Numerical Modeling of Thermal Energy Storage of CHPs in Porous Concrete

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Abstract: Energy storage is essential in the modern age because fossil energy sources are running out, so there are a variety of ways to store energy, such as operating costs, energy consumption. The primary emissions and emissions, or all three, are reduced. In this paper, the heat energy storage method is used as sensible heat. The primary purpose of this study is to use inexpensive and available materials for energy storage. The heat source in this study is the CHP system exhaust gas selected for a 10-unit residential building. Thermal energy storage material is porous concrete that stores thermal energy in perceptible heat. The modeling of the system was also performed for the storage of thermal energy (charge and discharge process) by Schumann equations for fluid and solid storage in the porous medium, and the numerical solution of the equations was done by the characteristic method. For the fluid charge process of the CHP exhaust gases and air for the fluid discharge process, the porous concrete tank is assumed to be coated with mineral wool thermal insulation without loss of thermal energy. Heat transfer is only considered as one-dimensional heat transfer along the vertical axis of the tank, due to the porous solid storage environment, the conductive heat transfer in all dimensions of the tank is ignored. The thermocline property of the storage tank is essential for the numerical solution of the Schumann equations for the tank, with a charging time of 6 and a half hours and a discharge time of 5 hours.

Keywords: Thermal Energy Storage, Thermocline, Porous Concrete, Schumann Equations, One-Dimensional Heat Transfer.

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1. Introduction

In recent years, the storage of various forms of energy has received much attention from researchers and artisans. The main reason for this is the crisis of various energy sources, most notably the rising cost of energy carriers and the depletion of fossil energy resources [1], the rising temperature of the environment, and the formation of heat islands in densely populated cities. Be it. Other reasons, such as reduced operating costs, reduced initial energy consumption, increased efficiency of energy systems, reduced pollutants in the air, have given serious consideration to the issue of energy storage [2].

Combined Heat and Power is rapidly developing, so it will be essential to store CHP systems and materials used for storage. It should also be highly efficient and economically viable for the thermal energy storage and storage materials.
used to meet the cooling and heating needs of the building [3].

The essential methods of energy storage are: electrochemical storage (batteries), compressed air storage, hydraulic deep storage and pumped storage, energy storage in the flywheel, Hydrogen Storage and Thermal Energy Storage [3].

Since storage is a type of thermal energy studied, this method is investigated. The essential methods of thermal energy storage are tangible and intangible thermal storage.

**Figure 1.** Conventional methods of thermal storage (this figure was permitted to reuse by Taler et al. [2])

In sensible heat storage (SHS), heat energy storage is performed without phase change, and by adding heat, the average storage temperature increases. Heat is transferred from the heat source to the liquid or solid storage medium. The following are examples of the properties of several solids [4].

| Material      | Specific weight (kg/m²) | Heat capacity (J/kg°C) |
|---------------|-------------------------|------------------------|
| Concrete      | 2240                    | 1130                   |
| Granite       | 2640                    | 880                    |
| Cast Iron Brick | 7900                  | 837                    |
| Magnesium oxide bricks | 3000                 | 1130                   |

Table 1. Solids sensible heat storage materials [4].

In latent heat storage (LHS), heat transfer is caused by phase change. In fact, in this method, heat is introduced from the heat source into the storage material and changes the phase of the storage material, the amount of heat storage being dependent on the mass and latent heat of the storage material.

Tangible heat methods are more cost-effective than other methods and are also more straightforward and more accessible. Concrete is one of the primary thermal energy storage materials.

| Heat capacity (J/kg°C) | Specific weight (kg/m²) | Melting point (°C) | Material |
|------------------------|-------------------------|-------------------|----------|
| 4220                   | 5270                    | 1000              | Ice      |
| 2680                   | 1420                    | 1470              | Globber salt |
| 2510                   | 2890                    | 770               | Paraffin |

Table 2. shows some of these materials [4].

The use of concrete for thermal energy storage of CHP systems is an innovation because both overseas and domestically, in addition to the issue of thermal energy storage of new CHP systems; however, the use of concrete for this type of storage is entirely new and requires extensive research [2, 5].

