are eaten in different ways. The obstacle to having potatoes at all times is that the food gets spoiled and becomes inedible with time. Potatoes perish quickly in hot weather.

Potato is a food that releases heat through respiration and loses moisture through evaporation. Potatoes age after they are picked and collected. To postpone this progression as much as possible, storage is employed. Suitable ventilation and storage conditions guarantee a reduction in mass loss and product quality.

The main method of handling perishable food in bulk between production and marketing preparation is cold storage. This technique involves regulating the temperature and humidity within the storage system to maintain the freshness of goods for a limited time. Keeping a low enough temperature is necessary to prevent freezing damage to the products. Additionally, most perishable foods require a relative humidity of at least 80-90% in the storage area, as both levels can have an unfavorable impact on the quality of the products.

The products are divided into three categories to resolve their thermal compatibility during cold storage into three temperature ranges [1]:

1. Most vegetable and animal products' cold storage temperatures range from (0–4°C), such as apples, grapes, carrots, and onions.

2. Vegetable products that are stored in moderately cold storage temperatures range (4–8°C), such as mangoes, oranges, potatoes, and tomatoes.
3. Some vegetable products are stored in cold storage temperatures above (8°C), such as pumpkins, bananas, and pineapples.

These categorizations allow for efficient and optimized cold storage practices for different types of products.

The most common cooling methods are traditional air-cooled refrigeration systems, which generally exhibit an acceptable coefficient of performance (COP). However, their performance heavily relies on the outside air temperature, assuming the cooled space maintains a constant temperature. In hot summer, air source refrigeration systems struggle and require greater effort to cool the area [2]. For instance, in regions like Iraq, traditional air-cooling refrigeration systems consume intensive energy when cooling potatoes during the summer. Development and industrialization are fundamentally dependent on energy efficiency. Unfortunately, a significant portion of our energy is sourced from environmentally harmful options like coal and fossil fuels, leading to increased CO_2, SOx, and NOx emissions [3]–[5]. Therefore, it is imperative to shift towards alternative and clean energy sources due to the high unit price of fossil fuels and to preserve the environment and health.

One method that is used in the literature to decrease the energy requirement for operating the refrigeration and heat pump systems is the utilizing the ground instead of air. Ground source refrigeration and heat pump systems offer greater efficiency compared to air-cooled systems due to the stable ground temperatures at a suitable depth. These systems are considered renewable energy sources, gaining significant attention in the context of global warming impacts [6]–[8]. Therefore, investigating the Thermal Energy Storage (TES) mechanism has become vital. Soil serves as a reservoir for storing energy in the TES, and various methods for improving TES performance have been established from these perspectives.

In warehouses, conventional vapor compression refrigeration cycle is the primary method of cooling applications. Dincer [9], [10] discussed techniques for describing, evaluating, and employing TES systems considering their economic, energy-saving, and ecological attributes. Rosen et al. [11] performed an energy and exergy analysis of cold thermal storage system and discovered that exergy analysis provides more accurate and realistic evaluations of their performance and effectiveness compared to traditional energy analysis.

Pan et al. [12] performed experimental and theoretical investigations on the long-term thermal performance of a 60,000 m^3 water pit thermal energy storage (PTES) in Denmark over five years. Their results indicated that the developed model predicts storage temperatures and heat flows accurately, with the soil region around the PTES taking about four years to reach thermal balance.

Petit and Meyer [13] conducted a comparison between the air cooling condenser and horizontal ground source cooling systems in South Africa , considering both technological and economic factors. This finding revealed that running costs are higher for air source systems, while ground source systems have higher capital costs.

Zogou and Stamatelos [14] investigated how climate affects the efficiency of heat pump systems used for cooling and heating spaces. De Swardt and Meyer [15] evaluated the heating and cooling capabilities of a ground source heat pump linked to a municipal water distribution network, comparing them to those of a traditional air source heat pump. Their findings demonstrated that this approach is a viable method for decreasing energy use in cooling systems.

The efficacy of solar heating systems with seasonal storages was assessed using the finite element method. Ucar and Inalli [16] resolved a time-dependent heat transmission problem between the storage and surrounding ground using a MATLAB computer code to determine the transient temperature distribution inside the earth around the tank. The study revealed that a reducing the storage volume led to lower storage temperature.

Kuang et al. [17] carried out experiments to examine the thermal performance of a water source heat pump, flat plate collectors, and hot water thermal storage system in north China. Their findings showed that the collectors gained an average of 21.29 kW h of useful energy per day. Additionally, the average system COP and collector efficiency were approximately 2.19 and 67.2%, respectively.

In their study, Wang and Qi [18]investigated the efficiency of subsurface thermal storage in a solar ground-coupled heat pump system for a residential building. Based on solar energy collected by collectors and overall solar radiation, the study indicated that the subterranean thermal storage's efficiency approached approximately 40% and 70%, respectively.

Ahmed and Ali [19] used energy and exergy analyses in an experimental study to improve a split air conditioning system that uses an evaporative compression refrigeration cycle with circulating cooling water and a water-cooled heat exchanger at various inlet water temperatures. They discovered that, as compared to a typical air conditioning unit, a high-water flowrate results in a 13% increase in exergy efficiency. In an experimental study.

Mohammed and Hamdoon [20] compared the performance of a hybrid solar air conditioner to that of a traditional air conditioner to determine its coefficient of performance (COP). According to their findings, the first and second hybrid solar air conditioner cases have the highest improvements in COP (12.2% and 16.3%, respectively, in contrast to the conventional air conditioner), and the first and second hybrid solar air conditioner cases have the highest electric energy savings rates (15.9% and 18.7%, respectively, in comparison with the conventional air conditioner).

