A New Approach for Storage Capacity and Allowable Injection Time Calculation in Carbon Capture and Storage (CCS) Reservoir

Anthony Kurnia Jaya, Zuher Syihab

1 Bandung Institute of Technology, Bandung, Indonesia
1 anthonykurniaj@gmail.com, 1 zuher.syihab@tm.itb.ac.id

Abstract. In reducing the CO$_2$ emissions in the atmosphere, some energy industry start to implement the Carbon Capture Storage (CCS). However, there still less restriction and considerations in calculating the storage capacity and allowable injection time of CCS reservoir which might lead into leakage problem. In overcoming this problem, there is a study conducted to make a new calculation with higher accuracy. In this study, the reservoir model is using CMG software with base model of East Natuna Field. Then, this model is used to make a sensitivity analysis for 10 CCS fields with a support of CMG-CMOST and Eureqa software. The result is an equation with an R-Square of 96.6% for storage capacity and 95.4% for allowable injection time. The considered parameter in the new equation are permeability, porosity, fracture pressure, thickness, area, reservoir temperature, and reservoir pressure. To validate the new equation, a case study is made for 3 CCS fields. The result shows that the new equation shows up to 21% smaller storage capacity and 7 years reduction in allowable injection time. The result is reasonable due to additional restrictions. Therefore, it is believed that the generated equation is valid and more beneficial compared to the conventional equation.

1. Introduction

The oil and gas sector still holds the majority energy source in the world with almost 63% in 2017 and it could not be replaced immediately [1]. The extraction of hydrocarbon will make a carbon footprint which will damage the environment and global warming. With the Paris Agreement that has a goal to reduce Greenhouse Gas (GHG) to achieve the global temperature increase below 1.5°C. As one of GHG type, CO$_2$ is the most GHG that being released into the atmosphere which takes 82% of total GHG in the atmosphere [2].

With the purpose to reduce the emission of CO$_2$, the CCS technology in the oil and gas industry start to be implemented. This component could be captured and compressed into reservoir. The critical factor in evaluating the storage is the reservoir capacity and allowable injection time. Currently, the calculation of storage capacity is using the Bachu equation that considers the parameter of effective porosity, irreducible water saturation, bulk volume, capacity coefficient and density of CO$_2$ [3]. For the allowable injection time, it use equation from Szulczewski which require a pre-calculation [4].

In order to reduce the complexity of calculation, engineers that assess the CCS storage will assume that the equation with less restriction could have an accurate result. This less restriction condition could make an over injection or under injection in the reservoir due to inaccurate calculation. These inaccuracy will reduce the interest from company to execute a CCS project. Therefore, these concrete problems show urgency to make a new approach in calculating storage capacity and allowable injection time.
2. Basic Theory

2.1. Reservoir Modelling
Numerical modeling is commonly used to calculate an injection process as it is accurate in prediction and optimization. The prediction will be used to know the flow path of the injected CO$_2$ and the optimum well location will need to be assessed. One of the simulations processes that have been applied to analyze the storage capacity in a saline aquifers reservoir is the GEM simulator generated by the Computer Modeling Group [5]. In CCS reservoir model, there are some parameters being used: (1) Grid specification, (2) Initial water saturation, (3) Regions, (4) Permeability, (5) Porosity, (6) Transmissibility, (7) Aquifer specification, (8) Basic reservoir component, (9) Rock fluid specification, (10) Injection well position, (11) Depth, and (12) Thickness.

2.2. CMG-CMOST Analysis
There are some parameters selected to be processed in this analysis which will be based on the relation with storage capacity and allowable injection time. Each parameter is analyzed in a specific range of value obtained by doing an analysis on other CCS field. The experimental case generator in this analysis is categorized into 3 types, Classic Design, Latin Hypercube Design, and User Defined Design. The result of this analysis is a proxy model generated by a regression process. Following the proxy model, there also a result comparison with the simulated result.