Concrete can be used as a storage medium because of its low cost. Concrete is available almost worldwide and is accessible to process and process. Materials used in concrete are also cheap and available. Concrete is an excellent preservative because it has the following properties:

1. High heat especially
2. Excellent mechanical properties (having good compressive strength)
3. Thermal expansion coefficient near steel (the material used in the pipe)
4. High mechanical resistance against thermal cycle loading

The resistance to the thermal cycle depends on the thermal expansion coefficient of the material used in the concrete. To maximize the strength of the basalt concrete, metal (steel) pins are added to the concrete to prevent cracking and corrosion. By doing so, the conductivity and thermal conductivity increase by about 15% at 100°C and about 10% at 250 °C [3].

Storage by concrete can be done by prefabricated plates or can be molded into large blocks at the storage site, which is much easier and more cost-effective. Porous concrete generally has embedded duct structure, parallel plate structure, or concrete rod structure, each with its advantages and disadvantages [6].

Which structure is best depends on the storage conditions. Figure 2 shows that the choice of concrete as a storage medium is both costly, and
the amount of heat storage in concrete is much higher than other inexpensive storage materials [7].

Figure 2. Comparison of different materials in terms of cost and thermal storage capacity (This Figure permitted for reuse by the Cai et al. [7]).

By presenting a model, Babieri and his colleagues in 2012 demonstrated the impact of thermal energy storage on the utility and efficiency of micro-CHP systems for residential buildings. In this study, four primary CHP actuators, internal combustion engine, Stirling engine, Rankine cycle, and thermofoltaic system, were studied [8]. In 2013, Bianchi and colleagues studied the performance analysis of the CHP integrated system and the thermal and electrical storage systems in residential buildings, which resulted in the development of a developed code that performs the economic and thermal analysis. This paper provides useful, practical results for determining the optimal size of CHP integrated system components. It assessed the profitability of this type of storage over a separate heat and power system. [9]

Smith and his colleagues in 2013 examined the benefits of thermal energy storage combined with CHP systems for a variety of commercial buildings.

The research was conducted on eight commercial buildings in Chicago and outlined the benefits of this integrated system over non-storage CHP systems. The three main components seen in CHP systems coupled with thermal storage include reduced operating costs, reduced primary energy consumption, and reduced emissions. Also, in this paper, studies have concluded that, except in hotels and large buildings, the size of complementary boilers in storage systems does not decrease. Find out [1]. In 2013, Mostafavi and his colleagues studied the hourly energy storage analysis and the feasibility of applying a thermocline storage method to the CHP system [2]. Newton et al. (2013) performed a comparative analysis of the latent heat energy storage tanks for micro-CHP systems. In this study, two types of latent storage were investigated, cylindrical tubes containing PCM and spherical PCM capsules.
Finally, it is found that PCM tubes can have optimal storage when little heat is available, whereas PCM capsules can only store at high thermal capacities of thermal energy [10].

In 2008, Ling and colleagues investigated thermal storage in concrete on a parabolic solar power plant, with a thermal storage capacity equivalent to 400 kWh with a concrete volume of 20 m³ (8.6 * 1.3 * 1.7) and The insulation thickness of mineral wool was 40 cm. Its temperature range between 300 and 400 °C was designed as a heat transfer fluid (heat oil) at 400 °C, and its pressure was set at 25 bar. Charging and discharging time is 6 hours to 6 hours. The study was innovative in operating with concrete at 400 °C and heat storage for 270 cycles using thermal insulation [11].

In 2014, Solomon and his colleagues investigated storage in concrete at a temperature range of 80-300 °C for a 5 MW power plant with a heat transfer fluid temperature between 120-300 °C. In this study, it was estimated that the operational cost of heat storage in concrete is 20 to 30 euros per kWh, which is an innovation in terms of reducing operating costs [12].

In 2014, Ming and colleagues investigated the effect of Betty structure on the thermal performance of thermocline storage tanks, four main structures including porous concrete, embedded channel structure, parallel plate structure, rod structure. Concrete was considered, and the effect of this structure on the thermocline property of the tanks was investigated, which eventually showed that the porous concrete structure was the best [6].

The following figure shows the temperature distribution of the four structures, which is best described as a thermocline in porous concrete.

