

Aquifer Thermal Energy Storage System of Low GWP Turbo Heat Pump Utilizing Unused Energy



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Groundwater, which lies in abundance beneath our feet, is retained in a geological formation called an aquifer made of materials such as sand and gravel. Compared with the outside air temperature, groundwater is warmer in the winter and cooler in the summer. Because of this difference in temperature, it is of high value as a heat/cold source, but this energy has been unused. In air conditioning systems known as aquifer thermal energy storage (ATES) systems, aquifers are used as if they were large heat/cold storage tanks. Using a centrifugal heat pump, waste heat produced during cooling operations and waste cold during heating operations are stored in aquifers. This enables the former to be effectively used for heating and the latter for cooling in different seasons. Mitsubishi Heavy Industries Thermal Systems, Ltd. developed a heating/cooling system that uses a high-efficiency centrifugal heat pump suitable for ATES systems and an energy management optimization control system.

1. Introduction

In Japan, most of the urban areas with a high energy demand density are located in alluvial plains. Underneath lie aquifers that are very valuable for thermal utilization. However, as the pumping of groundwater entails the risk of subsidence, restrictions on groundwater pumping are imposed in many areas and aquifers have remained unused. In ATES systems, since all the extracted groundwater is injected back immediately after being used as a heat/cold source, the risk of subsidence can be minimized. Using aquifers as if they were large heat/cold storage tanks makes it possible for thermal energy to be used more effectively, by storing waste heat produced during cooling operations and waste cold during heating operations and by utilizing the former for heating and the latter for cooling in different seasons. Therefore, ATES systems can be expected to be effective in conserving energy, reducing CO₂ emissions, mitigating the heat island effect and curbing global warming.

In the Netherlands⁽¹⁾, the introduction of ATES systems has seen rapid progress since 2000 and more than 2,000 ATES plants are currently operating. In China⁽²⁾, with increasing attention in recent years, ATES systems have also begun to be widely introduced. In Japan, however, ATES systems are still unfamiliar to the public and have yet to be extensively applied.

While summarizing ATES systems in terms of definition, configuration and advantages, as well as basic operation patterns, this report also presents the ATES systems that we have constructed and the optimization control system.

2. What is an ATES system?

2.1 Definition of aquifer

An aquifer is an underground geological formation that retains groundwater. It usually refers to a porous layer of sand and gravel, sandwiched between layers of impermeable materials such as

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clay (through which water is unlikely to flow). Aquifers have permeability high enough to secure the necessary supply of water from the well and can be used as a medium to store thermal energy if the flow of groundwater is slow.

2.2 ATES system configuration

As shown in **Figure 1**, ATES systems use groundwater, which is retained in an aquifer, as a heat/cold source for purposes such as building air conditioning and are comprised of the centrifugal heat pump, hot/cold water pump, coolant pump (heat/cold source water pump), well pumps, cooling tower water pump, paired warm/cold wells and their connecting pipes, heat exchanger, expansion tank, auxiliary devices and controllers.