2.3. Eureqa Analysis
To find out the best equation that has a higher R-Square and simplest form, another sensitivity analysis was made using Eureqa. The concept of this sensitivity process is to classify the important parameter relation which will have a big effect on the equation and make the regression result. Data input for this analysis comes from the experimental case from CMG-CMOST. For some parameters that have a low impact on the objective function, it will be eliminated automatically by Eureqa. This process differentiates Eureqa with the CMG-CMOST analysis that will try to make a correlation between every parameter with the objective function. This process also helps to generate a simpler form equation without reducing the confidence level. The generated equation in Eureqa sensitivity analysis needs to have a high maturity and stability to be a valid equation. The cut off for the maturity and stability needs to be higher than 50%.

2.4. Storage Capacity Calculation
The storage capacity of a CCS reservoir could be calculated by a volumetric method generated by Bachu which is shown in Equation (1) [3]. The concept of this equation is by calculating the volume of a reservoir through the thickness and area which is represented by the integral in 3 directions of x, y, and z.

\[
M_{co2} = Cc \int \int \int \phi_{eff}(-SWirr)\rho_{co2}dx\,dy\,dz ...(1)
\]

2.5. Allowable Injection Time Calculation
Besides calculating the storage capacity, the other important parameter is the allowable injection time. The definition of allowable injection time is the total duration from the injection start until the rate is too small and couldn’t be injected again. However, the current calculation of this parameter need a pre calculation to determine the maximum injection rate first as shown in the equation (2) below. This equation was generated by Szulczewski which consider the parameter of density from CO$_2$, the reservoir dimension, reservoir characteristic and the pressure [4]. Besides the needs of pre calculation, the determination for dimensionless pressure parameter will need a specific study from the reservoir.

\[
t = \frac{k}{\mu(Q_{\text{max}} + p(z_p + H + A + PP))^2} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (2)
\]
3. Methodology

3.1. Assumption
In building the model, there are some consideration and assumption that are used: (1) Seal for each reservoir layer is assumed to have no leakage, (2) Reservoir is assumed to be filled perfectly with saline aquifer, (3) Each layer of the reservoir have a homogeneous parameter, (4) The generated equation have a specific range of value for each parameter, (5) Mineral in the reservoir is assumed neglectable.

3.2. Sensitivity Analysis
10 CCS fields in the world that is used to determine the possible affecting parameters. Also, these fields are used to determine the specific range of value for each parameters. These fields are East Natuna, Indonesia; Sleipner, Norway; Snohvit, Norway; In Salah, Algeria; Gundih, Indonesia; Farnsworth, United States; Southeast Queensland, Australia, Lacq, France, SPE-196691-MS, and SPE-194629-MS [6, 7, 8, 9, 10, 11, 12, 13, 14, 15].

After analysing the possible affecting parameter, some parameters were chosen to be used in this process are CO2 content, Fracture pressure, Permeability, Porosity, Reservoir pressure, Specific Gravity, Thickness, Reservoir temperature, Area, Project’s lifetime and Irreducible water saturation.

4. Case Study
In this study, a reservoir model with the base model of East Natuna Basin data will be shown in Figure 1. This model was generated by a total of 1125 grid blocks (15x15x5) which represent 24000 acres area of this field. Properties from the same layer were assumed to have the same value. The composition for reservoir fluid was modeled by CMG-Winprop where the composition was 98% H2O and 2% CO2 as the targeted reservoir to store the CO2 in Deep Saline Aquifer.