![Figure 3: Storage tank cross-section with four different structures: a) the embedded channel, b) parallel plates, c) concrete sticks, d) porous concrete.](image)

In 2014, Anish Moody and his colleagues described another study of thermocouple thermal storage systems for concentrated solar power plants using equations of energy and fluid and substantial continuity in the porous medium. They demonstrated that in the porous medium, there is no conductive heat, and only the heat transfer of the displacement along the axis of the tank is considered. A one-dimensional numerical method was considered to solve the equations. Figure 5 illustrates the reservoir pattern and control volume [13].

![Figure 5: Porous reservoir and control volume discharge cycle.](image)
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In a study in 2011, Van Lu and his colleagues solved the Schumann equations presented for porous environments by the numerical method of properties, and by dimming two main energy equations for fluid and the porous concrete and the characteristic method obtained the temperature distribution in the charge and discharge process [14].

2. Materials and Methods

The residential building in question is a ten-unit building in the center of Tehran, with an area of 80 square meters. Using ASHRAE standards, the heating, cooling, and electrical loads of this building were calculated to be 93.77 kW, 105.49 kW, and 28 kW, respectively. A CHP microturbine system with a nominal electric charge of 30 kW is used to provide this load. The discharge and exhaust gas temperatures of this system are 0.3080 kg/s and 276 °C, respectively (15). Based on these data, the main objective of this study is to model the heat storage of these exhaust gases. As mentioned, concrete is affordable and economically inexpensive and justifiable. As the best storage solid for this study, porous concrete with the specifications of Table 3 was selected.

Due to the engine compartment space, a concrete cylindrical tank with a height of 2 meters and a radius of 6 meters is considered as a heat storage tank. Figure 6 shows an example of porous concrete.

| Porosity | Conductive H.E. coefficient (w.m⁻¹.k⁻¹) | Specific heat capacity (j.kg⁻¹.k⁻¹) | Density (kg.m⁻³) | Material |
|----------|----------------------------------------|-------------------------------------|------------------|----------|
| 0.4      | 5                                      | 916                                 | 2750             | Concrete |

Since the fuel of the CHP microturbine system is methane, the CHP exhaust gas is carbon dioxide assuming complete combustion. The thermophysical properties of the exhaust gas and the concrete crusher are considered during the same storage. It is important to note that under real combustion conditions, the exhaust gas will not just be carbon dioxide, but the presumed output is very little in line with the thermophysical properties. Therefore, complete combustion is considered for simplicity of calculation and use of thermodynamic tables, and the carbon dioxide is assumed to be the exhaust gas. Table 4 shows the thermophysical properties of the gas at the moment of exit from the exhaust, assumed during persistent storage.

| Viscosity (Pa.s) | Conductive H.E. coefficient (w.m⁻¹.k⁻¹) | Specific heat capacity (j.kg⁻¹.k⁻¹) | Density (kg.m⁻³) | Material |
|-----------------|----------------------------------------|-------------------------------------|------------------|----------|
| 0.2082*10⁻⁴     | 0.03                                   | 1030                                | 1/1614           | CO₂      |

During the charging process, the exhaust gases enter the tank top and exit the bottom of the tank after heat transfer with the concrete. This operation will continue until the exhaust gases are not thermally conductive. At this time, the charging...
process is completed. During the heat discharge process, the ambient air enters the bottom of the tank and exits above it. During this heat transfer, ambient air, which is assumed to be at 25 °C, begins to rise with heat from the concrete and continues to rise until the air temperature reaches 70 °C. Find out. The temperature is assumed to be at least 70 °C.

Energy equilibrium analysis for concrete and gas is carried out using the relevant equations for fluid and concrete temperatures. The temperature of the outlet gas flow from the heat storage tank is a critical parameter that indicates the performance of the thermal storage. In Fig. 5, a one-dimensional control volume is shown as dZ. Investigation of the charge and discharge process for fluid and concrete is performed in this volume control. For ease of analysis, the positive direction of the Z-axis is always the direction of the fluid flow. Therefore, in the charging process, the bottom of the tank Z = 0 and the bottom of it Z = H, and in the discharge process, the bottom of the tank Z = 0 and the top of it Z = H.