In research conducted by Wang et al. [21]., a solar-assisted ground-coupled heat pump system with solar seasonal thermal storage was investigated experimentally for use in extremely cold regions. The research revealed that the system efficiently meets the building's heating and cooling energy demands. Notably, solar collectors directly contributed to 49.7% of the total heating output. In the heating mode, the heat pump achieved a coefficient of performance (COP) of 4.29, while the system's average reached an even higher value of 6.55. During cooling mode, the system's COP increased to 21.35 as the heat pump did not need to be turned on. After a year of implementation, 75.5% of the heat stored by solar seasonal thermal storage was derived from the soil by the heat pump.

Hakan et al. [22], [23] examined the extended-term efficiency of a swimming pool heating system that utilizes waste heat energy, typically discarded from an ice rink's chiller unit, and accumulates it in a Thermal Energy Storage (TES) tank underground. The findings indicate high system performance, with the system reaching periodic operation after 6 to 7 years.

Ismaeel and Yumrutaş [24], [25] examined the possibility of using a heat pump to retrieve stored solar energy from an underground TES tank for a drying system on sunny days. They achieved a significant improvement in the coefficient of performance, with values of 4.43. 4.3, and 6.05 for the heat pump COP, system COP and Specific Moisture Evaporation Rate (SMER), respectively. Furthermore, they obtained improvement values of 5.55, 5.28, and 9.25 for heat pump COP, system COP and SMER, respectively. The Use of a Heat Recovery Unit (HRU) saved annual energy by 21.4% [23].

G. Kahwaji [26] investigated the use of thermal energy storage as a cooling solution for large mosques in the Iraqi city of Mosul. According to his findings, the peak power consumption has been lowered by 33.1%, and around 10% of the utilized power has been moved to a low-price duration.

In recent years, there has been a significant increase in the production of agricultural crops in Kurdistan Region, especially in the province of Dohuk. Potato cultivation, in particular, has experienced a massive growth in Dohuk province. Potatoes are harvested twice in the Kurdistan region of Iraq: at the beginning of summer (June), which is the main harvesting season, and at the end of fall season (November), when there is minimal production. The crop faces a challenge during harvest seasons, as it cannot be stored for extended periods without the use of cooling systems. As a results, crop prices drop dramatically, negatively affects farmers revenues. To avoid crop spoilage and revenue losses, potatoes need to be stored for longer periods in special cooled warehouses. This need for storage is especially crucial during the summer harvest season due to the high temperatures that may spoil the potatoes[27]. The air-cooled refrigeration systems currently used in Duhok provinces for storing potatoes in special warehouses for extended periods consume intensive energy.

While conducting a search in literature on warehouse cooling systems that utilize a thermal energy storage (TES) tank for storing potatoes, particularly in hot areas like Duhok city, Iraq, no related studies on this specific topic were found. Nevertheless, it is worth noting that TES tanks have proven effective in various industrial cooling and heating applications year-round. Therefore, the incorporation of TES tanks in warehouse cooling systems holds promising potential for future research and implementation.

The proposed cooling system has two original features. Firstly, it utilizes an underground spherical TES tank to receive the heat rejected from the condenser via a water loop and then dissipate the received heat into the ground through the tank surface. Secondly, the system evaluates its performance criteria on an hourly basis over the long-term using similarity transformation and Duhamel's superposition principle.

The main objective of this study is to develop a comprehensive theoretical model for a specialized warehouse cooling system that incorporates a thermal energy storage (TES) tank underground in Duhok province, designed for cooling potatoes. Duhamel's superposition and similarity transformation methods are used for solving the (unsteady) heat transfer issue for the TES tank for each hour. Energy equations for each refrigeration system component were used to build the model. Performance metrics and the system's periodic performance over several years are to be determined when the model is developed in MATLAB.

The cooling system consists of three key components: the warehouse, the refrigeration unit, and the TES tank. Each component underwent thermal analysis, and the results were integrated to establish a comprehensive mathematical algorithm for the innovative cooling system. Subsequently, a computational model was derived from these equations, and a MATLAB software was developed to evaluate various input data and establish the cooling system's performance metrics. These variables include the temperature of the water in the TES tank and coefficient of performance (COP) of the refrigeration system.

2. DESCRIPTION OF THE COOLING SYSTEM

The cooling system under investigation is an eco-friendly solution that significantly saves energy by employing a ground source, known as one of the renewable energy types. The system's configuration, depicted in Fig. 1, is situated in Duhok province. It consists of three primary components: a warehouse, a cooling (refrigeration) unit, and a Thermal Energy Storage (TES) tank.

2.1 Warehouse

Potatoes are a perishable commodity and require proper storage conditions to maintain their quality and prevent spoilage. For cooling potatoes,

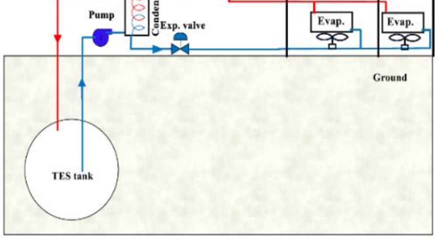

Fig. 1. Wearhouse cooling system with underground TES tank.

special warehouses constructed by sandwich panels made of Polystyrene are used. These warehouses are designed to provide optimal storage conditions for the potatoes crop by carefully controlling temperature and humidity during the summer seasons. The warehouse dimensions in this study measure 16.6 m in length, 10.6 m in width, and 5 m in height, resulting in a total volume of 879.8m^3.

2.2 Refrigeration unit

The refrigeration unit is a thermodynamic process that is based on the principles of phase change and heat transfer. In the refrigeration cycle, a refrigerant R404a is used as the working fluid that undergoes a series of state changes to achieve the desired cooling effect.