These generated equations from CMG-CMOST and Eureqa was used to calculate the base model first. This process aims to determine whether the simpler form of the equation could have a similar result or not. Besides the R-Square, the simplicity of the equation will be an additional concern in this study. The chosen equations were used to calculate the storage capacity and allowable injection time of three CCS field: East Natuna, Snohvit, and Southeast Queensland. Result and Discussion

4.1. CMG-CMOST Equation
The equation generated in CMG-CMOST will be based on the experimental cases with each parameter have a different range of values. The range of value from each parameter will be shown in Table 1.

| No. | Parameter       | Lower Limit | Upper Limit | Unit  |
|-----|-----------------|-------------|-------------|-------|
| 1   | CO2 content     | 0.6275      | 1           | %     |
| 2   | Fracture pressure | 1042        | 8000        | psia  |
| 3   | Permeability    | 20          | 400         | mD    |
Porosity 0.1 0.528 frac.
Reservoir pressure 1091 8000 psia
Specific gravity 0.5 2 frac.
Thickness 40 250 ft
Reservoir temperature 80 400 F
Area 40 60000 Acres
Injection duration/project’s lifetime 20 40 years
Irreducible water saturation 0.15 0.4 frac.

The generated equation is shown below for both Storage Capacity and Allowable Injection Time.

Storage Capacity (lb) = Coeff1 * Term1 + Coeff2 * Term2 + ... + Coeffn * Ternn ............(3)

With the tabulation for each coefficient and term is shown in Table 2.

| Term          | Coefficient |
|---------------|-------------|
| Interception  | 2.1477E+11  |
| CO2 Percentage| -1.0547E+11 |
| Fracpres      | -4.34664E+07|
| Perm          | -2.62375E+08|
| Pres          | -1.8609E+11 |
| Thickness     | -3.95385E+08|
| Tres          | -1.78007E+08|
| ACRE          | -1.94064E+06|
| SWirr         | -4.11982E+09|
| CO2Percentage*Tres | 3.24801E+08 |
| Fracpres*Fracpres | -1613.64       |
| Fracpres*Perm  | 9.50941E+07   |
| Fracpres*Thickness | 249657         |
| Fracpres*ACRE  | 961.434       |
| Perm*Perm      | -283645       |
| Perm*Por       | 9.43819E+08   |
| Perm*Pres      | -20498.5      |

Allowable Injection Time (month) = Coeff1 * Term1 + Coeff2 * Term2 + ... + Coeffn * Ternn ... (4)

With the tabulation for each coefficient and term is shown below in Table 3.

| Term          | Coefficient |
|---------------|-------------|
| Interception  | 238.156     |
| CO2 Percentage| -100.775    |
| Fracpres      | -0.034797   |
| Perm          | -1.22066    |
| Por           | 585.354     |
| Pres          | -0.00895164 |
| Specific_Gravity | 25.4938     |
| Thickness     | 0.243962    |
| Tres          | -0.0797618  |
| ACRE          | 0.00627766  |
| DURATION      | -1.83037    |

| Term          | Coefficient |
|---------------|-------------|
| Fracpres*Tres    | 6.01997E+05 |
| Fracpres*ACRE    | -5.20313E+07|
| Perm*Perm        | 0.00182654  |
| Perm*Por         | -0.44554    |
| Perm*ACRE        | 9.8006E+06  |
| Perm*SWirr       | 7.90001E+08 |
| Thickness*ACRE   | 9.13964     |
| Thickness*SWirr  | 2.76283E+07 |
| Thickness*Fracpres | 6.01997E+05 |
| Fracpres*Fracpres | -0.034797   |
| Fracpres*Perm    | 9.50941E+07 |
| Fracpres*Thickness | 249657      |
| Fracpres*ACRE    | 961.434     |
| Perm*Perm        | -283645     |
| Perm*Por         | 9.43819E+08 |
| Perm*Pres        | -20498.5    |
| Fracpres*Tres    | 6.01997E+05 |
| Fracpres*ACRE    | -5.20313E+07|
| Perm*Perm        | 0.00182654  |
| Perm*Por         | -0.44554    |
| Perm*ACRE        | 9.8006E+06  |
| Perm*SWirr       | 7.90001E+08 |
| Thickness*ACRE   | 9.13964     |
| Thickness*SWirr  | 2.76283E+07 |
| Thickness*Fracpres | 6.01997E+05 |
| Fracpres*Fracpres | -0.034797   |
| Fracpres*Perm    | 9.50941E+07 |
| Fracpres*Thickness | 249657      |
| Fracpres*ACRE    | 961.434     |
| Perm*Perm        | -283645     |
| Perm*Por         | 9.43819E+08 |
| Perm*Pres        | -20498.5    |
| Fracpres*Tres    | 6.01997E+05 |
| Fracpres*ACRE    | -5.20313E+07|
| Perm*Perm        | 0.00182654  |
| Perm*Por         | -0.44554    |
| Perm*ACRE        | 9.8006E+06  |
| Perm*SWirr       | 7.90001E+08 |
| Thickness*ACRE   | 9.13964     |
| Thickness*SWirr  | 2.76283E+07 |
| Thickness*Fracpres | 6.01997E+05 |
| Fracpres*Fracpres | -0.034797   |

