Feasibility of Using CO_2 and N_2 Injection as Cushion Gas in Underground Gas Storages, Based on a Conceptual Simulation

Askari Amir Abbas[1]*, Zanganeh Hossein[1], Behrouz Turaj[1], Teymuri Ali[2], Bonyad Hamid[2], Nori Parisa[2]

[1] Research institute petroleum of Iran (RIPI)

[2] National Iranian Gas Company (NIGC)

* Corresponding author: Reservoir Study and Field Development Division, Research Institute of Petroleum Industry (RIPI), Tehran, P.O. Box 14665-137, Iran, Tel. +98-21-4825-2158, Email: askariaa@ripi.ir

Abstract

Underground Gas Storage (UGS) secures the supply of gas and ensures seasonal gas flexibility. In natural gas storage, the working gas (methane) is injected and produced seasonally while a cushion gas that is not extracted at all is used to provide pressure support. Inert gas (CO_2 and N_2) injection in the depleted gas reservoirs can be carried out to produce the methane while simultaneously filling the reservoir with such cheap gas as cushion gas. This phenomenon can also increase reservoir capacity due to their thermodynamic and physical properties. Unfortunately, there is no enough knowledge about using these inert gases as cushion gas in each case study. In this paper, for assessing the feasibility of using integrate injection as cushion gas, firstly a conceptual model of a depleted gas reservoir is constructed, then during the inert gas injection, a sensitivity analysis for all of reservoir and operational parameters for identifying the most influence important parameters was done, and finally the process of gas mixing for two inert gas was compared together. In conclusion, it is determined that in case of CO_2 and N_2 injection the influence of parameters such as horizontal permeability, porosity, reservoir temperature, reservoir pressure, injection rate and aquifer porosity are important while in case of N_2 injection the interval production perforation is important, too. Based on simulation, the behavior of gas mixing in case of N_2 was shown better than CO_2 due to higher diffusivity coefficient. Also it was determined that the inert gases production in the surface will be decreased during the time. The opportunity to use CO_2 and N_2 injection as a cushion gas may arise as a way of getting additional benefits from a depleted gas reservoir based on some reservoir properties and operational constraints that can be suitable candidate in a particular project.

Keyword

Cushion gas, UGS, CO_2 injection, N_2 injection, Conceptual simulation, Sensitivity analysis

1. Introduction

Natural gas as a clean and a reliable fossil fuel will continue to play an important role in providing energy and be favored over oil and coal to provide energy, mainly in power plants, where gas can be used in highly efficient Combined Cycle Gas Turbines (CCGT) (Escobar and Arteaga, 2011). The major consumption of gas is for heating houses in winter and generation of electricity. As the demand for natural gas in winter usually exceeds three times of summer gas consumption, the high capacity pipelines should be installed to transmit the needed gas. Although, the gas providing can be handled using in-situ underground gas storage reservoirs without need of high capacity pipelines. Experience shows that saving in transmission costs are generally two to three times of the cost of storage (Coats, 1966). In warm environments, UGS reservoirs can shave the demand pick of power plants which provide electricity for air conditions or keep the production capacities of gas processing units and refineries in the summer (Teatini et al., 2010; Azin et al., 2008). Furthermore, UGS has many advantages over other methods of storage i.e. better management of gas production considering market demand, continuous import of gas with constant rate for suppliers and stimulation of competition by increasing the number of gas suppliers to a market (Dharmananda and Fasanino, 2004).

One of the most critical aspects of UGS projects is the volume of cushion gas, the gas which cannot be produced and must be remained in the reservoir to provide the pressure for reproducing the working gas. The volume of the cushion gas in UGS reservoirs is 20-80 percent of gas inventory (20-30 percent in salt cavities storage, 50-80 percent in aquifer storage and about 50 percent in depleted gas and oil reservoir projects) (FER Commission Staff Report, 2004; Berger and Arnoult, 1999; Carrie et al., 1985).