The cycle begins with the compressor, which is responsible for compressing the refrigerant gas to a high pressure and temperature. Then the high-pressure gas flows through the condenser, which is a heat exchanger that releases the heat from the refrigerant to the water that is circulated between the TES tank and the condenser. The water transfers the heat to the TES tank from the condenser then to the ground. The refrigerant then condenses into a high-pressure liquid as a result. The refrigerant then evaporates into a low-pressure liquid while the high-pressure liquid passes through an expansion valve, which lowers the pressure. This process is called adiabatic expansion, as no heat is added or removed from the system during this phase change. The low-pressure liquid flows through an evaporator, which is another heat exchanger that absorbs heat from the indoor space, where the potatoes are stored, and cools it down. This causes the refrigerant to become a low-pressure, low-temperature gas. The low-pressure gas is then drawn back into the compressor, and the cycle repeats. The overall effect is to transfer heat from the indoor space to the ground, resulting in a cooler indoor temperature.

2.3 TES tank

The TES tank plays a crucial part in the cooling system, promoting energy saving and helps the environmental benefits by reducing pollution [28]. The TES facilitates transfer heat from the warehouse to the ground, with its design being considered spherical. The cooling unit, another essential component of the system, is connected to the TES tank, serving as a cooling source. During the summer, the cooling system capitalizes on the naturally lower temperatures found underground, enabling the cooling technology to achieve higher level energy efficiency compared to conventional air conditioning systems that rely on ambient air temperature. The substantial mass and constant temperature of the ground make it an excellent energy storage medium [29]–[31]. The TES tank's preferred storage medium is water, due to its high heat capacity and rapid ability to charge and discharge thermal energy. This choice is further supported by the cost-effectiveness and advantageous properties of water in TES systems. As a result, the cooling system efficiently transfers heat from the indoor space to the ground, leading to a cooler indoor temperature.

3. MODELING OF THE COOLING SYSTEM

To create a mathematical model of the cooling system, energy terms for each system component must be defined. The system comprises three key elements: an underground, spherical TES tank responsible for absorbing heat from the cooling unit, a refrigeration unit, and a warehouse designed for summer cooling to store potato.

In this system, heat is absorbed from the warehouse as it passes through the evaporator and subsequently released to the water in the underground TES tank through the condenser. By utilizing the underground TES tank for cooling, the system achieves higher energy efficiency compared to the conventional air-cooled systems, which rely on the outside air temperature. This model includes the transient heat transfer problem outside the tank's solution, expressions for the COP, and required cooling load for the Warehouse. By resolving the transient heat transfer problem outside the underground TES tank, expressions for the hourly water temperature variations within the TES tank are obtained. These expressions will be explained in detail in the following section.

3.1 Solution of transient heat transfer problem of the TES tank

To determine the water temperature in the subterranean spherical TES tank on an hourly basis, a combination of the similarity transformation and Duhamel's superposition principle will be employed. Duhamel's superposition principle is a mathematical technique employed to simulate the transient distribution of temperature around the TES tank. It involves first solving for a step input and then using Duhamel's integral to superimpose the solution onto an inhomogeneous, linear, partial differential equation. This enables us to find the temperature distribution over time.

For this study, the TES tank is assumed to be a spherical structure filled with water at a significant depth underground. Initially, the tank's temperature is T_∞, which is the temperature below the earth's surface. The water inside the tank is assumed to be fully mixed at a temperature $T_w(t)$, and its temperature continuously changes throughout the hourly cycle due to heat exchange with the soil [32]. The analysis assumes that the earth has a consistent structure and thermal properties that remain stable over time. Figure 2 provides an illustration of the energy balance and a schematic of the spherical TES tank.

The current investigation deals with the unsteady heat transfer in spherical coordinates, assuming radial symmetry to simplify the model to one dimension. It is reasonable to assume a constant temperature for the ground away from the storage, as depths below a certain level tend to maintain stable temperature throughout the year. The presented equation in this section accounts for the heat transferred from the TES tank's water to the surrounding earth, considering factors such as the thermophysical properties of the soil and tank. as well as the temperature difference between them.

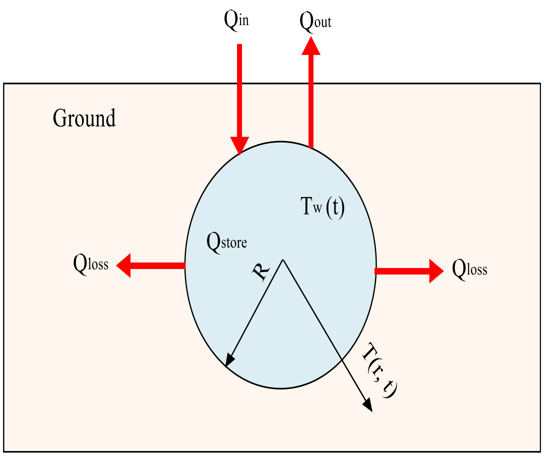

Fig. 2. Schematic energy balance of TES tank.

The issue of unstable heat transmission around the tank is addressed through the formulation of a differential equation, which provides a method to solve the transient heat transfer problem. The equation for the system is developed based on the initial and boundary conditions presented in the spherical coordinate system. [33]–[35].

$$\frac{\partial^2 T}{\partial r^2} + \frac{2}{r}\frac{\partial T}{\partial r} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \qquad (1)$$

$$T(R,t) = T_w(t) \quad (2)$$

$$T(\infty,t) = T_\infty \quad (3)$$

$$T(r,0) = T_\infty \quad (4)$$

The energy that is given to the tank is determined by the difference between the sensible energy gain of the tank and the conduction heat loss from the tank to the surrounding soil , as demonstrated in the following equation [36].

$$Q = \rho_w c_w V_w \frac{dT_w}{dt} - kA\frac{\partial T}{\partial r}(R,t) \quad (5)$$

The equation includes parameters such as the density ρ_w, specific heat c_w, and V_w volume tank, along with the thermal conductivity (k) of the surrounding earth, the tank's radius (R) of the, and its surface area tank (A).