The assumptions used for the analysis of thermal storage are as follows: (a) The uniform temperature distribution along the radial direction of the reservoir, thus converting the problem into a one-dimensional problem in the Z direction. B) The contact surface between the porous concrete components is assumed to be point contact, conductive heat transfer between the porous concrete is not considered; c) no heat loss from the storage tank, insulation Thermal is intended for mineral wool. These assumptions apply to both the charging and discharging processes.

First, the equations for fluid and then the equations for concrete will be mentioned. The basic equations expressed in this section of thermodynamics are easily extractable [14]. In the previous section, the assumptions were made.

The area of the cross-section through which the gas passes is calculated by Equation 1.

\[ a_f = \varepsilon \pi R^2 \]  

\( \varepsilon \) the coefficient of porosity of the concrete tank and the radius of the storage tank (m). The equilibrium gas energy balance equation of the control volume (dz) is:

\[
\rho_f \varepsilon \pi R^2 U(h_z - k_z T_d) + h_S(T_c - T_f) dz = \rho_f c_f \varepsilon \pi R^2 \frac{dT_f}{dz}
\]  

Equation 2

\( f \) fluid sign, \( c \) concrete sign, \( h \) fluid enthalpy in positions along the axis in (J / kg), \( q \) density in terms (kg / m³) and \( z \) in the vertical direction of the tank, \( h \) displacement heat transfer coefficient, \( T \) denotes temperature, Special heat \( C \), \( S_r \) Concrete heat transfer surface area per unit length of the tank and velocity \( U \) along the axis of the tank (m / s) calculated on the concrete bed from equation 3:

\[
U = \frac{m}{a_f \rho_f} (3)
\]

\( m \) the fluid flow through the concrete tank is in the process of charging and discharging. According to the definition of enthalpy, Equation 2 is rewritten as follows.

\[
\rho_f c_f \varepsilon \pi R^2 (T_c - T_f) = \frac{dT_f}{dt} + U \frac{dT_f}{dz} \]  

Equation 4

Now using the dimensionless variables below, we simplify Equation 4.

\[
\theta_f = (T_f - T_1) / (T_h - T_1) \]  

Equation 5a

\[
\theta_c = (T_c - T_1) / (T_h - T_1) \]  

Equation 5b

\[
z^* = z / H\]  

Equation 5c

\[
t^* = t / (H / U)\]  

Equation 5d

\( H \) is the height of the concrete tank, \( t \) time, \( \theta \) dimensionless temperature, \( t^* \) dimensionless time, and \( z^* \) dimensionless height. After simplifying Equation 4 with dimensionless variables, Equations 6 and 7 are obtained (TI the lowest fluid temperature, \( T_h \) the highest fluid temperature).

\[
\frac{\partial \theta_f}{\partial t^*} + \frac{\partial \theta_f}{\partial z^*} = \frac{1}{\tau_r} (\theta_c - \theta_f) \]  

Equation 6

\[
\tau_r = \frac{U H}{h_S r} \]  

Equation 7

It replaces a combination of density parameters, specific heat capacity, porosity...
coefficient, reservoir radius, fluid velocity, reservoir height, and etc., which, according to the relation 7, will be a constant. $S_f$ The area of heat transfer surface of the concrete is the unit length of the tank, calculated from the following equation.

$$ S_f = \frac{f_s \pi R^2 (1 - \varepsilon)}{r} $$  \hspace{1cm} (8)

In the above equation $r$, the radius is equivalent to the concrete particles, and $f_s$ the surface shape coefficient can vary from 2 to 3 depending on the type of concrete porosity. In this study, number 2 was selected. The heat transfer coefficient of the displacement is calculated by Equation 9 [16].

$$ h = \frac{0.191 m C_f}{\varepsilon \pi R^2} \text{Re}^{-0.287} \text{Pr}^{-2/3} $$  \hspace{1cm} (9)

The Prandtl number Pr and the Reynolds number Re are also calculated by correcting the Reynolds number relation for the porous media. [16]

$$ \text{Re} = \frac{4 G r_{char}}{\mu_f} $$  \hspace{1cm} (10)

$G$ is also the fluid mass flux in the porous bed calculated by equation 11.

$$ G = \frac{m}{\varepsilon \pi R^2} $$  \hspace{1cm} (11)

$r_{char}$ The characteristic radius or hydraulic radius is defined by the following equation. [16]

$$ r_{char} = \frac{\varepsilon d_c}{4(1 - \varepsilon)} $$  \hspace{1cm} (12)

$d_f$ Stands for the nominal diameter of porous concrete components.

