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MODELLING A FILED-SCALE COMPRESSED AIR ENERGY STOARGE IN POROUS ROCK RESERVOIRS

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ABSTRACT

Compressed Air Energy Storage (CAES) is one of the promising methods to store the surplus solar and wind energy in a grid scale. In this study, we used a non-isothermal multiphase flow simulator to model a field-scale study of a novel CAES by storing the compressed air in aquifer. The primary results show that the model is capability of modeling dynamics of pressure induced by air injection rates. The model was successful to model the well head pressure changes during the bubble development stage. This study suggests that further works shall be carried out to validate the model by simulating the injection-withdrawal cycle's experiments, as well as to investigate key factors affecting storage and thermal efficiency of compressed air in porous rock reservoirs.

Keywords: Wind/Solar energy, Compressed air energy storage, modelling and porous rock reservoirs

NONMENCLATURE

Abbreviations	
PM-CAES	Compressed air energy storage in in porous rock reservoir

1. INTRODUCTION

Wind and solar energy holds a lot of promise when it comes to replace the conventional energy sources such as fossil fuels and coal. Global wind and solar installed capacity has grown 61-fold since 2000 to over 1,000 GW in 2018 [1]. However, the sun doesn't always shine and the wind doesn't always blow. This poses questions about what we do with electricity generated from renewables at the 'wrong times', and how we maintain secure energy supplies at an affordable price when there is low wind and little sunlight.

In fact, 1.5TWh or 3.2% of wind generation was wasted as wind farms in the UK were turned down or off (called "wind curtain") in 2018 due to their output not being able to be used by the market. This costs the UK National Grid of £120 million in 2018. In China, 42TWh or 14% of wind generation and 7.3TWh or 6% of solar generation were constrained in 2017 due to the similar reason. The total amount of wind/solar curtain in 2017 in China is equivalent to ~ 70% of the 2015 Three Gorges Dam annual power output (87 TWh). These statistical data show that the development of innovative grid scale energy storage is required alongside the growth in renewables and the quest for efficiency.

Among other energy storage technologies (e.g., battery and hydrogen storage, pumped hydroelectricity storage), compressed air energy storage (CAES) is a promising technology to store the surplus solar and wind energy. CAES technology uses the surplus energy to pump and compress air into storage tanks on smaller scale, but on grid scale stored in underground caverns. The release of the compressed air can convert the high pressure into electricity with a gas turbine when needed. Currently, there are only two CAES facilities operating on grid scale in the world, one in Alabama and the other one in Huntorf, Germany. Both of them store the compressed air in underground caverns, with a storage efficiency of around 50%.

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The relative low energy storage efficiency and limited suitable sites are the two most important aspects preventing the current CAES technology being widely used. However, recent studies in CO_2 storage and the preliminary modelling studies [2, 3] suggested that deep saline aquifers would be suitable for compressed air energy storage. The advantage of Aquifer Compressed Air Energy Storage (ACAES) against the conventional CAES is widely available suitable sites. In addition, a higher storage air temperature allowed in aquifers than in a cavern could also potentially improve the energy storage efficiency.

The objective of the study is to conduct a series of new and sophisticated numerical analyses to assess ACAES performance against a field-scale investigation. This aims to build the numerical capability to investigate key factors on factors affecting storage and thermal efficiency of compressed air in porous rock reservoirs.

2. MATERIAL AND METHODS

2.1 Pittsfield Aquifer Compressed Air Energy field-scale study

An aquifer field test near Pittsfield, Illinois, USA was developed to demonstrate the feasibility of ACAES (R.D. Allen, 1981). The stratigraphy of Pittsfield aquifer field test is shown in Fig. 1. The permeable St. Peter sandstone was beneath the impervious Galena-Platteville-Joachim carbonate caprock complex. The injection/withdrawal (I/W) well was located at the peak structural high point and was drilled through an uppermost thin green layer of the St. Peter sandstone to a depth of about 200m. The St. Peter sandstone included three sub-layers, which were green layer, white layer, and grey layer, respectively.

The air injection began on October 2nd, 1982, and stopped on March 21st, 1983. Air with relative humidity less than 5% and temperature close to that of the natural reservoir was injected into the green St. Peter sandstone through the I/W well. The bubble development lasted almost 6 months due to the small air flow rate (R.D.Allen, 1985).