To simplify the transient heat transfer problem, the following dimensionless equations are utilized to convert it into a dimensionless form [36].

$$x = \frac{r}{R} \quad \tau = \frac{\alpha t}{R^2} \quad \phi = \frac{T-T_\infty}{T_\infty} \quad \phi_w = \frac{T_w-T_\infty}{T_\infty}$$
$$\phi_a = \frac{T_a-T_\infty}{T_\infty}$$
$$q = \frac{Q}{4\pi RkT_\infty} \quad p = \frac{\rho_w c_w}{3\rho c} \quad (6)$$

The equations used in this study are presented in a dimensionless form, including the radial distance x, time τ, temperature ϕ, and net energy transfer q to the tank. The ground parameters considered are the density ρ and specific heat c, while subscripts w and a represent water and ambient air, respectively [36].

$$\frac{\partial^2\phi}{\partial x^2} + \frac{2}{x}\frac{\partial\phi}{\partial x} = \frac{\partial\phi}{\partial\tau} \quad (7)$$

$$\phi(x,\tau) = \phi_w(\tau) \quad (8)$$

$$\phi(\infty,\tau) = 0 \quad (9)$$

$$T(x,0) = 0 \quad (10)$$

$$q = p\frac{d\phi_w}{d\tau} - \frac{\partial\phi}{\partial x}(1,\tau) \quad (11)$$

Yumrutas and Ünsal [33] present a comprehensive solution to the unstable conduction heat transfer described by Equations (7) to (11). Since the cooling system's performance parameters are dependent on the store temperature, this section focuses solely on providing the solution for the dimensionless water temperature in the tank. The dimensionless water temperature is given as follows:

$$\phi_w(\tau_n) = \frac{q(\tau_n) + \left[\frac{p}{\Delta_\tau} + \frac{1}{\sqrt{\pi\Delta_\tau}}\right]\phi_w(\tau_{n-1}) - \sum_{i=1}^{n-2}\frac{\phi_w(\tau_{i+1})-\phi_w(\tau_i)}{\sqrt{\pi\Delta_\tau(n-i)}}}{1 + \frac{p}{\Delta_\tau} + \frac{1}{\sqrt{\pi\Delta_\tau}}} \quad (12)$$

The water temperature of the spherical TES tank will be determined using Eq. (12). In this equation, $q(\tau)$ represents the net heat adds to TES tank. The amount of heat gain by the TES tank is influenced by the dimensionless compressor work and the cooling load expressed, which are collectively expressed as $q(\tau)$.

$$q(\tau) = \frac{w(\tau)}{\gamma} + q_L(\tau) \quad (13)$$

where $w(\tau)$ represents the dimensionless compressor work input, γ is a dimensionless parameter, and $q_L(\tau)$ denotes the dimensionless heat removed by evaporator for the cooling unit.

3.2 Energy required for the cooling unit.

The cooling system operates based on the principles of the vapor compression refrigeration cycle, consisting of four main components: the evaporator, compressor, condenser, and expansion device. First, the evaporator absorbs heat from the warehouse, then condenser releases this heat to the TES tank. To enhance energy efficiency, the system utilizes underground heat storage, capitalizing on the naturally lower temperatures of the ground at an appropriate depth compared to the ambient air during the summer .

The evaporator plays a crucial role in absorbing the heat gain within the warehouse , and the cooling load is defined as follows [37]:

$$Q_L = Q_{transmission} + Q_{internal} \quad (14)$$

3.2.1 Transmission load

The heat gained by the refrigerated compartment through its surface is known as the transmission load. In the present work, the selected cold storage size is 16.60 m long x 10.60 m wide x 5 m high. The combined total area of the walls and roof measures 447.96 m^2.

$$Q_{transmission} = (UA)_w(T_a(\tau) - T_i) \quad (15)$$

The term $(UA)_w$ represents the product of the overall heat transfer coefficient and the area. In the context, T_a denotes to the ambient temperature, T_i stands for the inside design temperature, and T_p represents the temperature of the potatoes [37].

To determine the overall heat transfer coefficient (U) for the warehouse's walls and roof, equations (16) and (17) are used along with the relevant parameters listed in Tables 1 and 2. As a result, the calculated Overall heat transfer coefficient (U) is found to be0.2035 W/m^2. K [37].

$$R_{total\ wall} = \frac{1}{h_i} + \frac{X_1}{K_{Al}} + \frac{X_2}{K_{Polly}} + \frac{X_3}{K_{Al}} + + \frac{1}{h_o} \quad (16)$$

$$U = \frac{1}{R_{total}} \quad (17)$$

Table 1. Thermal conductivity and thickness of the materials used in the Warehouse wall.

