Contribution ID: **455** Type: **Oral Presentation**

Optimizing Underground Hydrogen Storage through Surrogate Modeling: A CNN-LSTM-Attention Network Approach

Tuesday, 14 May 2024 11:10 (15 minutes)

Underground hydrogen storage (UHS) presents a viable solution for storing excess energy in suitable geological sites, ensuring a stable and scalable energy supply [1]. While extensive experience exists in underground natural gas storage [2], the significant differences in the properties of hydrogen pose unique challenges [3]. To deepen insights into the hydrogen recovery in UHS projects, conducting reservoir simulation and optimization to pinpoint optimal operating parameters becomes essential. However, this process is typically time-consuming. The integration of a surrogate model proves invaluable in expediting the optimization process, addressing the significant time constraints associated with traditional methods.

We develop a base UHS simulation model with a 3D heterogeneous depleted natural gas reservoir featuring an anticline structure. The model integrates various physics, encompassing compositional fluid flow, hydrogen methanation reaction, gravity segregation, hysteresis, and capillary effects. The cycling schedule starts with an initial phase of cushion gas injection and idle periods, followed by five distinct hydrogen injection-idle-production cycles spanning five consecutive years. Notably, injection rates and bottomhole pressure (BHP) of the production well vary across these cycles. The base model incorporates diverse cushion gas types and layers of perforation. Upon parameterizing these decision variables and employing the Latin-Hypercube method for sampling, we generate a comprehensive database comprising approximately 1000 simulation cases, executed in parallel. To predict cumulative productions of hydrogen and other components, we train a surrogate model utilizing a CNN-LSTM-Attention network, leveraging the NVIDIA RTX A6000. The CNN component transforms 3D heterogeneous permeability and porosity fields into 1D datasets. This well-tailored surrogate model seamlessly integrates into the optimization workflow based on the stochastic simplex approximate gradient (StoSAG) [4] method. The primary optimization objective is to maximize hydrogen recovery while concurrently minimizing losses attributed to micro-bio reactions within a predefined timeframe.

Due to gravitational segregation in the base model, hydrogen, cushion gas, methane, and water exhibit a vertical distribution from top to bottom. Additionally, we note a progressive enhancement in hydrogen recovery efficiency with consistent injection rates during production. Our numerical experiments highlight nitrogen's superior effectiveness as a cushion gas for augmenting hydrogen recovery compared to carbon dioxide and identify a specific percentage of micro-bio-induced hydrogen loss. Regarding the performance of the surrogate model, the R2 scores for both training and testing datasets mostly exceed 0.95, affirming its robustness and feasibility. To demonstrate the acceleration achieved through the proxy model in optimization, we compare CPU times between the reservoir simulation and surrogate models. The former averages 210-300 seconds per case, while the latter ranges from 0.01 to 0.1 seconds. This translates to a remarkable speedup of approximately 1000 times compared to optimization conducted solely with reservoir simulation, all while maintaining equivalent accuracy.

This research introduces a comprehensive framework designed for reservoir simulation and optimization in UHS, integrating a CNN-LSTM-Attention network and StoSAG. Important mechanisms, including compositional flow, cushion gas dynamics, and micro-bio reactions, are thoroughly incorporated in the UHS simulation. This framework serves as an important guideline, offering crucial insights into accelerating the optimization of the UHS process and related projects.

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Session Classification: MS15

Track Classification: (MS15) Machine Learning and Big Data in Porous Media