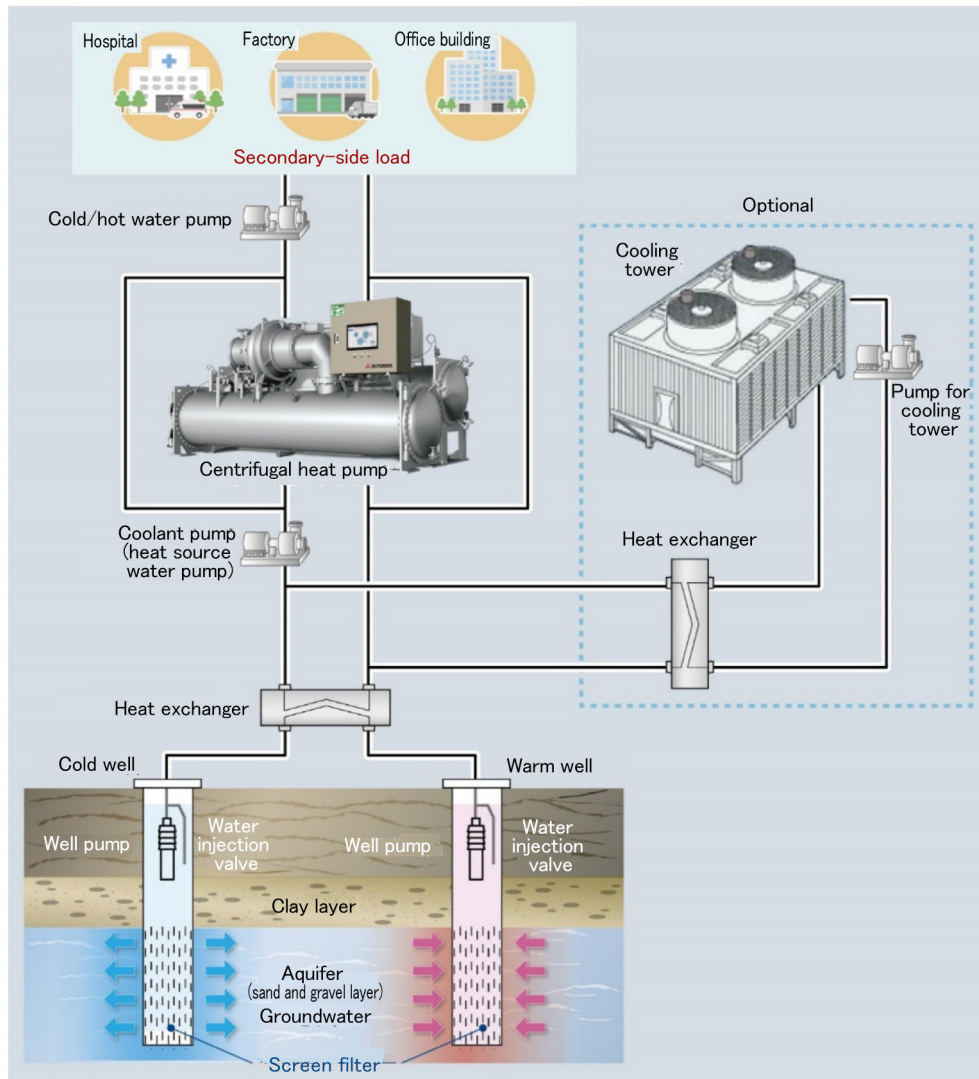


Figure 1 Outline of ATES system

2.3 ATES system advantages

The advantages of ATES are as follows.

(1) Stable groundwater temperature

The groundwater at 15 to 20 m below the ground or deeper is hardly affected by the outside air temperature and that the groundwater temperature is stable throughout the year. Therefore, it is proved to be suitable for use as a heat/cold source water (**Figure 2**⁽³⁾).

(2) Energy saving

By storing heat energy during cooling operations and cold energy during heating operations in an aquifer, the gap between the starting temperature and the set temperature level for cooling or heating becomes smaller. Thus, a considerable energy-saving effect can be realized throughout the year. **Figure 3** depicts power consumption with the use of the ATES system.

(3) Effective use of thermal energy (seasonal thermal energy storage and utilization)

By switching the groundwater pumps between winter and summer, waste cold during

heating operations in winter can be used for cooling next summer. Likewise, waste heat during cooling operations in summer can be used for heating next winter. This enables more effective use of thermal energy (Figure 4).

(4) Reduction of annual operating costs

Compared with a conventional air conditioning system with an air source heat pump, an ATES system can reduce the power consumption by about 38% while also reducing CO₂ emissions. Figure 5 compares the annual operating cost of an ATES system with other systems⁽⁴⁾.