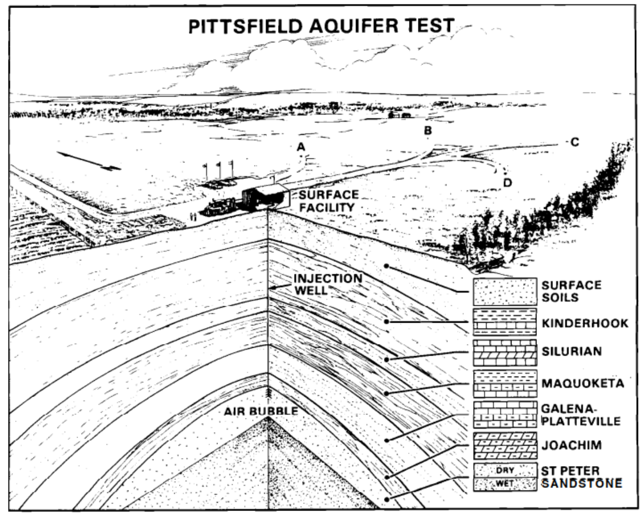

Fig. 1 Schematic section of Pittsfield aquifer field test stratigraphy

2.2 Non-Isothermal Multiphase Flow Simulator

The TOUGH3/EOS3 simulator was used to do the numerical simulations in this study. The TOUGH3 is a general-purpose numerical simulation program for multi-dimensional fluid and heat flows of multiphase, multicomponent fluid mixtures in porous and fractured media. It is developed by Lawrence Berkeley National Laboratory (LBNL) in USA. The EOS3 module was developed to describe the system consisting of H_2O-Air-Heat components in a porous medium.

2.3 Numerical Pittsfield ACAES Model

A conceptual model (R.D.Allen, 1983) for this study is shown in Fig. 2. The air was injected into an anticline-shaped dome. The diameter of I/W well was 0.2 m. The producing length of I/W well was 3 m.

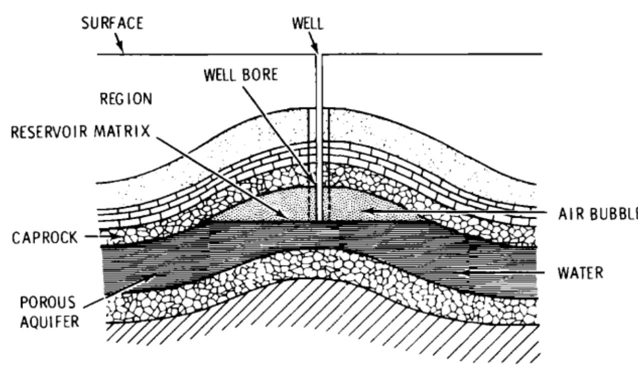

Fig. 2 Conceptual model for Pittsfield ACAES model

A numerical model was developed based on the conceptual model, with the scale of 3 km×3 km in horizontal and 172 m in vertical. Horizontally, the grids were refined gradually from the boundary to I/W well (Fig. 3). Vertically, this model was divided into 35 layers, including lithologies of soil, caprock, green layer, white layer, grey layer, and base rock, respectively.

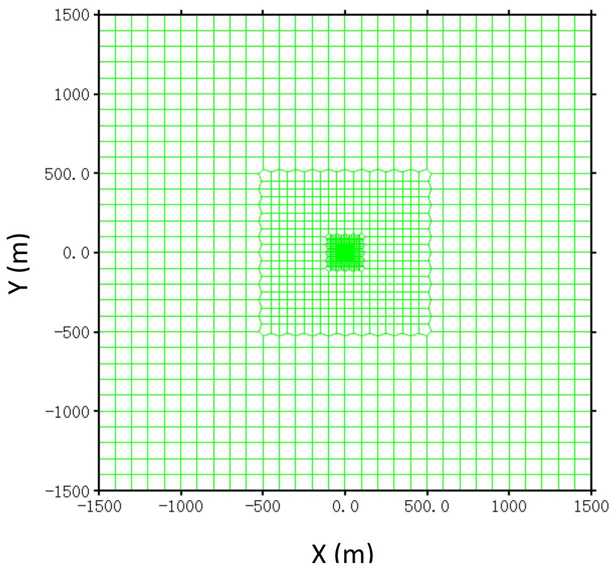

Fig. 3 Domain discretization of Pittsfield model

The upper boundary and bottom boundary were set up as constant pressure boundary, which have the pressure of 1.98×10^5 Pa and 1.88×10^6 Pa. The lateral boundary was set up as no flux boundary. The initial pressure of this model is shown in Fig. 4.

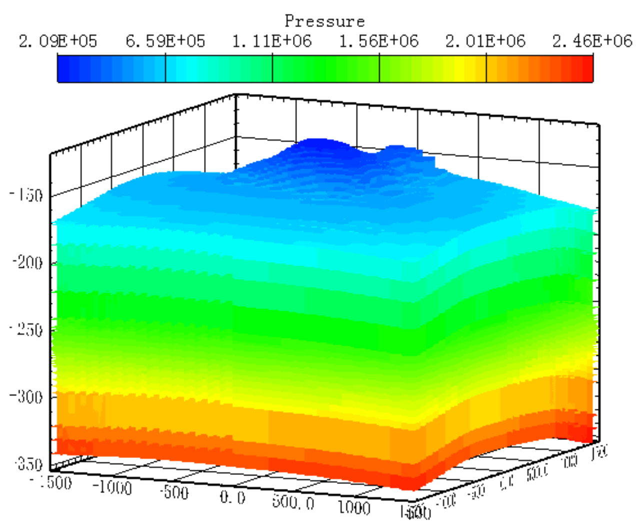

Fig. 4 Initial pressure of Pittsfield model

The parameter of aquifer are shown in Table 1 and Table 2, including permeabilities and porosities, which come from the experimental test conducted by Electric Power Research Institute (EPRI), California in Pittsfield site (Bui H.V., 1990).