Material	Thermal conductivity (w/mk)	Thickness (m)
Polystyrene	0.021	0.1
Aluminum	237	0.0005

Table 2. Convection heat transfer coefficient of air

Position	Convection heat transfer coefficient (w/m^2k)
h_o = Outside air	22.7
h_i = Inside air	9.37

3.2.2 Internal load

The primary refrigeration load originates from potatoes stored in the warehouse. It is also assumed that there are no additional internal loads, such as people and lights since their impact is negligible compared to the potatoes load. The heat that needs to be removed from the potato is referred to as the 'potato load'. This quantity of heat can be calculated using the following equation:

a) Potato load

$$Q_{potato} = m_p * c_v * (T_p - T_i) \quad (18)$$

where m_p is the mass of potatoes in kg, c_v is specific heat of potatoes in kJ/kg K, T_p is the temperature of the potatoes, and T_i is inside design temperature for the warehouse [37].

b) Respiration load

$$Q_{redpiration\ load} = m_p * heat\ of\ respiration \quad (19)$$

Combine Eq. (18) and (19) gives the following equation:

$$Q_{internal} = m_p * c_v * (T_p - T_i) + m_p * heat\ of\ respiration \quad (20)$$

3.2.3 Total cooling Load

The overall cooling load of a cold storage facility is a combination of internal and exterior loads, expressed as follows [37]:

$$Q_L = Q_{\text{transmission}} + Q_{\text{internal}}$$

$$Q_L = (UA)_w(T_a(\tau) - T_i) + m_p * c_v * (T_p - T_i) + m_p * heat\ of\ respiration$$

$$Q_L = (UA)_{Ev}(T_i - T_c) \quad (21)$$

here, $(UA)_{EV}$ represents the product of the heat transfer area of the evaporator and the overall heat transfer coefficient, and T_c is the mean temperature of the evaporator unit.

The COP of the cooling system can be expressed as [35]:

$$COP = \frac{Q_L}{W} = \frac{Q_L}{Q_H - Q_L} \quad (22)$$

where W denotes the compressor work, and Q_H represents the heat rejected to the TES tank. These are related to the Carnot efficiency, η_c, which is the ratio of the real COP for a cooling system and the Carnot COP_C [35].

$$\eta_c = \frac{COP}{COP_C} \quad (23)$$

The Carnot COP_C can be mathematically defined based on the source temperature T_w and the sink temperature T_e, as follows [35]:

$$COP_C = \frac{T_e}{T_w - T_e} \quad (24)$$

Combining Eqs. (23) and (24), yields:

$$COP = \eta_c \frac{T_e}{T_w(\tau) - T_e} \quad (25)$$

The Carnot efficiency η_c ranges from 0 to 1 with a Carnot refrigeration cycle having an efficiency of 1. By combining equations (14) and (21) and solving for T_e, then substituting the resulting expression for T_e into equation (25) while using the dimensionless parameters from equation (6), we obtain.

$$COP = \eta_c \frac{u(\phi_i - \phi_a(\tau)) + \phi_i + 1}{u(\phi_a(\tau) - \phi_i) + \phi_w(\tau) - \phi_i} \quad (26)$$

Equations (14) and (26) can be used to substitute into equation (22), resulting in an expression for the dimensionless compressor work:

$$w = \frac{W}{(UA)_H T_\infty} = \frac{((\phi_a(\tau) - \phi_i) + J) * u(\phi_a(\tau) - \phi_i) + \phi_w(\tau) - \phi_i}{\eta_c * [u(\phi_i - \phi_a(\tau)) + \phi_i + 1]} \quad (27)$$

Here, the parameter u in Eqs. (26) and (27) is defined as:

$$u = \frac{(UA)_W}{(UA)_{Ev}} = \frac{(T_i - T_e)}{(T_a(\tau) - T_i)} \quad (28)$$

Additionally, J is defined as:

$$J = \frac{Q}{(UA)_W T_\infty} \quad (29)$$

4. COMPUTATIONAL PROCEDURE AND INPUT DATA FOR THE WAREHOUSE COOLING SYSTEM

A computational procedure has been developed to investigate the performance parameters of a cooling system in a warehouse. The procedure involves numerical calculations using MATLAB software, based on the current analytical model. The software’s purpose is to investigate various aspects of the cooling unit's operation, including the variations of water temperature inside the TES tank and the hourly COP over a specific period. The hourly ambient temperatures for the Warman warehouse, located in Duhok province and selected for this study , are taken from [38].

4.1. Wearhouse

For this study, the summer design cooling load for a warehouse situated in Duhok has been calculated to be 36 kW hour, using Equation (14), for storing 150 tons of potatoes. The warehouses inside design temperature (T_i) and outside design temperature (T_a) have been set at 5°C and 45°C, respectively. The value of $(UA)_w$ was determined to be 91.18 W/°C. Moreover, the parameter (u), as defined in equation (28), was found to be 0.033. For the current analysis, It has been assumed that the initial water temperature inside TES tank (T_w) to be 15°C, equivalent to the temperature of the soil at a suitable depth. Additionally, the Carnot efficiency has been considered to be 0.4 [14].

4.2. The thermal characteristics of the soil surrounding the TES tank

The performance of the cooling system is significantly influenced by the thermophysical characteristics of the geological soil surrounding the TES tank. The amount of heat transfer from the water to the earth depends on soil properties, directly impacting the temperature of the water in the TES tank. For this study, Granite has been selected as a ground type due to its optimal performance for the cooling system. Additionally, the study investigates the impact of different types of soil, such as granite, limestone, and clay, on the system's performance. Table 3 outlines the characteristics of these three soil types [39].

4.3. TES tank

The hourly water temperature in the TES tank can be calculated by using Eq. (12), while the COP of the cooling system can be determined using Eq. (26). Several assumptions have been made regarding the water present in the TES tank. It is assumed that the water is fully blended and possesses specific heat and density values of 4.18 kJ/kg °C and 1000 kg/m^3 , respectively. The initial water temperature is considered to be 15°C, equal to the subsurface temperature. Additionally, no heat transfer resistance is assumed between the tank and earth. For the current investigation, the tank volume is fixed at 600 m^3. Moreover, the analysis also explores the impact of different tank volumes, specifically 500, 600, 700 and 800 m^3, on the TES tank temperature.