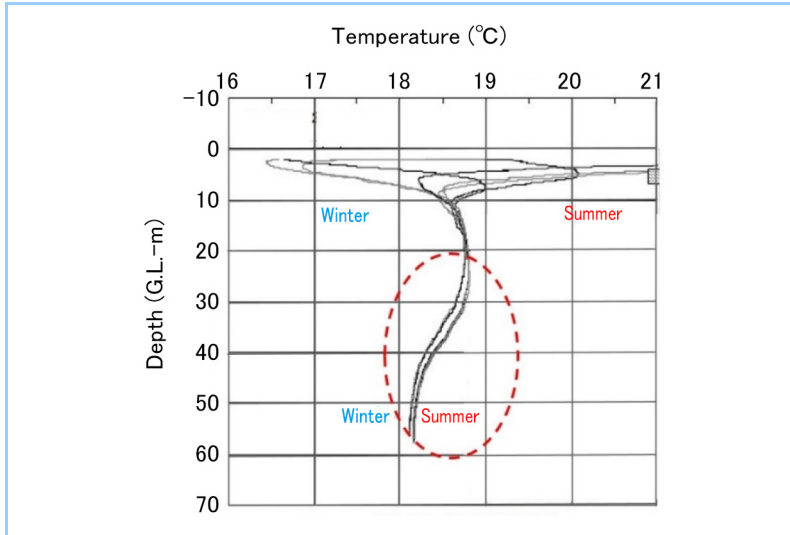


Figure 2 Temporal change of groundwater temperature distribution

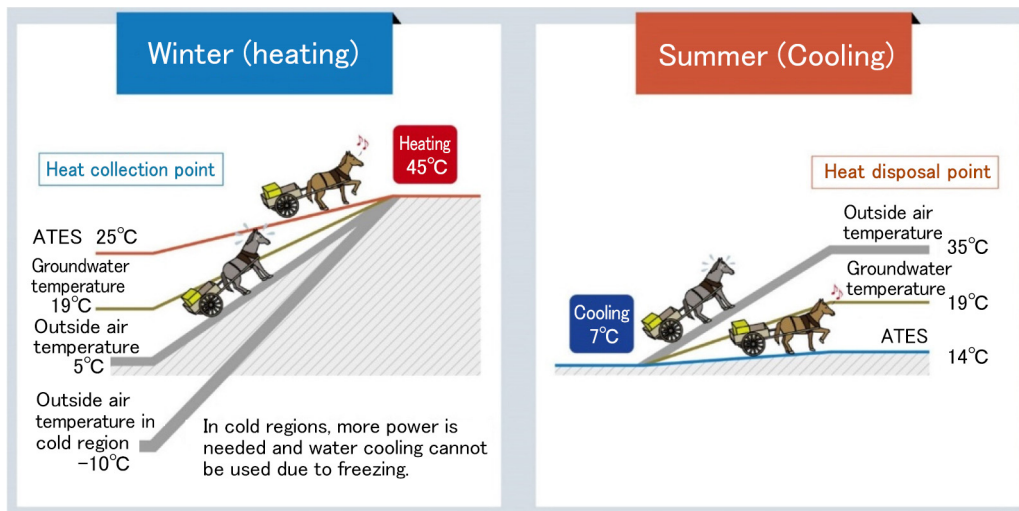


Figure 3 Illustration of power consumption in the case of using ATES system

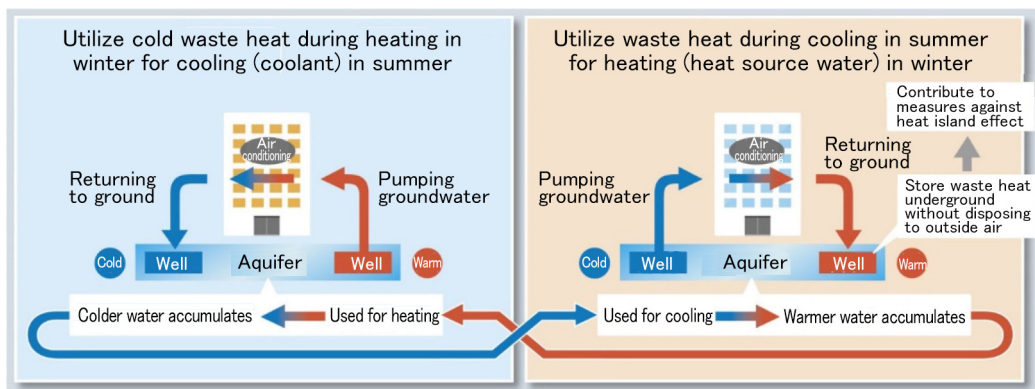


Figure 4 Illustration of seasonal buffering using heat/cold storage

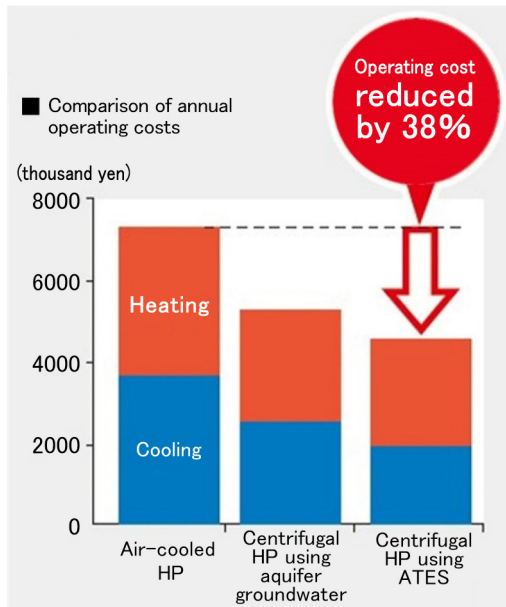


Figure 5 Comparison of annual operating costs

3. Basic operation method of ATES system

By simply using geothermal heat/cold as shown in **Figure 6** without considering the difference in air conditioning load (heat amount) between summer and winter, the sustainable utilization of geothermal heat/cold cannot be realized, because the resulting imbalance of heat amount between the cold water load and the hot water load causes the heat/cold storage mass of waste heat or waste cold to continuously expand. Therefore, by applying the ATES system operation method shown in **Figure 6** and automatically combining the system flows using our proprietary energy management optimization control system dedicated to the ATES system, the imbalance of the air conditioning heat amount and the amount of water used between summer and winter is eliminated and the sustainable utilization of geothermal heat/cold is realized.

No. 1: Heating and cold storage with cold water in winter

This is an operation mode in which the groundwater in the warm well is used as heat source water for the centrifugal heat pump and the waste heat of the heat pump is used as heat energy for heating. At the same time as heating in winter, cold is stored in preparation for cooling in summer by automatic control of constant-temperature cold water injection into the cold well.

No. 2: Cold storage with cooling tower in winter

This is an operation mode in which cold is stored in the cold well using the cold water cooled by a cooling tower. When the outside air temperature is sufficiently low and cold water colder than the required low temperature of the system can be obtained by the cooling tower, the cold storage operation using the cold water cooled by the cooling tower is automatically performed to store cold in preparation for cooling in summer.

No. 3: Cold storage with centrifugal heat pump in winter

This is an operation mode in which cold is stored in the cold well using a centrifugal heat pump. Cold is stored in preparation for cooling in summer and the waste heat of the heat pump is cooled by the cooling tower. This operation mode positively utilizes the characteristics of an inverter centrifugal heat pump, greatly improving its performance when the outside air temperature is low.

The No. 2 and No. 3 operation modes are cold storage operation modes aimed at eliminating the imbalance of heat load (heat amount) in summer and winter. The power consumption of each mode is compared according to the conditions of outside air temperature and humidity and the operation mode with the lower power consumption is automatically selected.

No. 4: Cooling and heat storage with hot water in summer

This is an operation mode in which the groundwater in the cold well is used as cooling water for the centrifugal heat pump to perform cooling in summer. At the same time, heat is stored in preparation for heating in winter by automatic control of constant-temperature hot water injection

into the warm well.