For the equilibrium energy balance equation, the same control volume, as in Figure 5, is used. The porous concrete substrate takes heat from the gas during the charging process and returns heat to the air during the discharge process. This heat transfer of the concrete and gas is accomplished at the cost of changing the internal energy of the concrete. The equilibrium energy balance equation is given below.

$$ h S_f (T_c - T_f) dt = \rho_c C_c (1 - \varepsilon) \pi R^2 \frac{dT_f}{\varepsilon} $$  \hspace{1cm} (13)

By replacing the dimensional variables, Equation 13 becomes the following:

$$ \frac{d\theta_c}{dt^*} = \frac{H_{CR}(\theta_c - \theta_f)}{\tau_r} $$  \hspace{1cm} (14)

$$ H_{CR} = \frac{\rho_f C_f \varepsilon}{\rho_c C_c (1 - \varepsilon)} $$  \hspace{1cm} (15)

HCR replaces a combination of density, specific heat capacity, and porosity coefficients, and will be a constant parameter given the relation 15. The numerical method of attributes is used to solve the equations mentioned [17]. Gas and concrete energy balance equations can be solved by numerical methods along with the characteristic equations. $t^* = z^*$ Dimensional characteristic equations 6 and 14 are used to facilitate the integration operation since these equations are transformed into univariate equations with full differential [14]. Equation 6 is transformed into a univariate equation by using the characteristic equation (this equation is used for ease of integration to continue solving the problem). $t^*, z^*$ Variables are reduced to $t^*$ partial derivative and become a complete differential.

$$ \frac{D\theta_f}{Dt^*} = \frac{1}{\tau_r} (\theta_c - \theta_f) $$  \hspace{1cm} (17)

By dividing and integrating along with the characteristic, the following equation is obtained.

$$ \int d\theta_f = \int \frac{1}{\tau_r} (\theta_c - \theta_f) dt^* $$  \hspace{1cm} (18)

Likewise, the equilibrium energy balance equation in Equation 14 becomes the following equation, along with the characteristic equation $z^* = \text{const.}$

$$ \frac{d\theta_c}{dt^*} = \frac{H_{CR}(\theta_c - \theta_f)}{\tau_r} $$  \hspace{1cm} (19)

By dividing and integrating along with the characteristic for Equation 19 we have:
After the formation of two characteristic equations bounded by place and time. A discrete dot grid, one dimension at a time, and the other at that location are obtained by nodes being created at the intersection of these axes. A graph of these points is depicted in Fig. 8. Vertical lines represent the motion on the wave equation \( z^* = \text{const} \) and angular lines on the wave equation \( t^* = z^* \), which are the basis of the numerical solution method.

\[
\int \frac{H}{r} \left( \theta_c - \theta_f \right) dt^* \quad (20)
\]

The numerical integration to the right of Equation 21 is performed by a trapezoidal method.

\[
\theta_{f,2,2} - \theta_{f,1,1} = \frac{1}{\tau_r} \left( \frac{\theta_{f,2,2} + \theta_{c,1,1}}{2} - \frac{\theta_{f,2,2} + \theta_{f,1,1}}{2} \right) \Delta \tau \quad (22)
\]

While the \( \theta_f \) value is \( \theta_{f,1,1} \) at \( \nu_{1,1} \) and the \( \theta_f \) value is \( \theta_{f,2,2} \) at \( \nu_{2,2} \), and similarly, the same is true for \( \theta_c \). By integrating equation 20 on, \( z^* = \text{const} \) we obtain the following equation:

\[
\int_{\nu_{1,1}}^{\nu_{2,2}} \frac{H}{r} \left( \theta_c - \theta_f \right) dt^* \quad (23)
\]

The numerical integration to the right of Equation 23 is performed by a trapezoidal method.

