Modelling of Aquifer Thermal Energy Storage Connected to Hospital Buildings: A Case Study in Denmark

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Abstract

Aquifer thermal energy storage (ATES) is a type of underground seasonal thermal energy storage which uses underground water as the storage medium. Different modeling and simulation tools have been used to model ATES coupled with building and district energy systems. However, most of these methods use co-simulation techniques, which are computationally expensive, time consuming and complex to set up and debug. This paper illustrates a simplified cooling-mode operation of an ATES-based system model developed entirely using the Modelica language. Results indicate that Modelica is an appropriate tool for developing energy system models consisting of ATES to assess their performance. For the case study analyzed in this paper, we controlled the aquifer circulation pumps to supply a constant water temperature of 12 °C to the buildings. Furthermore, the model allowed us to predict the aquifer temperatures in the warm well over time at different distances.

1. Introduction

Buildings account for about 32% of the total energy demand in the EU. According to the International Energy Agency (IEA), to meet the EU's goal of net carbon neutrality by 2050 (“Buildings - Energy System”, 2023); important measures must be taken in the building and district energy sector to include a higher share of renewable energy in the supply mix. To increase the share of renewable energy in district energy systems, researchers have explored ways to utilize geothermal energy as a source of heating and cooling in district energy networks. Since geothermal energy is a readily available source, it is used to meet the demands of consumers for space heating, space cooling and domestic hot water. In recent years, research into geothermal energy as a renewable source for district heating and cooling networks has gained increasing interest.

Utilizing geothermal energy storage technologies can enhance the integration of renewable energy sources into the energy supply mix. Seasonal energy storage systems can effectively provide heating and cooling solutions during peak demand hours. Aquifer thermal energy storages (ATES) are one type of seasonal thermal energy storages which have been utilized for decades to provide heating and cooling to buildings by use of groundwater (Fleuchaus et al., 2018). An ATES system typically functions in two modes as shown in Fig. 1. During winter, the ATES system extracts water from the warm wells of the aquifer, which is then directed to a heat pump. The heat pump transfers heat from the warm water to the building’s heating system, increasing the water temperature for effective heating. The cooled water is then redirected to the cold well of the aquifer for storage. In cooling mode, the water from the cold wells is used to provide space cooling. In some cases, a third regeneration mode is used to maintain a thermal balance in the wells (Vanhoudt et al., 2011), or to store excess heat when electricity is cheap from renewable sources such as wind and solar.

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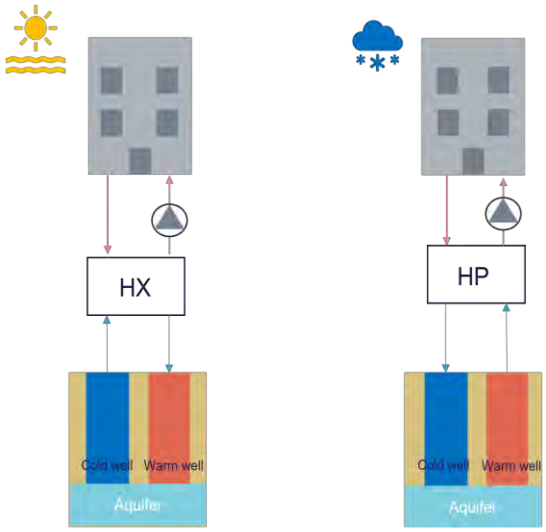

Fig. 1 – ATES operation during summer and winter months

In recent years, there have been significant advances in the research on optimizing the performance of ATES systems. For example, Ribas Tugores et al. (2015) and Todorov et al. (2020) have utilized modeling and numerical simulations to analyze the operational dynamics of ATES systems.

Modeling of ATES systems has been done using different modeling tools (Lee, 2010). Different parameters are considered when evaluating the performance of an ATES system. Based on the requirement of the ATES system, research based on derived KPI's was performed by (Abuasbeh et al., 2021). The thermal efficiency, recovery ratio and hydraulic balance were considered for long term performance of the aquifer. Over a four-year period, the temperature in the cold side of the aquifer increased by 2 °C indicating thermal breakthrough. Further studies in ATES efficiency were conducted by Beernink et.al (2022). Optimal well placements were explored to improve the efficiency and reduce the overall GHG emissions of the ATES coupled energy system. The study concluded that densely placed wells lead to lower electricity consumption from heat pumps and at the same time reduce GHG emissions from other sources of heat such as gas or electric boilers. A method to optimize the DH grid using large-scale thermal energy storages was explored by (Tosatto, Dahash, & Ochs, 2023) where the system performance was evaluated based on the energy and exergy analysis of the TES.