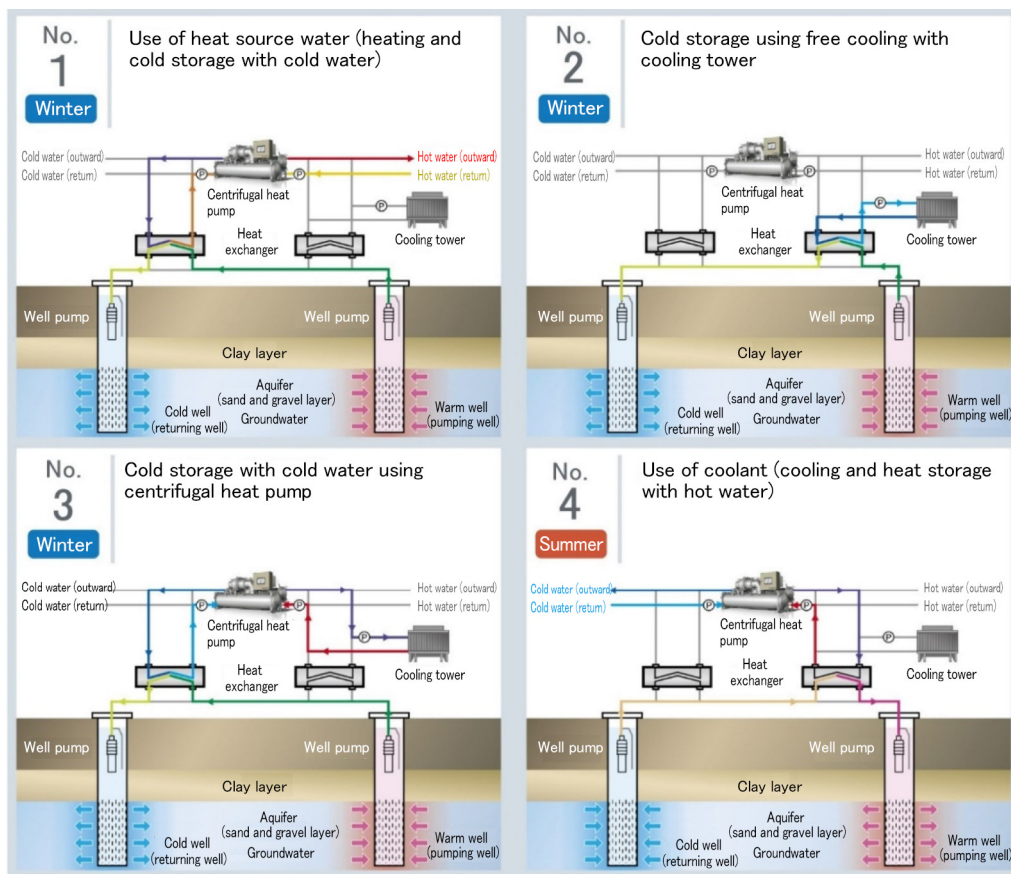


Figure 6 Basic operation methods of ATEs system

4. Examples of ATEs system

We have constructed four ATEs systems so far. We conducted demonstration tests and subsurface investigations for ATEs systems and introduced them to regularly-used air conditioning equipment as a subsidized project. This chapter presents ATEs system examples including the technical knowledge obtained from the introduced air conditioning equipment.

4.1 Takasago Machinery Works, Mitsubishi Heavy Industries, Ltd.

(a) Overview

We constructed Japan's first large-scale ATEs system using a centrifugal heat pump as a heat source at Mitsubishi Heavy Industries Takasago Machinery Works in 2016, carried out the demonstration test for about two years from the warm/cold well excavation work to the final heating and cooling demonstration test and supplied heating and cooling to a factory with a building area of 4,000 m². Figure 7 shows the overall layout and Figure 8 depicts the overall equipment flow diagram. This system uses a primary pump system that supplies cold and hot water to the air conditioning load side using a heat source water pump.