Table 1 Aquifer properties of Pittsfield model (Guo, 2016)

Aquifer properties	Value	Unit
Grain density	2600	kg/m^3
Heat conductivity	2.51	W/m℃
Grain specific heat	920	J/kg℃
Relative permeability (k_r) model	Van Genuchten-Mualem	
Capillary pressure (p_{cap}) model	Van Genuchten	
Residual liquid saturation (S_{lr})	0.27	
Residual gas saturation (S_{gr})	0.20	
Maximal capillary pressure (P_{max})	1.0×10^5	Pa

Table 2 Aquifer porosities and permeabilities of model

Lithology	Porosity	k_h (md)	k_v (md)
Green layer	0.17	181	76
White layer	0.16	403	662
Grey layer	0.16	870	727

3. RESULTS AND DISCUSSIONS

The comparison between modelled pressure and monitoring pressure is shown in Fig. 5. It is indicated that the simulated pressure is closely related with mass flow rate. It is shown that the wellhead pressure of simulation data and monitoring data fit well. The average pressure at the wellhead is about 2.1 MPa after 30 days air injection. Due to the complexity of air movement in I/W well at the beginning of bubble development, the pressure between them is not fit very well. Furthermore, the pressure difference between wellhead and well bottom is about 5×10^5 Pa from 50 days bubble development.

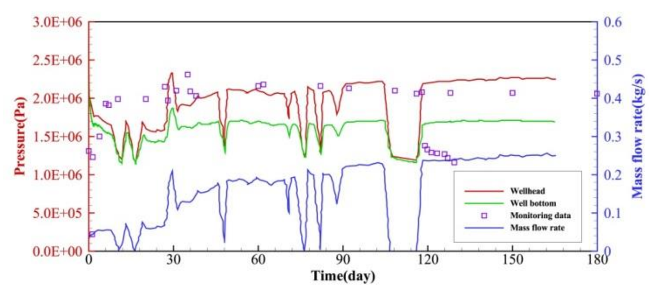

Fig. 5 Comparison between modelled pressure and monitoring data

Due to operational reason, the air injection was stopped about 10 days (from 108 to 118 days), the wellhead pressure was simulated with abnormal values (from 1.0 MPa to 1.5 MPa).

The performance of gas saturation at different distance is shown in Fig. 6. It is presented that the horizontal distance reached 0.6 m after 30 days bubble development. The site at 100 m from I/W well was influenced by bubble development after about 40 days air injection, and its gas saturation reached up to about 0.4.

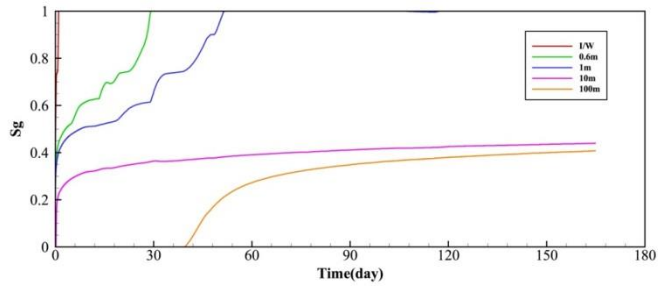

Fig. 6 Gas saturation at different distances from I/W well

The gas saturation at the model boundary keeps zero during the bubble development (not shown in Fig. 6), which represented that the bubble didn't reach the boundary.

After about 165 days air injection, the gas saturation of I/W well is presented in Fig. 7. It is shown that the plume of air bubble can reach up to 350 m. The maximum thickness of air bubble is about 20 m.

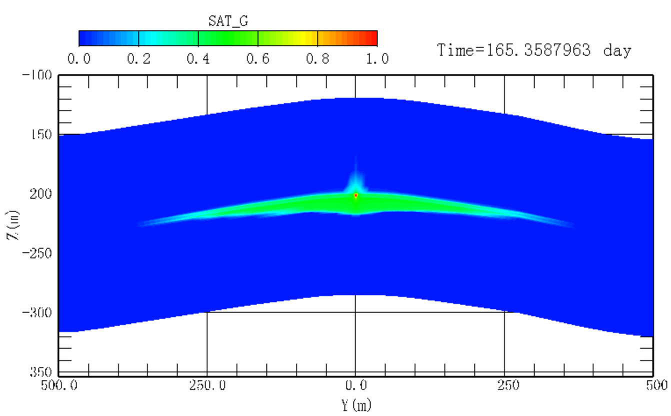

Fig. 7 Distribution of gas saturation after air injection finished

4. CONCLUSIONS

This study suggests that the numerical model is capable of simulating the multiphase flow and heat transfer in the aquifer compressed air energy storage system. The well-fitting between modelled results and monitoring data during the bubble development period indicated that the model well presents the geological setting of the subsurface system and capture the key heat and multiphase flow processes during air injection. Future work will be based on the result of the bubble development simulation, and to conduct new simulations to evaluate thermal efficiency of energy storage of ACAES in daily, weekly and seasonal cycles. Furthermore, high injected air temperature will be conducted to investigate its impact on round-trip efficiency of ACAES. .

ACKNOWLEDGEMENT

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