Because all gases are compressible, just about any gas can be used as a cushion gas. As the methane from a depleting gas reservoir can be sold for profit, the operator's aims are to produce most of the gas and therefore, injection of a cheaper inert gas for use as the cushion gas is often considered. Whilst this also generates additional gas and thus revenue for depleted gas reservoirs, in the case of aquifer or salt cavern storage. It also means that the operator does not have to buy and use expensive methane as a cushion gas (British Geological Survey for the Health and Safety Executive, 2008). Although the use of inert cushion gases in the USA has been considered, they are not widely used (Oldenburg, 2003; British Geological Survey for the Health and Safety Executive, 2008). However, inert gases such as nitrogen (N_2) have been successfully injected specifically for use as cushion gas in Europe. The physical properties of carbon dioxide (CO_2) make it a potential choice as a cushion gas in pore storage scenarios. This is related to its high effective compressibility near its critical pressure when it undergoes a large change in density (Oldenburg, 2003). Injection of CO_2 has, for many years, been undertaken in a number of oil fields and is used to enhance oil and/or gas recovery. At the same time use of CO_2 would have the added bonus that whilst filling the reservoir with CO_2, it would also provide a method of carbon sequestration (Oldenburg, 2003).

In this work the feasibility of using CO_2 and N_2 as cushion gas was studied based on a conceptual simulation. The study was completed by conducting sensitivity analysis on reservoir parameters and operational conditions.

2. Model Description

A conceptual model based on some gas reservoir parameters were prepared to study the phenomena. The model was prepared using compositional simulation method. It has 22×23×12 cells with dimensions of 3215×2960 m^2 and it contains 6 billion standard cubic meters of gas with 5 components (CH_4, C_2H_6, C_3H_8, $C_{4\text{-}6}$, C_{7+}).

A single porosity sandstone was used as porous media and the relative permeability curves was generated using Corey method (Ahmed, 2000). As the conceptual model was prepared to sensitivity analysis of different parameters and the study of the effects of these parameters, the static reservoir parameters were considered uniform and the effect of parameters was examined with several scenario designs. Fig. 1 illustrates a 3D schematic of the reservoir. Two vertical wells were placed in the reservoir. One of the wells was for injection of inert gas. So, this well was perforated in the bottom of the reservoir. The second one was used to cyclic injection and production of working gas with aim of UGS.

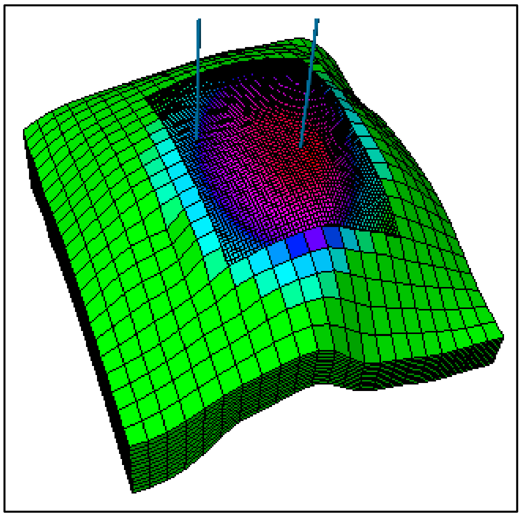

Fig. 1. 3D schematic of the conceptual reservoir

3. Underground Gas Storage Scenario

At the beginning the UGS scenario the reservoir was considered as a depleted reservoir at abandonment pressure. The inert gases (N_2 and CO_2) were injected into the reservoir in the bottom of reservoir interval to pressurize it. In this phase reservoir base gas was produced at top perforation due to sweeping by the inert gas which means enhanced gas recovery (EGR). After the pressure build up in the reservoir, the cyclic injection and production of working gas with 7 month time interval for injection and 5 for production were continued for about 11 years. The first phase (EGR) has lasted 18 years.

4. Sensitivity Analysis of Different Parameters

The sensitivity analysis of different reservoir and operational parameters is the main part of this study. The investigation of the sensitivity of objective functions like amount of natural gas and inert gas reproduction helps to make decision about the feasibility of the process.