(b) Construction of warm/cold well

In this demonstration test, we constructed warm/cold wells for the ATEs system that allow water pumping/injection of 108 m³/h in an area with high groundwater salt and iron concentrations using the newly-developed reverse return airlift excavation method^{*1}.

*1: Reverse return airlift: A method of borehole excavation without casing that drills the ground by rotating a drilling bit, sucks up and discharges earth and sand together with the water in the hole and protects the hole wall with the hydrostatic pressure of the water.

In the initial state after drilling, the water level drops of warm/cold wells 1 and 2 were 5.0 m and 1.6 m, respectively, at a pumping volume of 60 m³/h. One year after the start of operation, the water level drops of warm/cold wells 1 and 2 were 5.3 m and 1.2 m, respectively, at a pumping volume of 60 m³/h, which indicates that no clogging occurred and the warm/cold well performance could be maintained.



Figure 7 Overall layout

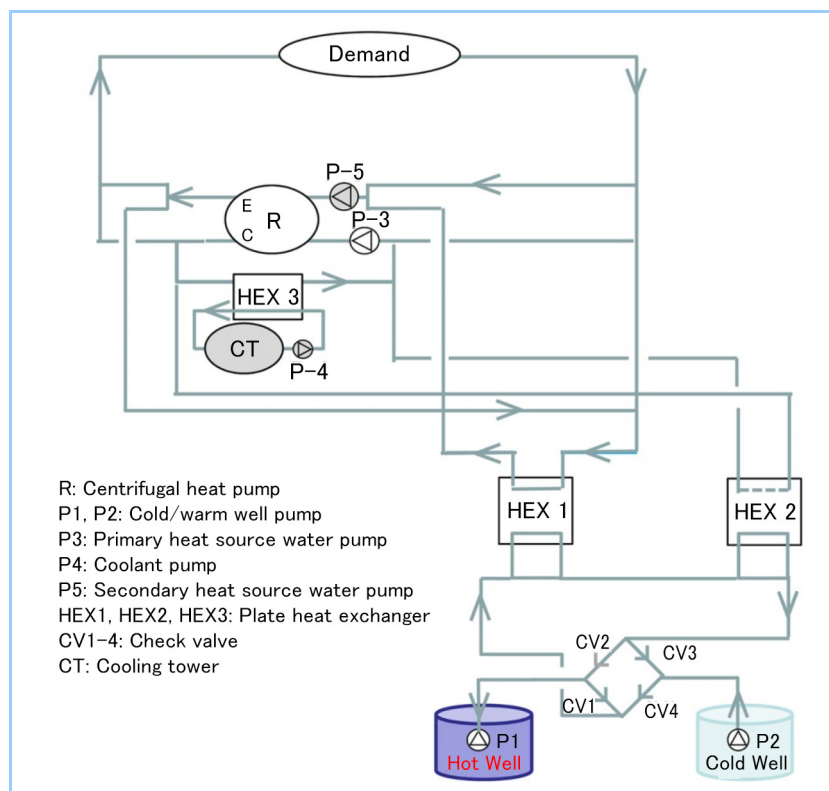


Figure 8 Overall equipment flow diagram

(c) Other

We had a hard time with the excavation method when constructing this demonstration test, but we finally reconsidered the excavation method and were able to operate the system with the excavated wells for one year.

(d) Overall equipment performance evaluation

Table 1 lists the actual data of the full-year performance results.

1. During the operation period of heating and cold storage with cold water in winter, the annual average COP of the centrifugal heat pump alone was 3.8 and the annual average COP of the heating system was 3.3.
2. When the cold was stored using cold water produced at the same time as heating and then used directly for cooling during the cooling period (without using the centrifugal heat pump), the annual average COP of the cooling system was 48.3.
3. When the heat source water was used during the operation period of cooling and heat storage with hot water in summer, the annual average COP of the centrifugal heat pump alone was 9.4 and the annual average COP of the cooling system was 6.1.
4. The full-year average COP of the heating and cooling system was 3.8. Further improvement

in efficiency can be expected if these operation modes are switched at an appropriate time and operated at an appropriate temperature and flow rate.