4.2. Eureqa Equation

Below is the generated equation from Eureqa for storage capacity:
\[ SC' = 1.55 \times 10^8 \times k \times \phi + \frac{346 + H + \text{Por}^3 \times A^2}{k} - \left( \phi \times A \times H \times (29.2 \times \text{Pres} - 27.8 \times FP) \right) \] ........(5)

Storage Capacity (lb) = 6.46 \times 10^9 + \frac{\left(1.49 + SC' \times k\right) - \left(26.4 + SC'\right)}{k + (0.401 \times \text{Pres}^2)} - (5.97 \times 10^7 \times k) \] ...........(6)

The calculation is used two step equation, where the equation (5) is the first step equation and used as the coefficient in the second step equation (6).

The generated equation from Eureqa for allowable injection time is shown in equation (7) shown below:

\[ \text{Maximum Injection Time (month)} = \frac{(0.1 \times 10^5) + 171 \times \phi \times A - 13.4 \times k \times \text{Tres}}{9.46 \times \text{Tres} + [FP \times (1 + 0.0145 \times k)]} \] ..........................................................(7)

4.3. Case Study Result

Both of the generated equations from CMG-CMOST and Eureqa are used to calculate the verification data generated in CMG-CMOST. The result of this comparison is shown in Table 4. It is shown that the generated equation from Eureqa have a higher R-Square and lower error. Therefore, the Eureqa-generated equation is used for case study.

| Tool: Eureqa | Tool: CMG-CMOST |
|-------------|-----------------|
| Storage Capacity | Allowable Injection Time | Storage Capacity | Allowable Injection Time |
| Maximum Error (%) | 51.27 | 53.2 | 53.5 | 65.72 |
| Minimum Error (%) | 5.35 | 5.68 | 7.48 | 5.79 |
| Average Error (%) | 9.88 | 10.27 | 10.07 | 10.73 |
| R-Square (%) | 93.23 | 92.8 | 89.21 | 89.77 |

The generated equation from Eureqa was used to calculate CCS Field in East Natuna, Snohvit, and Southeast Queensland as the case study. The storage capacity result is shown in Table 5 and allowable injection time is shown in Table 6.

| Lyr. | East Natuna Field | Snohvit Field | Southeast Queensland Field |
|------|-------------------|---------------|---------------------------|
|      | Predictive (mmTon) | Conv. (mmTon) | Diff (%) | Predictive (mmTon) | Conv. (mmTon) | Diff (%) | Predictive (mmTon) | Conv. (mmTon) | Diff (%) |
| 1    | 6.96              | 7.85          | 11.3     | 0.69              | 0.70          | 1.2     | 0.27              | 0.35          | 21.9    |
| 2    | 63.19             | 78.14         | 19.1     | 0.88              | 1.03          | 14.8    | 0.49              | 0.50          | 2.8     |
| 3    | 72.06             | 80.67         | 10.7     | 1.07              | 1.09          | 1.9     |                   |               |         |
| 4    | 73.57             | 82.34         | 10.7     |                   |               |         |                   |               |         |
| 5    | 74.31             | 83.77         | 11.3     |                   |               |         |                   |               |         |
Table 6 Case Study Allowable Injection Time Calculation Result