To investigate the impact of different parameters and their corresponding uncertainties affecting the whole process, a vast amount of sensitivity analysis and reservoir simulation studies are necessary. Also having a combination of the aforementioned factors may give different results compared to the single variables sensitivity analysis. Because of the limitations of time and simulation expenses, it is almost impossible to achieve a fully inclusive understanding of the process in a reasonable manner (Zangeneh et al., 2013). For this reason performing statistical analysis in order to reduce the number of simulations is inevitable. Design of experiment (DOE) is one of the methods to maximize the information gained from each simulation and to investigate the significance of the different parameters (Montgomery, 2001: 1–19).

Ten parameters (reservoir porosity, reservoir horizontal permeability, reservoir temperature, reservoir pressure, aquifer porosity, critical gas saturation, minimum water saturation, injection rate, production and injection perforation intervals) were chosen to perform the sensitivity analysis with natural gas and inert gas production as objective functions. Analyzing these parameters by two-level factorial design needs 3×2^{10} (3072) simulation runs, which is time consuming due to high simulation run times. Therefore, the D-optimal method which needs less runs (3×61 runs) has been employed for analyzing sensitivity (Montgomery, 2001; Kleijnen, 2008).

Fig. 2 shows the result of statistical analysis on the simulation responses. This figure shows the effect of all factors on the net present value CH_4, N_2 and CO_2 production (objective functions) using D-optimal method. This is a plot of the absolute value of the effects (main effects and interaction effects) estimated against their cumulative normal probabilities. The straight line on the half-normal plot always passes through the origin and should also pass close to the fiftieth percentile data value (Montgomery, 2001). This figure illustrates that in the case of using the CO_2 and N_2 as cushion gas the reservoir porosity (A), horizontal permeability (B), injection rate (H), aquifer porosity (E) and some interactions like AB (for both case) DK, CD (for CO_2 case), DF and CHJ (for N_2 case) have more priority than others.

Although, a single parameter sensitivity was performed on the mentioned parameters in different levels which approved the last results.