Table 1 Actual data of full-year performance results

Item	Heating and cold storage with cold water in winter	Direct use in summer	Cooling and heat storage with hot water in summer
Operation period	February 2 to March 9	June 7 to July 20	July 27 to September 22
Actual operating days	25 days	36 days	41 days
Average pumping water temperature [°C]	17.8	9.1	14.9
Average injection water temperature [°C]	6.5	17.6	22.7
Annual factory load [MWh]	122.0	87.1	184.7
Annual cold storage with cold water [MWh]	90.7	-	-
Annual heat storage with hot water [MWh]	-	98.4	207.1
Annual power consumption of chiller [MWh]	31.7	-	19.7
Annual total power consumption of equipment [MWh]	36.7	1.8	30.1
Annual average COP of centrifugal heat pump alone	3.8	-	9.4
Annual average COP of cooling system	-	48.3	6.1
Annual average COP of heating system	3.3	-	-
Full-year average COP of heating and cooling system	3.8		

4.2 Osaka Umekita area

(a) Overview

The Osaka Umekita area is within the restricted area of the Law Concerning the Regulation of Pumping-up of Ground Water for Use in Buildings, so the heat source water cannot be used for buildings. We conducted a two-year demonstration test to verify the ground subsidence suppression effect of the ATES system and the effectiveness of clogging evaluation, etc.

(b) Construction of warm/cold well

Utilizing our experience with the excavation method described in 4-1, we constructed warm/cold wells that allow water pumping/injection of 100 m³/h. Through the operation of these warm/cold wells, it was proved that the aquifer in Osaka city (alluvial plain) can be utilized for ATES systems without any issues.

(c) Performance evaluation of warm/cold well

We carried out various pumping/returning operations at a maximum of rate of 100 m³/h for up to 4 consecutive months in the Osaka Umekita area. In this project, we confirmed the progress of the clogging of the wells and examined recovery measures, while also observing changes in the ground height due to changes in the water level and evaluated the effects.

Regarding the subsidence, it was proved by the actual result data that the influence of the groundwater fluctuation on the clay layer was within the range of the elastic change during the entire operation period of 4 months. As a result of examining the impact on the surrounding ground environment, it was confirmed that subsidence does not occur in the densely pressurized ground.

Clogging is considered a critical issue for ATES systems. In about 4 months of continuous operation in the demonstration test, signs of clogging began to gradually appear. On June 18, 2018, during the demonstration test, the Northern Osaka Earthquake with a seismic intensity of 6-minus on the Japanese seismic scale of zero to 7 occurred and the clogging further progressed as a result. For this reason, well cleaning was carried out when the ratio of the drop in water level to the amount of pumped water, which is an index of the well performance, lowered to about 70% of the initial value. As a result, the initial well performance was restored. No defects were found in the well structure due to the earthquake and there were no problems with subsequent operations, which verified that the well structure was robust against earthquakes.

4.3 Kobe Shipyard, Mitsubishi Heavy Industries, Ltd.

(a) Overview

We installed an ATES system at our centrifugal chiller manufacturing shop in Kobe Shipyard in 2018 using subsidies such as the Ministry of the Environment's FY2018 Carbon Dioxide Emission Control Project Costs. The system has been providing heating and cooling of the shop with a building area of 4,000 m².

(b) Construction of warm/cold well

For this system, warm/cold wells that allow pumping of the groundwater at a rate of 60m³/h were planned as a result of the survey prior to boring. However, the pumping amount allowed for one of the warm/cold wells was about half of the planned amount. As a countermeasure, a new ATES system was constructed using three warm/cold wells as shown in **Figure 9** and an amount of pumping/injection water sufficient for shop heating and cooling has been secured. As a cause, it was considered that a branched fault structure of the Osaka Bay fault passes through the Wadamisaki region in Kobe where this ATES was constructed and the aquifer is not distributed horizontally at a certain altitude by the effect of the fault.