5. RESULTS AND DISCUSSION

To assess the efficiency of the warehouse cooling system, it is essential to identify the performance parameters of the TES tank and COP.

Table 3: Properties of the earth structures outside the thermal energy storage tank [39].

Earth type	Density (Kg m^3)	Thermal conductivity (W $m^{-1}K^{-1}$)	Thermal diffusivity (m^2s^{-1})	Specific heat (J $Kg^{-1}K^{-1}$)
Granite	2640	3.0	1.40×10^{-6}	820
Clay	1500	1.4	1.1×10^{-6}	880
Limestone	2500	1.3	5.75×10^{-7}	900

For this purpose, the model presented in Section 3, is employed to develop a computer code. This code calculates water temperature inside the TES tank at each hour and determines the required time for the annually intervallic operational phase and evaluates the COP of the vapor compression refrigeration cycle for the specific warehouse in Duhok, Iraq.

The performance analysis in this section focuses on assessing the impact of individual input parameters. These parameters include the Carnot Efficiency (CE), tank volume, and the type of geological structure affecting the storage temperature and COP of the cooling system. In the subsequent subsections, the influence of each parameter is examined to gain insights into the system's overall efficiency.

5.1. Effect (TES) tank volume

The storage tank volume is a crucial parameter that significantly impacts the system's performance, particularly when the surrounding geological structure is granite, as shown in Figures 3, 4. Opting for a larger tank size proves advantageous, as it facilitates quicker heat dissipation from the storage tank, resulting in reduced stored water temperature. However, it is essential to consider economic factors when determining the tank size, as larger tanks entail higher initial costs.

For instance, choosing a tank volume of 800 m^3 results in a maximum water temperature of around 25℃ in September, maintaining a water temperature lower than the surrounding air temperature, which is crucial for achieving satisfactory performance parameters. Conversely, opting for a tank volume of 500 m^3 leads to a water temperature reaching approximately 28 °C, indicating a less efficient cooling system. Thus, selecting a larger tank volume implies a higher-performance cooling system, but economic considerations should also play a vital role in making the final decision.

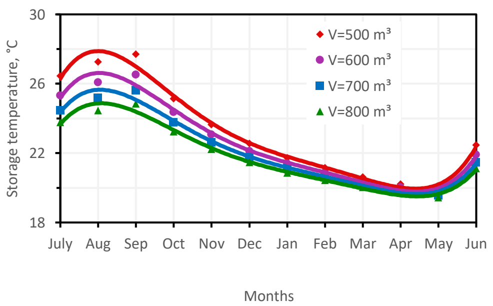

Fig.3. Effect the tank volume on TES tank temperature.

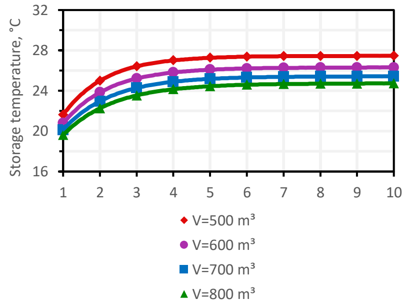

Fig.4. TES tank temperature with tank volume in Aug.

5.2. Effect of Carnot efficiency (CE) on TES tank and COP

The Carnot Efficiency (CE) is a crucial factor that directly influences the cooling system's performance and storage temperature. It signifies the ratio of the actual COP of the cooling system to the ideal COP. Zogou and Stamatelos [14] recommended CE values between 0.30 and 0.50 for small electric systems. As part of this research, three CE values, namely 0.30, 0.40, and 0.50 were selected.

Figure 5 illustrates how the water temperature in the TES tank varies throughout the year. Notably, an increases in CE results in a decrease in water temperature decreases, significantly impacting the COP, as shown in Figure 6. Over the course of ten years, an elevated CE leads to an initial increase in COP, which then gradually declines each year until reaching an annual periodic operating state. This outcome aligns with the findings presented in reference [25].

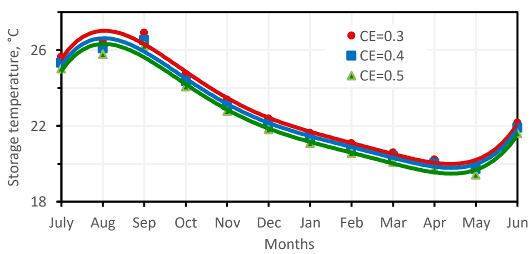

Fig. 5. Effect of CE on the water temperature during the fifth year of operation.

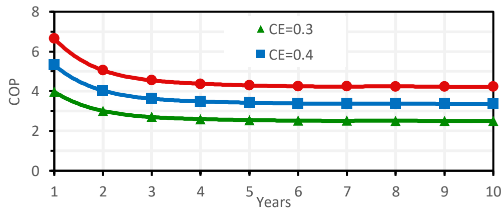

Fig. 6. Effect of CE on the COP.

5.3. Periodic operation of the cooling system

Figure 7 depicts the annual water temperature variation in the storage tank for the first, third, fifth, seventh, and ninth years of operation. The graph highlights that the water temperature exhibits significant variation during the initial years of operation, gradually reducing over time. In the early stages, the extracted and transferred energy are not balanced, leading to a gradual increase in storage temperature until it reaches the annual periodic state. Once an energy equilibrium is achieved between the storage tank and the surrounding earth, with the input heat equal to the transfer heat, the temperature stabilizes, and the system attains the annual periodic state. Both Figures 7 and 8 depict the evolution towards the annual periodic condition.