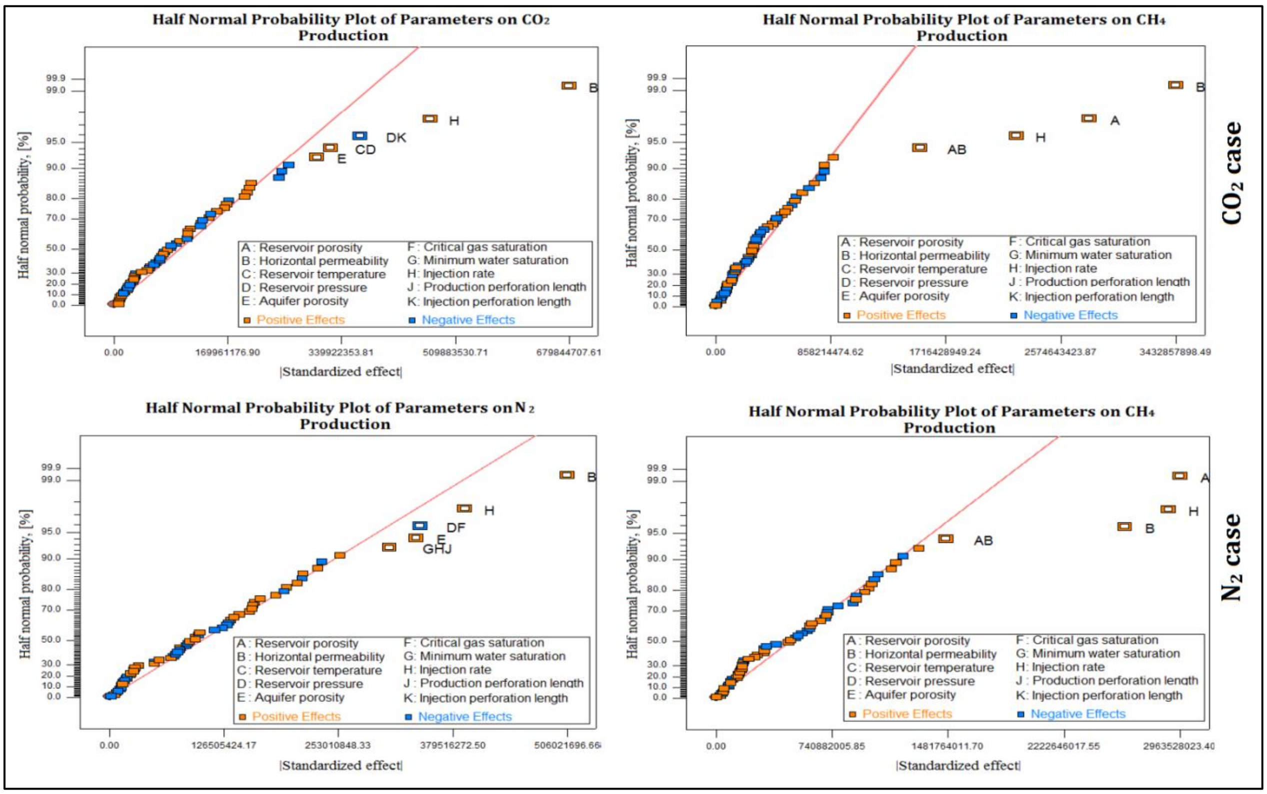

Fig. 2. Statically analyzed effects of all design factors on objective functions with D-optimal method

4. Investigation of Effect of Molecular Diffusion on the Process

The molecular diffusion is the most challenging phenomena in the process of using inert gases as cushion gas in UGS reservoirs. This is because of the potential of mixing in the cushion and working gas which is fully in contact with each other. Although the process of molecular diffusion is a slow phenomenon, it can cause a vast effect on the reservoir on numerous cyclic injection-production intervals. The diffusion in this reservoir was studied using Fick's equation and the phenomena was considered as equi-molar counter diffusion (Wei et al., 2007). The diffusion coefficient was calculated using Wike and Lee method and was evaluated for CO_2 and N_2 as 0.1156 and 0.1465 cm^2/s.

Fig. 3 and 4 depict the effect of diffusion on CO_2/N_2 and CH_4 production in the case of using CO_2/N_2 as cushion gas. The production was shown as a molar percent of produced gas. Considering these figures some facts about diffusion phenomena in this reservoir can be demonstrated. First, it shows that molecular diffusion decreases the inert gas production at surface which is unexpected.

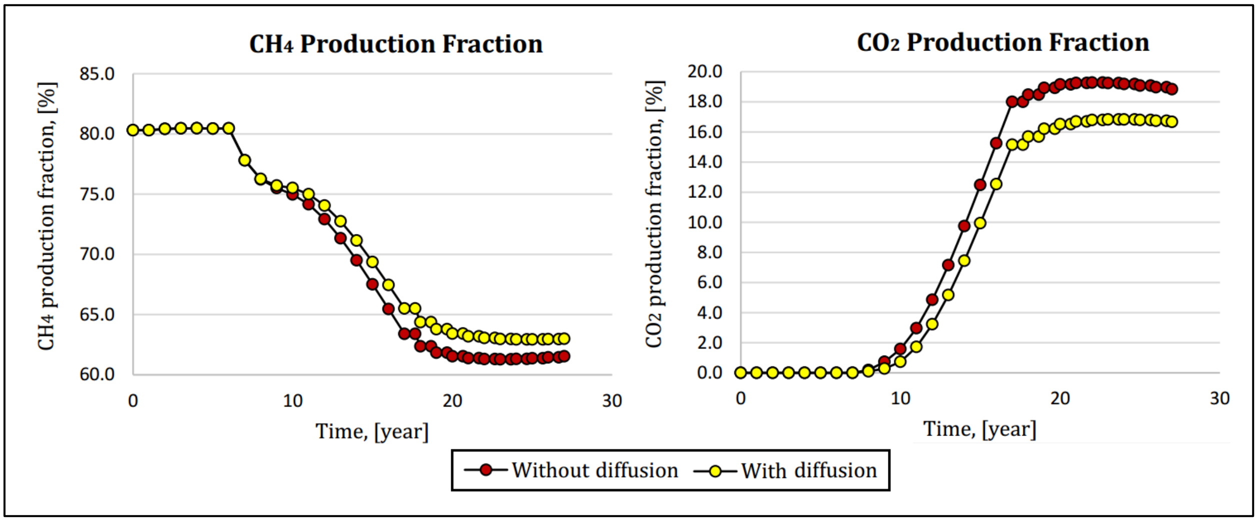

Fig. 3. The effect of molecular diffusion on CO_2 and CH_4 molar fraction in the case of CO_2 as cushion gas