System integration of ATES with district energy systems was recently explored by Bozkaya et al. (2018) where a co-simulation approach was utilized to simulate the operation of the ATES connected to buildings. TRNSYS was used to develop the building model, while COMSOL was utilized to model the aquifer storage. Typically, to analyze the performance of coupled sub-surface and above-surface components of ATES systems, sophisticated and computationally expensive co-simulation techniques are used. This is mainly due to the lack of sub-surface ATES models that can be seamlessly integrated into building and district energy simulators. Recently, Maccarini et al. (2023) developed a low-order sub-surface ATES model using the Modelica language. The accuracy of the model was verified against other simulators, confirming its suitability to be used in the development of integrated system models based on ATES technology.

This paper aims to demonstrate the application of such a sub-surface model for a case study involving an ATES system connected to hospital buildings. This work focuses on the analysis of the cooling-mode operation of the system during the summer months.

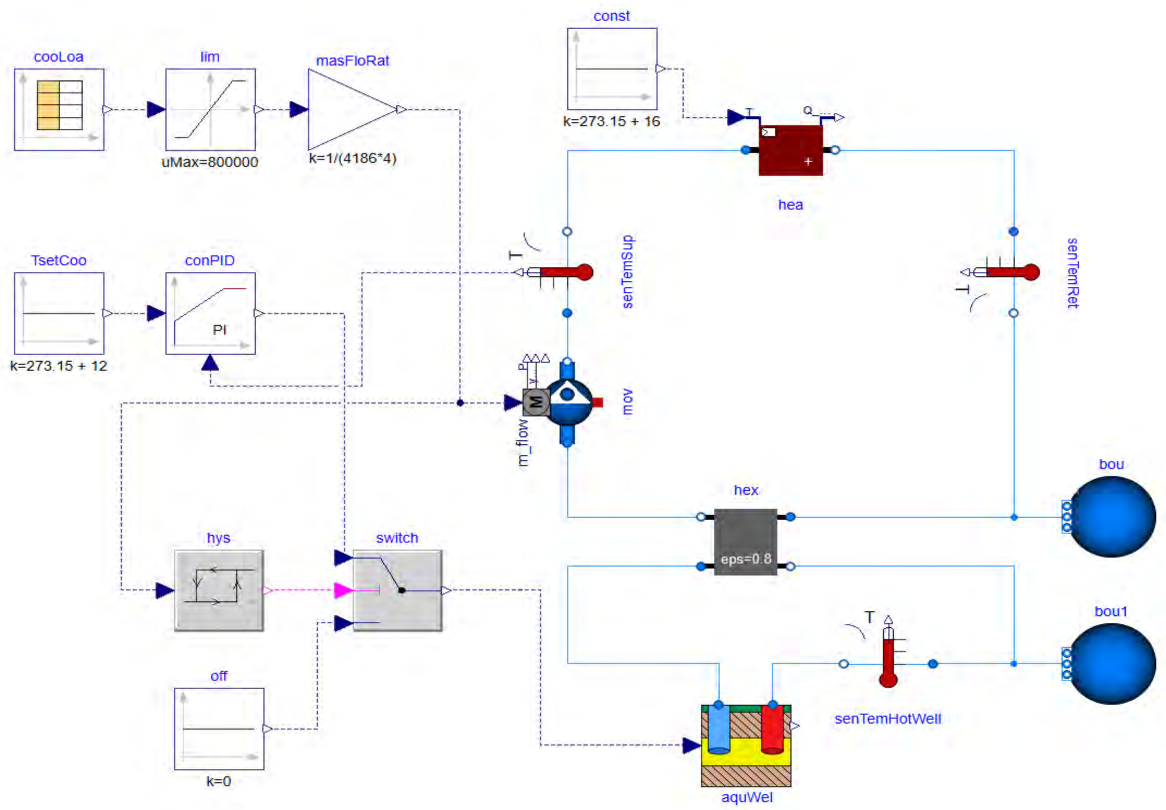

Fig. 2 – Modelica diagram of the ATES system. (The dashed lines represent the control sequence, and the solid lines represent the component connections)

2. Methodology

2.1 Pilot Site Description

The ATES case study is located in Copenhagen, Denmark and it consists of 12 wells (6 hot wells and 6 cold wells). During winter months, heat pumps are used to heat the water from the warm wells to meet the heat demand. During summer months, cooling is provided by the groundwater ATES system to the hospital. Domestic hot water is supplied by the district heating network in the region. The heat pumps are not in operation during the summer months. As previously mentioned, this paper focuses only on modeling the cooling-mode operation of the cooling system that provides the hospital buildings with cold water during the summer months. The information on the installed cooling system inside the hospital substations is unavailable to the authors.