Specifically, Figure 7 demonstrates the annual variance in the tank's water temperature, which rises until the seventh year of operation, indicating that the system operates on a seven-year periodic basis. After seven years of operation, the energy input to the tank equals the heat transferred to the earth, resulting in energy balance. Additionally, Figure 8 displays the water temperature for the months of June, July, and August over ten years of operation, providing further insights into the system's performance.

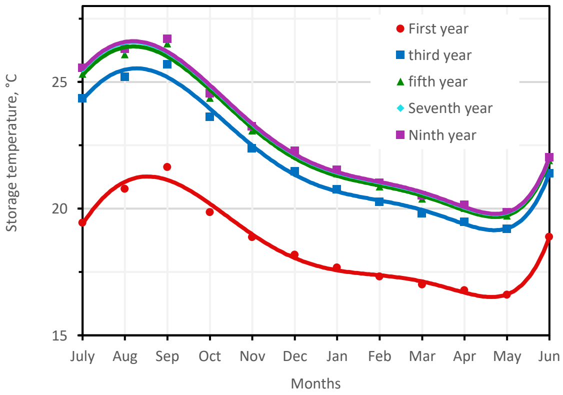

Fig.7. TES tank temperature with operation time.

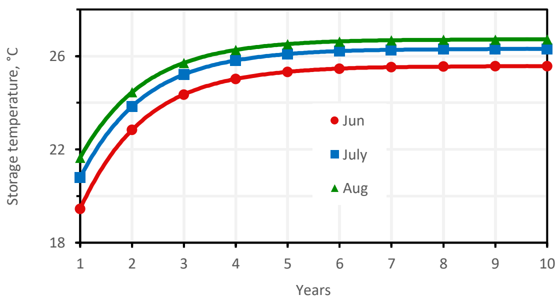

Fig.8. TES tank temperature in Jun, Jul, Aug.

5.4. Effect of geological earth structures

The geological composition of the earth play a crucial role in significantly impacting on the cooling system's performance. Figure 9 illustrates the deviation of the TES tank's water temperature for three distinct kinds of geological soil - granite, limestone, and clay - during the fifth year of utilization. The temperatures are presented not only for the hot seasons but for the entire year. Granite outperforms clay and limestone, maintaining lower storage temperatures due to its notably higher thermal conductivity and thermal diffusivity, as listed in Table 3.

The variation in storage temperatures for different types of earth are attributed to their thermophysical properties. Granite, compared to limestone and clay, exhibits significantly higher values for thermal conductivity and thermal diffusivity, enabling the rapid dissipation of heat absorbed from the TES tank into the surrounding ground.

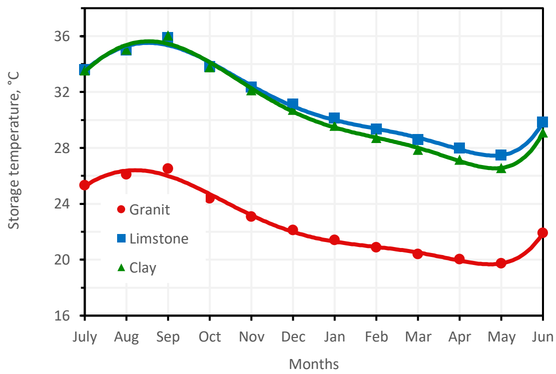

Fig.9. Effect of different earth type of TES tank water temperature.

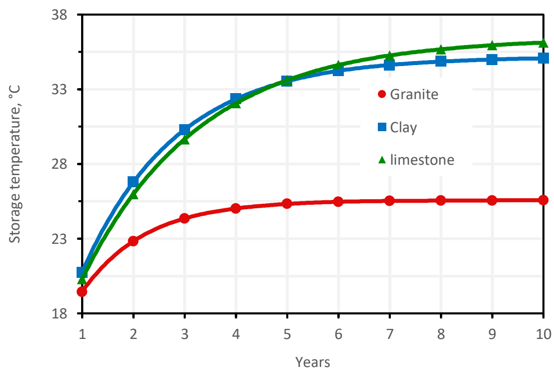

Fig. 10. Effect of earth type on the TES tank temperature for July.

During the winter months when the cooling system is not in operation due to the absence of potatoes in the warehouse, the TES tank cools down, reaching its coldest storage temperature at the end of winter. The highest storage temperatures occur when the TES tank is covered by limestone earth, while the lowest temperatures are observed when the tank is bordered by granite earth.

Figure 10 depicts the fluctuations in water temperature over time in the TES tank surrounded by the three types of earth in July: granite, limestone, and clay. According to Figure 10, the water in the tank is at its lowest temperature when surrounded by granite and its highest when surrounded by limestone. These different outcomes can be attributed to three key thermophysical characteristics of the earth, density, specific heat, and thermal conductivity- which significantly influence heat capacity and thermal diffusivity. Table 3 provides an overview of these thermophysical properties.

6. CONCLUSION

This study focuses on the mathematically modeling and simulating of a ground-coupled warehouse cooling system with an underground Thermal Energy Storage (TES) tank. This study aimed at investigating the long-term performance parameters for storing potatoes in Duhok province. Currently, the warehouse cooling system operates with a traditional air-cooled vapor compression refrigeration cycle. The primary goal of this study is to simulate the cooling system with a TES tank to enhance its COP, ultimately reducing electrical energy consumption. This will result in cost saving for farmers and contribute to reducing environmental pollution.

A MATLAB code was developed to evaluate the system's performance on an hourly basis, considering various design parameters and operational conditions. To solve the hourly heat transfer to the surrounding area of the TES tank, a similarity transformation and Duhamel's superposition principle were employed.