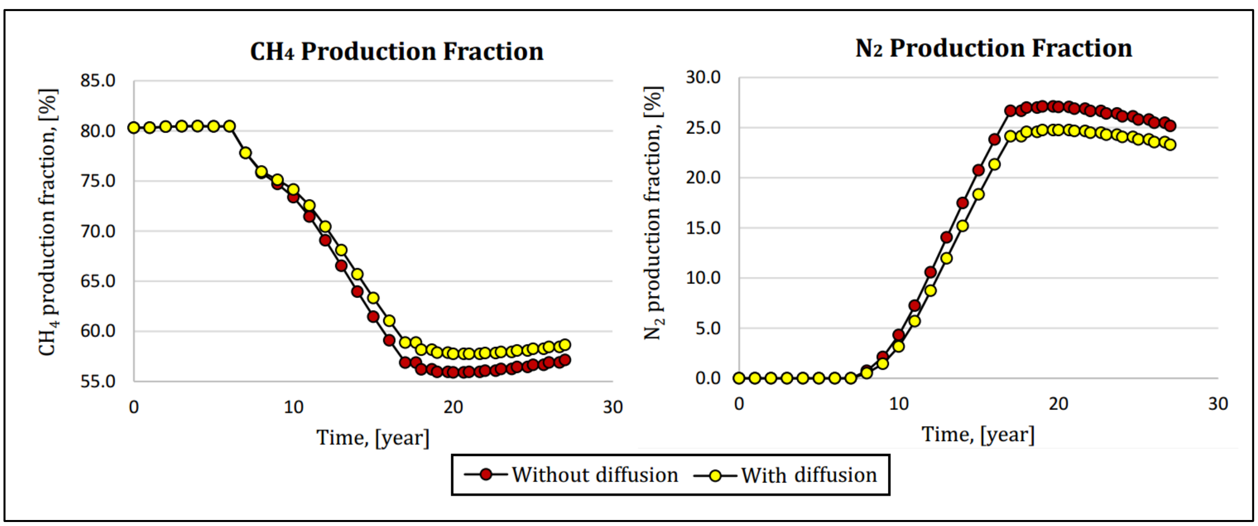

Fig. 4. The effect of molecular diffusion on N_2 and CH_4 molar fraction in the case of N_2 as cushion gas

Fig. 5 compares the effect of diffusion on the processes thoroughly. This figure gives a better understanding of diffusion phenomena in each stages of the process. This figure illustrates the production fraction change due to molecular diffusion (fraction with diffusion minus fraction without diffusion). As can be seen in this figure, the molecular diffusion decreases inert gas production and increase the amount of natural gas production in the first phase of the process (EGR phase). This is because of increasing the contact area of the injected gas and base gas due to increase of the dispersion of the inert gas which enhance the sweep efficiency. As the diffusion coefficient of N_2 is larger than CH_4, the decrease of N_2 is more. Although, in the second phase of the process (UGS cyclic injection-production), the molecular diffusion increases the mixing and inert gas production consequently. In this stage, the increase of N_2 production is faster due to higher diffusion coefficient.