3. Modelling approach

The model of the ATES system was developed using the Modelica language, and it describes the thermal and hydraulic dynamics of the system, together with the control logic. Modelica is a freely available, object-oriented, and equation-based language for modeling physical systems and controls (Mattsson, Elmqvist, & Otter, 1998). Component models from the Modelica Buildings Library version 11.0.0 (Wetter et al., 2014) were used in this work. Simulations were run using Dymola 2024 on Windows with the DASSL solver and a tolerance of 1E-6. Fig. 2 illustrates the Modelica diagram view of the ATES system.

The system model includes the following main component models:

- Sub-Surface aquifer storage.
- Heat exchanger connecting aquifer and building hydraulic circuits.

- Circulation pump for the building hydraulic circuit.
- Control logic

The sub-surface aquifer storage component is modeled based on the partial differential equation (PDE) for 1D conductive-convective transient radial heat transport in porous media. In the Modelica implementation, the domain is assumed to be spatially discretized along the radial direction. The heat transfer process within the aquifer is represented by a series of thermal capacitances and resistances. The fluid flow between the wells through the subsurface was modeled by adding a series of fluid volumes, which are connected to the thermal capacitances via heat ports. Circulation pumps are included in the model and can be controlled using a dedicated connector. The aquifer model was developed with the following assumptions,

- The computational domain is homogenous.
- Movement of water in the aquifer is only in the radial direction.
- No vertical heat transfer and the flow of groundwater is neglected.

More details can be found in (Maccarini et al., 2023). The number of well doublets in the model can be adjusted using the parameter, *nPai,* which represents the number of paired wells.

The heat exchanger component models the heat transfer between the fluids using an effectiveness coefficient of 0.8.

The circulation pump in the building hydraulic circuit was modeled to be capable of providing the required mass flow rate at any time by overcoming the corresponding pressure loss. The required mass flow rate was calculated from the cooling loads as

$$m=Q/\ (C_p*\text{delta T}) \qquad (1)$$

where C_p is the water specific heat capacity and delta T = 4 K is the water temperature difference between supply and return. The cooling load of the hospital buildings is shown in Fig. 3 for the period between 1st April–30th November, 2023. The cooling load was obtained from the operational data gathered from the buildings during the period.

Table 1 shows the main input parameters used to model the sub-surface aquifer, which is made of limestone.

Table 1 – Simulation parameters for the ATES model

Aquifer properties	Values
Undisturbed aquifer temperature	10 °C
Number of well pairs	6
Aquifer thickness	70 m
Domain radius	250 m
Thermal conductivity of limestone	1.7 W/(m K)
Density of limestone	2800 kg/m³
Specific heat capacity of limestone	840 J/(kg K)

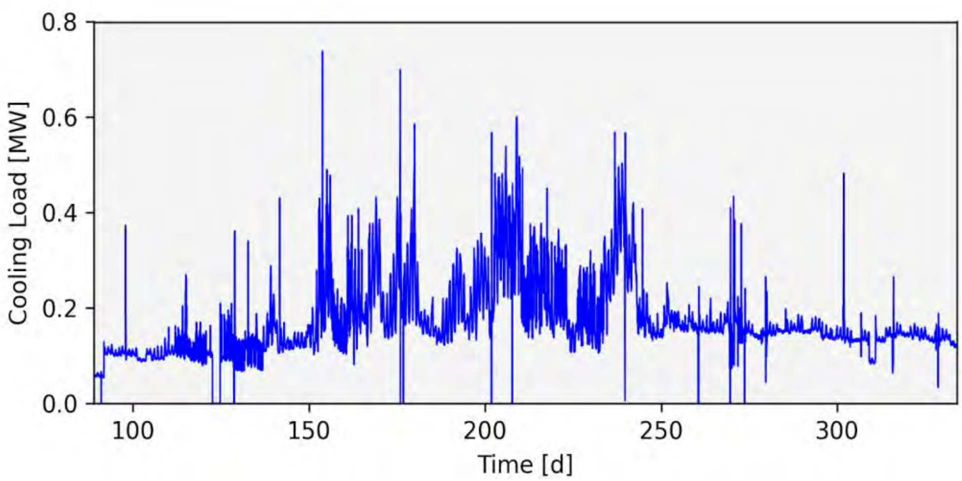

Fig. 3 – Cooling demand of the hospital buildings (period between 1st April–30th November)

3.1 Control Strategy

To guarantee that the system effectively meets the required cooling demands, we implemented control logic based on the operational strategy implemented in the installed ATES system. The goal is to track a supply water temperature setpoint of 12 °C in the building cooling circuit. This is achieved by using a PI controller that modulates the water flow extracted from the cold well. The proportional and integral gain of the PI controller was initially set to default values recommended in the building library for similar system topologies. Minor adjustments were then made to enhance the system's response such that the supply temperature was stable. A switch block is employed to ensure that during periods of no cooling demand in the building, there is no flow from the aquifer wells. This prevents recirculation in the aquifer wells through the heat exchanger.

