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Field tests and multiphysics analysis of a flooded shaft for geothermal applications with mine water

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ABSTRACT

This paper introduces the scientific part of a large-scale study in the Upper Peninsula (U.P.) of Michigan, a historical mining area, for exploring the water in deep abandoned copper mines as a geothermal energy resource. The main focus of the paper is placed on the scientific understanding of the natural mine water-geologic formation system, especially the transport of heat and mass in this large-scale natural system, which is critical to the efficiency and sustainability of the energy renovation. For this purpose, a field study involving measurements of temperatures and chemicals in a local mine shaft in the U.P. is conducted to reveal the major issue in recovering geothermal energy in the water from the shaft, i.e., the temperature distribution. Water samples are also collected in situ to investigate the distribution and concentrations of major chemicals. Afterward, a theoretical framework for the thermo-hydrodynamic process in the mine water coupled with heat transfer in the surrounding geologic formations is developed to outline a mathematical description for studying the scientific issue. Simulations are finally conducted, based on the real geologic information, to preliminarily investigate the quasi-equilibrium water movement in this local mine shaft due to geothermal gradients to provide insights into the phenomena observed in the field study.

1. Introduction

Geothermal energy recovery from flooded underground mines has been gaining momentum worldwide since the pioneering work in Canada in 1989 [1]. The application of the use of the water in flooded mines, i.e., mine water, as a geothermal resource is a variation of the Surface Water Heat Pump (SWHP) system [2], which falls into the category of low-temperature geothermal applications [3]. The SWHP is less common than the other Geothermal Heat Pump (GHP) systems, i.e., Ground-Water Heat Pump (GWHP) system and Ground-Coupled Heat Pump (GCHP) system, as the SWHP involves environmental and legal concerns when accessing natural waters (e.g., lake, pond, and river). Moreover, the SWHP can represent a higher-quality geothermal energy resource because bulk water provides a better medium for heat transfer than the pore water used in the GWHP and the water in pipes and backfill soils in the GCHP. As a variation of SWHP, the concept of the geothermal application in this study is to pump the water from deep abandoned mines and exchange heat between the pumped water and buildings for heating/cooling purposes. This type of SWHP application thus takes advantage of abandoned facilities [4,5], provides more economical energy compared to the conventional heating methods (e.g., fuels) [6], and avoids many concerns with the use of natural water bodies in the conventional SWHPs [1]. But some aspects of this type of SWHP for its application need to be considered. Especially, the scientific questions behind the application are much different from those behind the conventional SWHPs, because the mine water-geologic system possibly represents a much more delicate system due to the extremely low velocity of the mobile water, high geothermal gradients, and complicated geologic and mining situations.

However, there is no doubt that the use of the mine water as a geothermal resource inherits most of the socioeconomic and environmental benefits of conventional GHP applications: safe [7], green [8], relatively renewable and adaptable [9,10]. In addition, from a technical perspective, the nature of the SWHP application with the mine water provides more attractive advantages, making it a much higher grade geothermal resource: eco-friendly and environmental utilization of

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waste materials (abandoned mine water), higher-quality geothermal energy (higher geothermal gradient), highly efficient exploration (heat transport of bulk water), and economical utilization (utilization of existing facilities). The mine water has a unique feature which can even further magnify the above benefits: it can move due to both natural convection (caused by geothermal gradients and salinity) and forced convection (water from surrounding geologic formations, surface water, and the energy extraction process) [11,12]. This feature (i.e., bulk water movement due to both natural convection and forced convection), in fact, is very useful and highly desirable. This is because the natural convection in bulk water triggers warm water (at the bottom with a higher temperature) to move upward to heat cold water (at the top); the forced convection caused by the heat extraction process will lead to a greater temperature difference, which can further expedite this natural convection process. Therefore, the heat transfer due to this feature can exceed that in the conventional GWHPs and GCHPs by many orders. Though still far from being satisfactory, numerical simulations have been adopted to understand the underlying mechanisms. Hamm and Sabet [12] modeled the hydraulic behavior of the mine reservoir and the mine water temperature in a production shaft. Their study revealed the impact of the natural convection, the production flow rate, and the permeability of the surrounding rocks on the geothermal potential for explorations. More efforts have been made with an emphasis on several critical issues for the topic. One example is that Streb and Wieber [13] investigated the locality for extracting the mine water at a required temperature without causing a decrease in the potential of the discharge using a hydraulic model. The lifespan of the required temperature supply from the mine water in the flooded coal mines was also discussed by Arias et al. [14] and their numerical results indicated that the studied mine water-based geothermal system would serve over 30 years.