\[
\theta_{c,2,2} - \theta_{c,1,1} = \frac{H}{\tau_r} \left( \frac{\theta_{f,2,2} + \theta_{c,1,1}}{2} - \frac{\theta_{f,2,2} + \theta_{f,2,1}}{2} \right) \Delta \tau \quad (24)
\]

Equations 22 and 24 can be considered as a set of algebraic equations for two unknowns \( \theta_{f,2,2} \) and \( \theta_{c,2,2} \) while both \( \theta_c \) and \( \theta_f \) are in nodes \( \nu_{1,1} \) and \( \nu_{2,1} \) are known.

\[
\begin{bmatrix}
\frac{1}{2\tau_r} \Delta^* - \frac{\Delta^*}{2\tau_r} \\
\frac{H}{\tau_r} \left( \theta_{f,2,2} \right) + \frac{H}{\tau_r} \left( \theta_{c,2,1} \right) = \\
\theta_{f,2,1} \left( 1 - \frac{\Delta^*}{2\tau_r} \right) + \theta_{c,1,1} \left( 1 - \frac{\Delta^*}{2\tau_r} \right)
\end{bmatrix}
\]

By solving Equation 25, two unknowns \( \theta_{f,2,2} \) and \( \theta_{c,2,2} \) will be considered, and calculated, in the second and second nodes, respectively, of the gas and concrete dimensionless temperatures. It is essential to state that all variables and coefficients in Equation 25 are calculated only once, which is very important for the calculation time. This is much more efficient.
than the methods described in references 18, 19, and 20.

It is first assumed that the tank is recharged, and the temperature of the concrete and gas inside it is 270 degrees Celsius. The discharge process then begins with 25 °C air intake and continues until the outlet air temperature reaches 70 °C.

For the charging process, the final condition of the discharge process is also considered as the initial condition. At the last moment, the discharge process is considered as the initial temperature distribution of the charging process, respectively. Moreover, the CHP exhaust gas enters the tank at 270 degrees Celsius, and the charging process will continue until the gas temperature reaches 270 degrees Celsius. The charging and discharging process will continue like this.

Figure 8 shows that the temperature of the concrete and gas in the nodes \( v_{1,1} \) is considered as the initial condition. Gas and concrete temperature in the nodes \( v_{1,j} \) are also considered as input conditions wherein \( v_{1,j} \) the constant gas temperature and concrete temperature change over time. The gas temperature at the points in the charging process is the temperature of the CHP exhaust gases that are considered constant over time. The CHP is assumed to be in the primary and constant charge state, so the outlet gas temperature will be constant at 270 °C. The temperature of the concrete can also be calculated as a function of time at the gas inlet using Equation 19 for each gas inlet temperature.

Therefore, and the \( v_{1,1} \), \( v_{1,2} \), \( v_{2,1} \) values are known, and the temperature of the concrete and gas \( v_{2,2} \) can easily be calculated using Equation 25. The above computation sample is extended to all points in the time-space network, and the matrix is obtained to calculate the temperature of the concrete and fluid at all nodes.

Finally, exergy loss equations are considered to calculate the exergy loss in charge and discharge process concerning the topics discussed in optimizing the exergy flow. Since the relationships between the discharge and discharge process are the same, only the relationships of the discharge process are expressed. [21]

\[
\sigma T_0 = \text{Ex}(Q) - \left( \text{Ex}_2 - \text{Ex}_1 \right) \quad (26)
\]

According to Fig. 5, the amount of exergy loss \( \sigma T_0 \), concrete exergy \( \text{Ex}(Q) \), and fluid exergy of concrete \( \left( \text{Ex}_2 - \text{Ex}_1 \right) \) can be calculated for each \( \Delta Z \) element in each \( \Delta t \) time interval. [21]

\[
\text{Ex}(Q) = \rho_c \pi R^2 \left( 1 - \varepsilon \right) C_f \left( T_{G_l,j} - T_{G_l,j+1} \right) \Delta Z \left( 1 - \frac{T_0}{T_{\text{lm,c}}} \right) \quad (27)
\]

\[
T_{\text{lm,c}} = \left[ \frac{T_{G_l,j} - T_{G_l,j+1}}{\ln \left( \frac{T_{G_l,j}}{T_{G_l,j+1}} \right)} \right] \quad (28)
\]