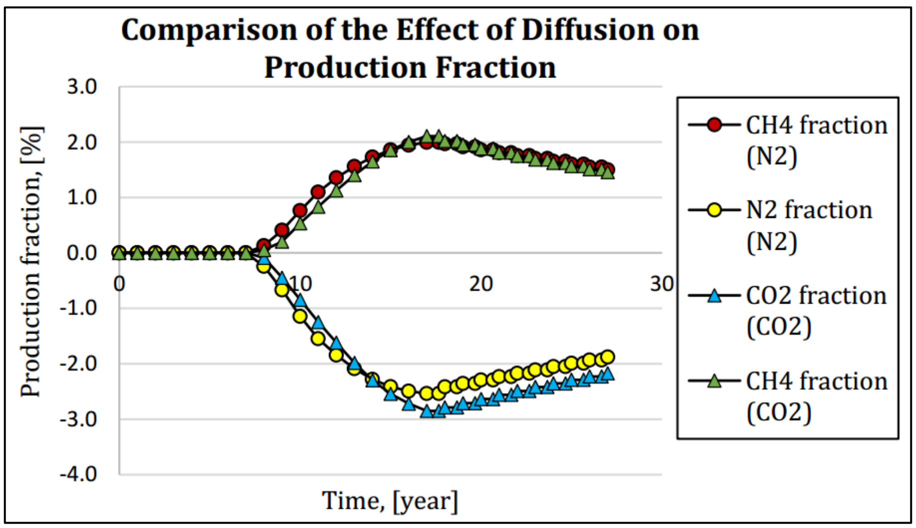

Fig. 5. Comparison of diffusion effects on CH_4, CO_2 and N_2 production fraction

After studying the effects of different parameters and phenomenon in the process of using inert gas as cushion gas an example case for CO_2 was optimized using Genetic Algorithm (GA). Fig. 6 shows the plot of objective function values versus generation number. This figure illustrates that if the parameters of the process was adjusted in the optimum value, the process can be successful with low inert gas reproduction (lower than 10 percent).

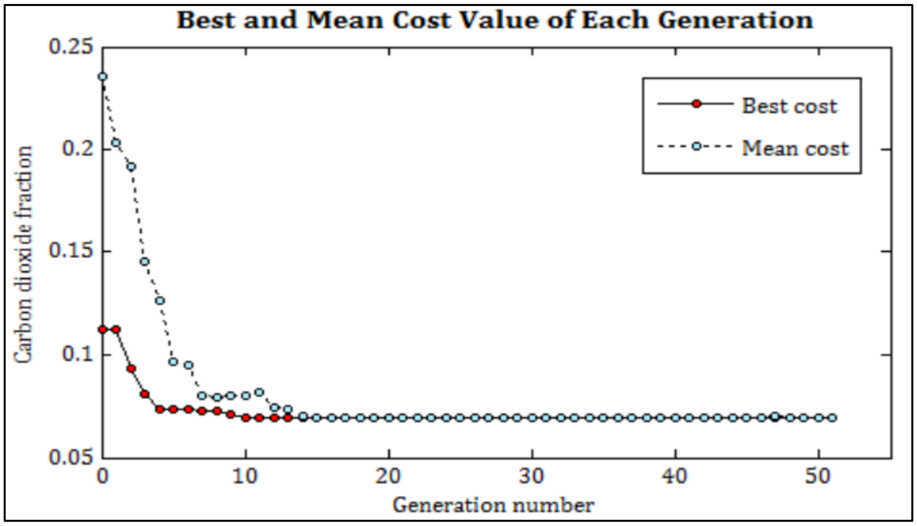

Fig.6. The plot of best and mean cost value of each generation in the process of optimization

5. Conclusion

In this work, the process of using inert gases (N_2 and CO_2) as cushion gas was studied based on a conceptual simulation model. So, a sensitivity analysis was performed on different reservoir and operational parameters and the effect of molecular diffusion was studied of the process, too. The following results can be concluded based on this study:

- Sensitivity analysis of the process of using inert gases as cushion gas in UGS reservoir shows that parameters such as reservoir porosity, horizontal permeability, injection rate, aquifer porosity and reservoir pressure and temperature are important and play main role.
- The molecular diffusion decreases inert gas production and increase the amount of natural gas production in the first phase of the process (EGR phase). This is because of increasing the contact area of the injected gas and base gas due to increase of the dispersion of the inert gas which enhance the sweep efficiency. As the diffusion coefficient of N_2 is larger than CH_4, the decrease of N_2 is more. Although, in the second phase of the process (UGS cyclic injection-production), the molecular diffusion increases the mixing and inert gas production consequently. In this stage the increase of N_2 production is faster due to higher diffusion coefficient.
- Finally, the results of optimization on CO_2 case illustrates that if the parameters of the process was adjusted in the optimum value, the process can be successful with low inert gas reproduction (lower than 10 percent).

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