Despite several real demonstration projects launched worldwide for the mine water-based geothermal application [1,15], a thorough scientific understanding of the mechanisms associated with recovering geothermal energy from the mine water is still absent. However, such an understanding is critical to the practical implementation of the energy technique. Since economic paybacks are usually the major driving force for the application, the first two things of interest are usually what will be the water temperature available for the geothermal heat pumps (efficiency) and how will that temperature vary as the exploration proceeds (sustainability). However, as mentioned above, the mine water has a unique feature when it is considered as a geothermal resource: energy is convected by moving fluid elements of the mine water. The significance of this factor is not predictable. The major phenomenon in the mine water was summarized as ‘thermohaline staircases’ caused by a thermosolutal flow [11]. To be more specific, a buoyancy-driven flow, which results from the density difference due to temperature (thermal) and salinity (solute) differences, is proposed to be the major process of interest in the mine water. Experimental and numerical studies suggested that seepage from surrounding geological formations [1,16] and the configuration of the mine working spaces [17,18] may also play significant roles.

Due to the complexity of and limited accessibility to the underground mining space, the underlying uncertainty may only be disentangled by means of numerical simulations with the help of limited site measurements. Though not common, numerical studies have been made to investigate either the sustainability concern regarding the energy recharge from the geologic formations around the mine water [19] or the efficiency concern regarding the hydrodynamics (buoyancy-driven flow for heat variation) in the mine water [12,20]. In particular, two numerical studies have been conducted to understand non-isothermal hydrodynamics of the mine water, which is a key in this geothermal application by controlling the temperature variation and distribution. Hamm and Sabet [12] investigated the temperature variation of the mine water in a vertical shaft using non-isothermal hydrodynamics without the thermal coupling between the mine water and the surrounding geologic formations. In the other study, Reichart et al. [11] investigated the temperature variation of the buoyancy-driven flow triggered by both temperature and salinity using a small computational scale of the mine water (around 1 m). However, the existing studies were concentrated on either geologic formations or mine water, instead of the multiphysics of the whole system. This fact is possibly attributable to several reasons: (1) the complexity of the physical mechanisms in the natural process, (2) high computational cost, and (3) limited data from the field. In addition, numerical simulation for the topic is mostly separated from field studies due to the limited accessibility to abandoned underground mines. A comprehensive study of mine water-based geothermal applications (i.e., a variation of SWHP system), including a field study, the theoretical understanding, and numerical analyses, is highly desirable. This paper will fill this knowledge gap by presenting such a study. A field test on Hancock Shaft 2 is presented in Section 2. A theoretical framework is developed in Section 3 for the thermo-hydrodynamic process in the mine water coupled with heat transfer in the surrounding geologic formations. A preliminary assessment of Shaft 2 is presented in Section 4 to shed light on the buoyancy-driven flow.

2. Field measurements

It is known from Section 1 that the temperature distribution within the water in deep abandoned mines is a key issue to this geothermal application. However, it is usually difficult to obtain such data. This is because abandoned underground mining working spaces may partially collapse after flooding and very limited information can be obtained regarding what structures remain after the mine is closed. Some field data are available indirectly from those environmental and mining investigations into water stratification in abandoned mines [18]. However, few field measurements can be found for the purpose of recovering geothermal energy from flooded mines, let alone field measurements conducted in parallel to other site explorations and numerical analyses.

This section introduces a field study for measuring the temperature and chemical distributions in an abandoned copper mine shaft located in the Upper Peninsula (U.P.) of Michigan. This copper mining region was the first major copper mining region in the U.S., which started in the 1840s and ceased in 1968. Hundreds of deep mines were developed during this period with some mines reaching depths of 2.4 km due to the depth of the lodes. Among them, the Quincy mine was the most famous copper mine, which had the deepest shaft worldwide (i.e., Shaft 2 in Fig. 1) with a depth of 2.82 km, when it ceased production in 1945. Another copper mine on the southwest of the Quincy mine was the Hancock mine, which had two major shafts (Shaft 1 and Shaft 2). These mines were flooded with groundwater soon after their closures and are available as potential geothermal energy resources.

Shown in Fig. 1 is the layout of the underground mining spaces of the Quincy mine and the Hancock mine close to the downtown of the Hancock City in the state of Michigan in the U.S. The 3D underground mining structures are projected to the map for visualization. The black lines from the southeast (top) to the northwest (bottom) are the major mine shafts, e.g., Hancock Shaft 2 and Quincy Shaft 7 (projection). The red lines are the horizontal drifts (projection) from the southwest to the northeast. The drifts are approximately parallel to each other and perpendicular to the shafts. The shafts are connected by the horizontal drifts. In this study, a nearly vertical shaft, i.e., Hancock Shaft 2 in the lower left corner of Fig. 1, was chosen for the field test. The field measurement location was marked with a red dot, which is located in the Hancock City.

Technically, the Hancock Shaft 2 was not “abandoned” but sealed many decades ago. The excavation for the shaft was started in December of 1906, which reached 400 feet (122 m) deep by the end of the year. By November of 1908, it reached 1300 feet (396 m) with the shaft being sunk to the massive dimensions of 29′ 6″ by 9′ 6″ (9 m by