\[
\left( \text{Ex}_2 - \text{Ex}_1 \right) = \rho_f \pi R^2 \left( 1 - \varepsilon \right) C_f \left( T_{f_i,j+1} - T_{f_i,j+1} \right) \Delta Z \left( 1 - \frac{T_0}{T_{\text{lm,f}}} \right) \quad (29)
\]

\[
T_{\text{lm,f}} = \left[ \frac{T_{f_i,j+1} - T_{f_i,j+1}}{\ln \left( \frac{T_{f_i,j+1}}{T_{f_i,j+1}} \right)} \right] \quad (30)
\]

\( T_{\text{lm}} \) is the logarithmic temperature of the element \( i \) at time \( j \), and \( T_0 \) is the ambient temperature.

3. Results and Discussion

According to the numerical method described, the input and initial assumptions and conditions were written with the help of Matlab software. References 6, 13, and 14 were used to validate the results and graphs, using these relationships and numerical methods, thermocline diagrams, and similar general results. In the coding, the code for the discharge process was first written, and then the code for the charging process. In the discharge process, it was assumed, the temperature distribution of the tank and the gas inside it was 270 °C and continued with the inlet air 25 degrees from the bottom of the discharge process and continued until the outlet air temperature reached 70 degrees.

The high discharge time of 5.02 hours. Following is an image of the different times, the discharge process, which results from the coding.
output. Fig. 9 shows the thermocline property of the concrete tank, which is visible during discharge.

In the process of discharging the inlet gas to the tank, the air is 25 °C, which enters the end of the tank. Inlet air discharge equal to the discharge of CHP exhaust gas, 0.3080 kg/s.

As shown in Fig. 9, due to the changing color of the tank, the tank's thermocline is merely visible. The temperature distribution of the fifth discharge hour, visible in Fig. 9, is considered as the initial condition of the charging process.

The amount of heat received from the concrete during the discharge time is 1133.7 MJ.

The temperature distribution of the concrete tank varies over time during the discharge process, so that the thermocline moves over time from the bottom of the tank to the tank disaster. This indicates the thermal discharge of the tank. In Figure 10, this is visible.

In the explanation of Figures 10 and 11, it is necessary to point out that the graphs in Fig. Ten are upward because the graphs show the temperature distribution at different times of the discharge process, and since The tank starts to cool from the bottom, so the top of the tank is at a higher temperature. This has caused charts to rise. Fig. 11 shows plots showing the temperature of a particular point in the reservoir, so it was evident that the temperature of each point in the reservoir decreases over time and decreases to the specified temperature.

For example, the temperature distribution of several points of the tank during the discharge process is illustrated in Fig. 11. This graph also shows a good picture of the temperature distribution. Unlike Figure 10, this distribution is in descending order.

Similarly, the temperature distribution of the fluid during the discharge process can be shown. Figure 12 shows the distribution of air temperature throughout the tank at different discharge times, and Figure 13 shows the fluid temperature...
distribution at specified locations of the tank over time. The interpretation of these two forms is similar to the concrete temperature distribution graphs in the discharge process.

![Figure 13. Fluid temperature distribution at the bottom, 0.5 meters, 1 meter, 1.5 meters and at tank's top](image)

In the charging process, the inlet gas to the tank from which it enters is carbon dioxide, which is the CHP. It is necessary to point out that if we were to take account of air properties for computation and coding, it would be acceptable since the thermophysical properties of these gases are very close together.

Carbon dioxide gas enters the tank from above at 270 °C. At the beginning of the charge, the temperature distribution of the concrete is the final state of the discharge process. The final distribution of concrete in the discharge process can be seen from Figure 10 and the block diagram.

![Figure 14. Concrete temperature distribution at discharge first moment](image)

It then starts charging as the gas enters the concrete tank and changes the temperature of the concrete tank. The charging process continues until the concrete temperature at the gas outlet reaches 270 °C. After completing the coding for this part, the charging process took 6.49 hours. The inlet gas discharge to the tank is considered to be 0.3080, and then heated to the concrete tank is 1366.3 MJ. As can be seen, the charging time is approximately one hour longer than the charging time. The reason for this is due to the initial conditions of the two charge and discharge processes, which is the initial temperature distribution. The temperature distribution for the beginning of the two processes is shown below.

