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Research Paper

Experimental study of seawater seepage and heat transfer in a laboratory vertical beach well

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HIGHLIGHTS

- VBWI is built in lab to study the characteristics of water seepage and heat transfer.
- Pumping tests are conducted to obtain aquifer's hydraulic parameter and flow state.
- Tests on thermal influence of water-level variations are conducted.
- The numerical model of VBWI is built and validated by the laboratory experiments.

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ABSTRACT

Vertical beach well intake (VBWI) is considered as an ideal approach to provide seawater for seawater source heat pump (SWHP) in coastal areas due to its attractive advantages of seawater with high quality, lower temperature in summer and higher temperature in winter compared to raw surface seawater. A laboratory VBWI system was built and experimental strategy was proposed in this paper. First, pumping tests were conducted to obtain hydraulic parameters of the aquifer and estimate the state of water flow within aquifer region. As results of these tests, permeability coefficient of the aquifer was calculated to be 0.0209 m/s, and the water seepage in aquifer could be recognized as laminar flow. Then the influence of water-level variations on temperature in VBWI system was explored. Results showed that water temperature variation of the pumping well influenced by wave-induced water level fluctuations can be negligible in this laboratory VBWI. These testing results were adopted to provide information of hydraulic parameter and simplify the governing equation of seepage and heat transfer of VBWI model. And then numerical models describing seepage and heat transfer process of VBWI system for a SWHP were established. Finally, verification tests for the validity of the numerical model were conducted. Compared experimental results with numerical simulation of pumping temperature under cooling and heating mode respectively, simulation results showed great agreement with experimental data. The results revealed the numerical model can be well validated by laboratory experiments on VBWI system.

1. Introduction

Seawater source heat pump (SWHP) is used to provide heating and cooling to buildings with high energy efficiency in coastal region [1,2]. The most existing SWHP projects get cold quantity or heat directly from the raw surface seawater [3,4]. Temperature of the feedwater to heat pump is an important parameter and directly influence the running efficiency of heat pump unit. So, in this paper, we will pay attention to a subsurface intake which is vertical beach well. This intake can provide seawater with higher quality and higher temperature in winter and lower temperature in summer, which helps to improve the efficiency of SWHP system.

As for seawater intake, there are two main categories namely surface intakes and subsurface intakes [5]. Direct or surface intake system is the most popular method of obtaining raw seawater. Conventional surface intakes are usually straight-forward in the design and construction and can provide unlimited intake capacity. However, these intakes extract natural seawater that contains macroscopic and microscopic biota and natural organic matter. Also, impingement and entrainment of fish, larvae and a variety of other marine organisms may have potential environmental impacts [6]. Indirect or subsurface intakes are an alternative method to obtain feed water with a generally higher quality [7]. Subsurface intakes use the natural geology at the shoreline or

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beneath the seabed to filter the raw seawater. Several types of subsurface systems are used as intakes, such as vertical wells, horizontal wells, angle wells, collector wells, collector tunnels, seabed galleries, and beach galleries, depending on the geological characteristics of facility location [7]. The most common type of subsurface intake is vertical beach well intake (VBWI) [6] as shown in Fig. 1.

The quality of seawater extracted from the VBWI is very site specific. Because seawater extracted via subsurface filtrates naturally through the seabed, VBWI technology could be a costly choice if there aren't appropriate site specific conditions. But under favourable hydro-geological conditions, SWHP combining a VBWI with simplified pre-treatment prior to HP can significantly reduce the environmental impacts of the system when compared to a typical surface intake and other pre-treatment SWHP configurations. Furthermore, because subsurface intake capacity is limited by permeate capacity of seabed and available hydrostatic pressure, VBWI is commonly suggested to be built on seashore within 100 m of the sea to ensure the quantity of feedwater for equipment [5].

In seawater reverse oamosis desalination (SWRO) system, it has been documented that VBWI systems have a positive impact on feedwater quality [8,9], however few data are available on documented its temperature which influences the energy performance of SWHP. So, in this research, we will verify the numerical seepage and heat transfer model through the water-temperature data based on a laboratory VBWI, and present the temperature distribution of the model by the numerical results.