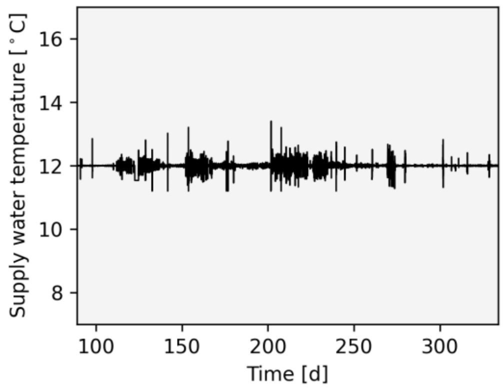

Fig. 4 – Supply water temperature to hospital buildings

The temperature in the aquifer was analyzed as a function of distance and time. Fig. 5 shows the temperatures in the aquifer at different distances from the warm well over the simulated period. The results indicate that the aquifer temperature is influenced by the injected water up to approximately 20 meters from the center of the well. As expected, the closer the analyzed location is to the well, the more rapidly the aquifer temperature approaches the injected temperature (around 15 °C).

The increased temperatures observed in the warm well during summer months suggest that the accumulated heat can be utilized during winter to enhance the performance of heat pumps.

4. Results and Discussion

Fig. 4 shows the water temperature supplied to the hospital buildings. The figure shows that the control logic can maintain the water temperature at approximately 12 °C over the entire cooling period. The small oscillations around the set-point value are due to the tuning parameters chosen for the PI controller.

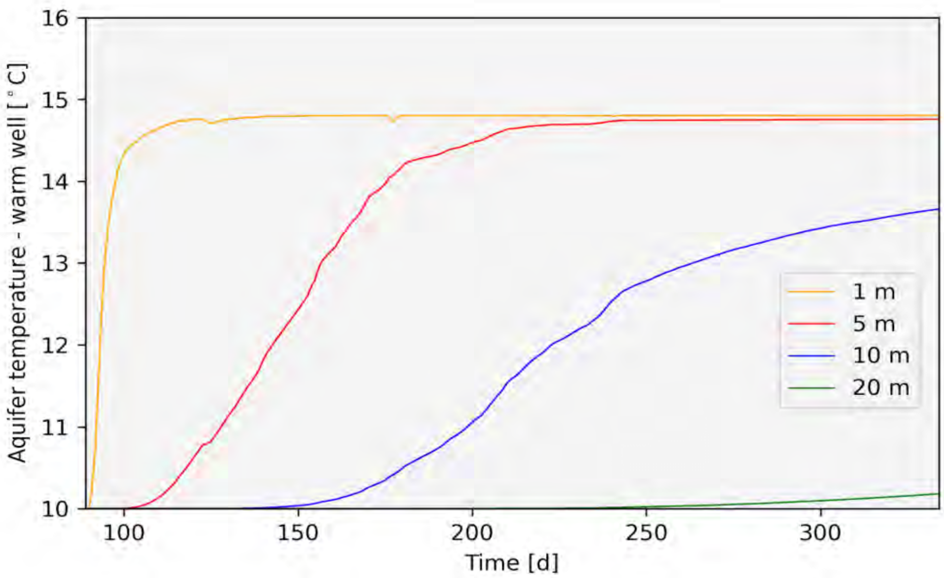

Fig. 5 – Temperature in the warm well of the aquifer at different distances

5. Conclusion

In this paper, we developed an ATES model which simulates the cooling operation of an energy system connected to hospital buildings. The system model resembles an installed ATES system located in Denmark. Results indicate that the model can be used to effectively analyze the operation of ATES systems including sub-surface and above-surface components connected to each other. To regulate the system, the authors implemented a simplified control strategy with the objective of stabilizing the supply water temperature at 12 °C.

For future studies, the authors plan to advance their model by developing a comprehensive full plant simulation. This upgraded model will integrate more sophisticated control strategies aimed at accurately predicting the operation of the ATES system across both heating and cooling seasons. The overall goal is to enhance the system's efficiency and performance.

In addition to its current applications, future uses of the model may involve power-to-heat applications, allowing excess heat to be stored in aquifers during periods of affordable and clean electricity from wind and PV.

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Nomenclature

Symbols

m	Volumetric flow rate (m^3/s)
Q	Heat flow (W)
c_p	Specific heat capacity (J/(kg K))
T	Temperature (°C)

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