(c) Performance evaluation of warm/cold well

Two years have passed since the system started operation, but it has been operating without any problems until now and the effects of subsidence, clogging, etc., have not been found.

With this ATES system, which is used for regular heating and cooling equipment, we will evaluate the heat source performance during long-term operation and verify maintenance methods, as well as continue to accumulate expertise on warm/cold wells.

(d) Other

Construction of an ATES system in an area with complex ground requires careful planning after a thorough subsurface investigation.

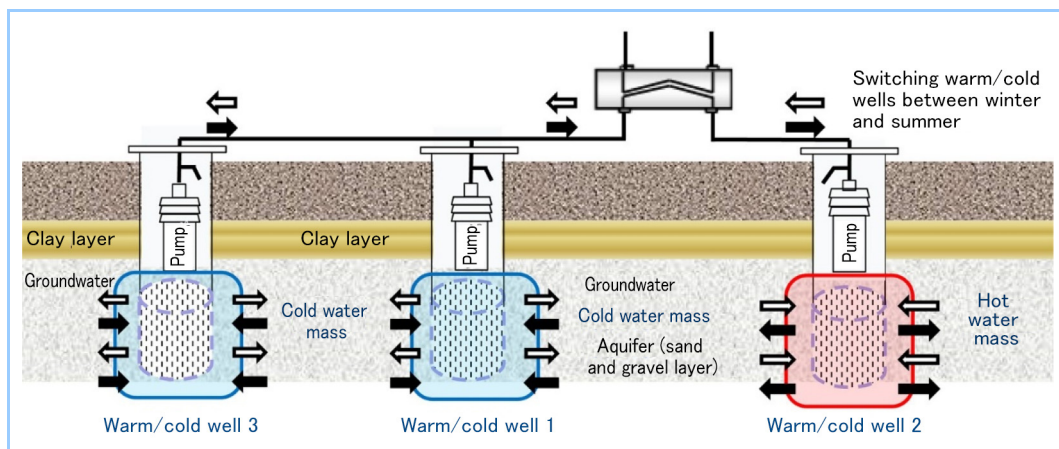


Figure 9 Illustration of three wells construction

4.4 Amity Maishima

(a) Overview

We installed an ATES system at Osaka City MAISHIMA Sports Center for Persons with Disabilities (Amity Maishima) in Maishima, Osaka city as a consignment of the FY2018 Development and Demonstration Project of Technologies for Guiding the Strengthening of Carbon Dioxide Emission Reduction Measures. We conducted the demonstration test until March 2021 and will start actual operations in April 2021.

(b) Construction of warm/cold well

Since Maishima is reclaimed land, slag was generated when the wells were constructed, so it was necessary to change the construction method on the fly. However, we constructed warm/cold wells that allow pumping/injection of the water from/to the two upper and lower aquifers at a rate of 100 m³/h each, in one heat source well for the first time in the world.

Data of the actual results are currently being verified.

(c) Performance evaluation of warm/cold well

Data of the actual results are currently being verified.

(d) Other

The Osaka city area has high potential for ATES-based cooling/heating. The potential map is published on the Osaka City website^{*2}. Osaka City plans to use the demonstration results in Umekita and Maishima to expand the introduction of ATES systems in the city area in the future.

*2: Potential map <https://www.mapnavi.city.osaka.lg.jp/osakacity/Portal>

5. Conclusion

We have gained a lot of design, construction and operation expertise from the four ATES system cases and accumulated data. Furthermore, we have developed an optimal automatic control system for ATES systems toward practical use. In the future, we will create an aquifer potential map for all of Japan and encourage local governments in the applicable areas to adopt ATES systems in order to expand this project.

Moreover, we will invite many people to observe the ATES systems constructed in our company and highlight their superiority. We will also continue to study appropriate well management through long-term operation of ATES systems and based on the knowledge obtained, we will make efforts so that customers can use the system with peace of mind.

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