The findings highlight the improved COP of this system compared to traditional air-source cooling systems. Moreover, the results emphasize the significance of factors such as storage tank volume and soil earth types in determining the overall performance of the cooling system. By considering these factors, it is possible to optimize the system's efficiency and achieve substantial energy savings in warehouse operations.

The study yields several noteworthy findings regarding the cooling system parameters:

- Firstly, it was observed that the system achieves an annually periodic functioning state starting from the ninth year onwards.
- Secondly, the storage tank volume emerges as a crucial parameter significantly influences the system's performance. For instance, with a tank volume of 500 m^3, the projected water temperature is 28 °C, whereas a tank volume of 800 m^3 results in a lower water temperature of 25 °C.
- Another important factor impacting the cooling system's performance is the Carnot Efficiency (CE), which represents the system's efficiency. It was observed that a higher CE value leads to a higher COP, thereby enhancing the overall performance of the cooling system.
- Moreover, the type of earth used in the system is identified as a critical factor with a significant impact on performance. Among the selected soil types, granite demonstrates superior thermal performance for the cooling system compared to clay and limestone. This highlights the importance of carefully considering the earth type when designing and implementing ground-coupled cooling systems.

Based on the conclusions drawn from the study, the following ideas are suggested as recommendations for future research to optimize the performance of warehouse cooling systems, conserve energy, and decrease operating costs:

- Conduct further experimental research to assess the practical performance of cooling systems incorporating Thermal Energy Storage (TES) tanks. This in-depth exploration will help enhance the efficiency and cost-effectiveness of warehouse cooling systems.
- Explore alternative coolants with enhanced thermal properties, such as nanofluids or phase change materials, for the condenser and heat transfer to the TES tank. These advanced coolants have the potential to significantly improve the cooling process, offering more efficient and sustainable alternatives to conventional coolant.

NOMENCLATURE

c	Specific heat of soil ($J\,Kg^{-1}\,K^{-1}$)
c_w	Specific heat of water in the tank ($J\,Kg^{-1}\,K^{-1}$)
COP	Coefficient of performance of cooling system
i	Complex argument
k	Thermal conductivity of soil ($W\,m^{-1}\,K^{-1}$)
p	Dimensionless ρc product
q	Dimensionless heat transfer to the tank
Q_L	Cooling load for warehouse (w)
r	Radial distance from the thank center (m)
R	Tank radius (m)
t	Time (s)
T	Soil temperature (k)
T_a	Ambient temperature (k)
T_e	Temperature of evaporator (k)
T_i	Design inside air temperature (k)
T_w	Water temperature in the storage tank (k)
T_∞	Deep earth temperature (k)
$(UA)_W$	The product of heat transfer coefficient and area for the warehouse (WK^{-1})
$(UA)_{Ev}$	The product of heat transfer coefficient and area for the evaporator (WK^{-1})
V_w	Volume of the tank (m^3)
w	Dimensionless compressor work
W	Compressor work (w)
x	Dimensionless radial distance

Greek letters

α	Thermal diffusivity of soil ($m^2\,s^{-1}$)
γ	Dimensionless parameter, $4\pi Rk/(UA)_w$
ρ	Density of soil ($Kg\,m^{-3}$)
ρ_w	Density of water ($Kg\,m^{-3}$)
τ	Dimensionless time
$\emptyset_a$	Dimensionless ambient temperature
$\emptyset_i$	Dimensionless design inside air temperature
ψ	Dimensionless temperature
A	Tank surface area (m^2)
u	Dimensionless parameter, $(UA)_h/(UA)_{he}$
η_c	Carnot efficiency

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فحص الأداء لنظام تبريد مستودع مقترن بالأرض مع خزان تخزين الطاقة الحرارية تحت الأرض.

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الملخص

تم التحقيق في معلمات الأداء الحراري لنظام تبريد المستودع المقترن بالأرض مع خزان تخزين الطاقة الحرارية تحت الأرض (TES) *في هذه الدراسة. يتكون النظام من مخزن ووحدة تبريد وخزان* TES *تحت الأرض. تم إنشاء برنامج* MATLAB *لتقييم أداء النظام لكل ساعة مع الأخذ في الاعتبار معايير التصميم وظروف التشغيل المختلفة. لحل انتقال الحرارة إلى خزان* TES *المحيط لكل ساعة، يتم استخدام طريقة تحويل التشابه ومبدأ تراكب* Duhamel. *تشير النتائج إلى أن حجم خزان* TES *ونوع الأرض المحيطة به من العوامل الحاسمة التي تؤثر على أداء النظام. يعرض الجرانيت أعلى أداء للنظام من بين أنواع الأرض التي هي الجرانيت والحجر الجيري والطين الترابي. تكشف النتائج أيضًا أن درجة حرارة الماء في خزان تخزين الطاقة الحرارية* TES *تصل إلى 25.33 درجة مئوية كحد أقصى في تموز، والتي تظل أقل بكثير من درجة حرارة الهواء المحيط القصوى البالغة 45.67 درجة مئوية مما أدى إلى ارتفاع معامل الأداء للمنظومة (*COP=3.42*) مع حجم خزان تخزين الطاقة الحرارية* TES *بسعة 600 متر مكعب وكفاءة كارنوت 40٪ ونوع الأرض من الجرانيت. يحقق النظام التشغيل الدوري بدءًا من السنة التاسعة فصاعدًا لمدة 15 عامًا من التشغيل. هذه التحسينات تؤدي إلى توفير الطاقة وتقليل التأثيرات البيئية.*

الكلمات المفتاحية:

تبريد البطاطا ، المخزن ، خزان تخزين الطاقة الحرارية TES ، معامل الأداء COP ، تحليل الطاقة.