Researches on water seepage and heat transfer in soils are common in ground source heat pump (GSHP) systems. There are two main related types of GSHP systems [10]. The ground-coupled heat pump systems consist of a heat pump connected to a closed-loop network of thermally fused plastic piping that is buried in the ground. A water antifreeze solution is circulated through the inside of the pipe network transferring heat from the ground to the heat exchanger. No groundwater enters the pipe network; but groundwater seepage can improve the heat transfer performance of ground heat exchanger [11–13]. Groundwater heat pumps, the second subset of GSHP systems, directly exploit the significant heat capacity of groundwater [14–16]. Using an extraction (or production) well, the water is conducted directly to the heat pump, where heat is added or removed from the water. The heated or cooled water is then returned to the ground through an injection well. Influence of groundwater flow in aquifers on the well's performance are usually studied. Different to GSHP, fluid in VBWI system is not ground water, but surface raw seawater.

Field tests for the seepage and heat transfer model of VBWI have conducted in some documents [17,18]. However, those field tests have many uncontrollable factors which can influence the validity and suitability of the experimental results. So we built a VBWI system in laboratory and proposed experimental strategy on it. First, pumping tests were conducted to obtain hydraulic parameters of the aquifer and estimate the condition of water flow within aquifer region. Then the influence of water-level variations on temperature in VBWI system was explored. Testing results were adopted to provide information of hydraulic parameter and simplify the governing equation of seepage and heat transfer of VBWI model. Finally, verification tests for the validity of the numerical model were conducted. Based on these tests in lab, we can obtain a verified numerical seepage and heat transfer model for a given VBWI.

2. Experimental setup

Fig. 2 shows the schematic diagram of the test setup located at Campus of Yanshan University. Experiments were performed in a tank (1.4 m long × 0.8 m high × 0.8 m wide). The physical model used in the experiments was three layers of soil and water was used as the working fluid. The porous material consisted of gravels which were placed in the middle layer of tank as aquifer with a median size of 2 mm and a particle size distribution varying from 1 mm to 5 mm. The porosity of the gravel was 0.46.

The experimental apparatus were consisted of a water pump (1), a flowmeter (2), a heat pump unit (3), Pt100-type temperature sensors (4), a valve (5), multipoint digital data logger for thermal resistance (6), and three wells (7), as shown in Fig. 3. Two calibrated Pt100-type temperature sensors which were placed at the inlet region (raw water) and exit region (pumping well) of the aquifer were used to measure the temperatures of inlet and outlet. Each thermal resistance was connected individually to a separate channel of multipoint digital data loggers which could display output of the thermal resistance by temperature with a measurement range of −19.9 to 600 °C. Water levels were measured by graduated scales in the wells. One self-priming pump provided raw water from a water tank. The volume flow rate of water was adjusted by the ball valve and measured by a float flowmeter. Table 1 showed the range and accuracy of all the measuring instruments.

3. Pumping test

Generally, hydraulic parameters of the aquifer can be obtained by pumping test in field [19–21]. In this paper, pumping test was conducted on the VBWI system in lab, in order to judge the flow

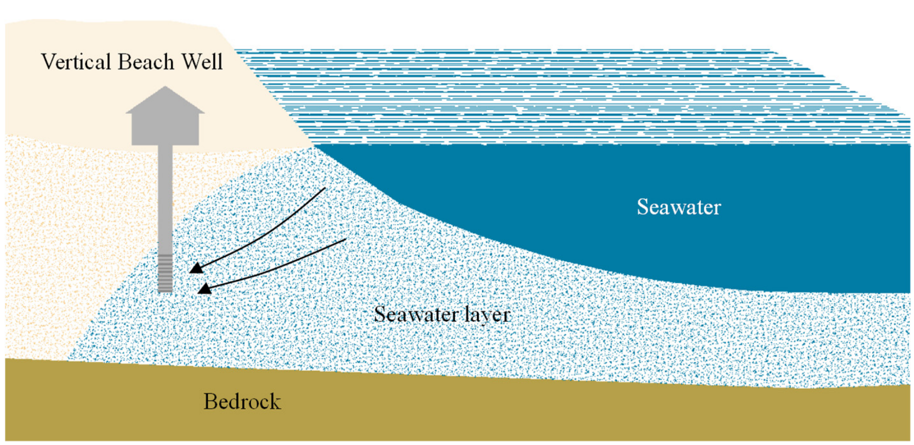

Fig. 1. Vertical beach well intake system.