The temperature distribution of the concrete and air in the discharge process is marked in red and green, and the value of both in the entire reservoir at the starting point of the process is 270 °C. The blue and black graphs show the temperature distribution of concrete and air at the beginning of the charging process.

To illustrate the charging process, the graphical temperature distribution of the charging process is used at different times. Figure 15 shows the results.

![Figure 15. Tank's thermocline Schematic during the charging process](image)

Thermal efficiency can be calculated for this concrete tank, which indicates the proper performance of this thermocline tank. The temperature distribution of the concrete tank varies over different times during the charging process, as the thermocline moves over time from the top of the tank to the bottom of the tank. This indicates the heat charge of the tank. In Figure 16, this is visible.

\[
\eta = \frac{Q_{\text{discharge}} \times \text{100}}{Q_{\text{charge}}} = \frac{1133.7 \times \text{100}}{1366.3} = 82.97 \%
\]
For example, the temperature distribution of several points of the tank during the charging process is illustrated in Fig. 17. The explanation for Figures 16 and 17 is similar to the logic used in the explanation for Figures 10 and 11.

Also, using the equations 26-30, the exergy loss of the full charge and discharge process was calculated. By calculating the exergy loss for each element $\Delta Z$ over time $\Delta t$ and calculating the sum of all the losses during the recharge and discharge process, the total exergy loss was determined. Exergy loss was obtained during the recharge process of 1.35 kW and for the recharge process of 2.39 kW. This loss is negligible compared to the amount of heat transferred in the charging and discharging process. Also, during the charging process, the exergy difference in the concrete as a heat well-equalled 2.247*10^8 joules and the exergy difference in the hot gas of the cogeneration system as the heat source equaled 2.5519*10^8 joules. During the discharge process, the exergy difference in the concrete as heat source equaled 2.247*10^8 joules, and the exergy difference in the air passing through the concrete tank was calculated as thermal wells equal to 1.8112*10^8 joules.

The reduction in carbon dioxide production in this storage, provided that we use only one storage cycle daily, is equal to the rate of discharge of the exhaust gas during the discharge time divided by the density of carbon dioxide if twice the cycle. Storage will be doubled. This will be followed by a reduction in carbon dioxide production once per storage cycle, which is 5757.34 cubic meters per storage cycle. This reduction will have a significant contribution to reducing pollution in a city like Tehran.
undesirable. Also, the amount of energy stored by concrete decreases with increasing radius. The optimum radius of the porous particles is 0.01 m.

The effect of the number of nodes, or the same number of elements, on the quality of the temperature distribution was also investigated, which resulted in a negligible effect of the number of elements on the fluid and solid storage temperature distribution. This is shown in Fig. Eighteen for the fluid temperature and can be seen in similar studies [14]. The graphs are very close together and are highly accurate.

4. Conclusions

In this study, porous concrete was selected as the storage material that had the best thermal performance among other structures. The use of concrete in CHP storage is an innovation in the storage of thermal energy in the exhaust gas of the heat and power cogeneration system. According to the description of the introduction of the numerical method, it is possible to use this method in any solid-fluid and porous media for modeling and storage. Due to the linearity of the equations and the need for repetitive calculations to obtain the fluid and concrete temperature in a particular node as well as the need for no initial guess, it is observed that this method is used for thermodynamic modeling and calculating the aggregate loss. The transient, exergy difference and calculation of the amount of energy stored and taken from the concrete, the hot exhaust gases from the CHP, and the air in the charging and discharging process are very suitable. Charging and discharging times were estimated at approximately 5 to 6 hours each, indicating the availability of this type of storage around the clock due to its proper charging and discharge time. The benefits of reducing carbon dioxide production and its significant contribution to the reduction of (environmental) pollution can also be mentioned. Given the low cost of concrete and the excellent heat capacity of this material over other materials, it will undoubtedly reduce economic costs, reduce maintenance and maintenance needs. Selecting the optimum radius for the porous particles concerning the exergy dissipation changes is another achievement of this study.

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Conflicts of Interest

“The authors declare no conflict of interest.”

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