| Layer | East Natuna Field (Years) | Snohvit Field (Years) | Southeast Queensland Field (Years) |
|-------|---------------------------|-----------------------|-------------------------------------|
| 1     | 18.78                     | 3.44                  | 4.14                                |
| 2     | 17.25                     | 4.02                  | 5.77                                |
| 3     | 16.95                     |                       |                                     |
| 4     | 16.58                     |                       |                                     |
| 5     | 16.39                     |                       |                                     |

5. Conclusion

The result of this study shows that the equation generated by Eureqa software for both storage capacity and allowable injection time has a more accurate result if compared with the conventional equation. The utilization of this equation is simpler if compared with the CMG-CMOST generated equation. The R-Square of this equation reaches 96.6% and 95.4% for storage capacity and allowable injection time. The final equation for both equations only considers seven parameters, permeability, porosity, fracture pressure, reservoir pressure, reservoir temperature, thickness, and area.

The result from calculating the three CCS fields shows that the generated equation from Eureqa could give a difference ranging from 1-21% less than the current result due to the additional restriction and consideration. For the allowable injection time, the result shows reduction for up to 7 years.

References

[1] Smil V 2017 Energy and Civilization (Massachusetts: MIT Press)
[2] EPA U 2015 2014 Annual Performance Report (Washington D.C.: US Environmental Protection Agency)
[3] Bachu S 2015 Review of CO2 Storage Efficiency in Deep Saline Aquifers International Journal of Greenhouse Gas Control 188-202.
[4] Szulczewski M 2009 Storage Capacity and Injection Rate Estimates for CO2 Sequestration in Deep Saline Aquifers in the Conterminous United States (Massachusetts: Massachusetts Institute of Technology, Libraries Archives)
[5] Ajayi T, Gomes J S and Bera A 2019 A Review of CO2 Storage in Geological Formations Emphasizing Modeling, Monitoring and Capacity Estimation Approaches Petroleum Science, 1028-1063
[6] Cherdasa J R 2018 Formation Evaluation and Contingent Storage Capacity Estimation for Carbon Capture Storage and Utilization: A Case Study from East Natuna Modern Applied Science Vol. 12 No 4
[7] Chadwick R 2004 Geological Reservoir Characterization of a CO2 Storage Site: The Utsira S and, Sleipner, Northern North Sea Energy Journal vol. 29 no. 9-10 1371–1381.
[8] Buscheck T 2016 Managing Geologic CO2 Storage with Pre-Injection Brine Production: a Strategy Evaluated with a Model of CO2 Injection at Snohvit Energy & Environmental Science vol 9 no 4 1504–1512.
[9] Rutqvist J 2010 Coupled Reservoir-Geomechanical Analysis of CO2 Injection and Ground Deformations at In Salah, Algeria International Journal of Greenhouse Gas Control vol 4 no 2 225-230.
[10] Sapiie B 2015 Geological Characteristic and Fault Stability of the Gundih CCS Pilot Project at Central Java, Indonesia 12th SEGJ International Symposium Tokyo
[11] Balch R and Mcpherson B 2016 Integrating Enhanced Oil Recovery and Carbon Capture and Storage Projects: A Case Study at Farnsworth Field, Texas SPE Western Regional Meeting pp 23-26
[12] Cinar Y 2007 Geo-Engineering and Economic Assessment of a Potential Carbon Capture and Storage Site in Southeast Queensland *SPE Asia Pacific Oil and Gas Conference and Exhibition* Australia

[13] Monne J 2012 The Lacq CCS Pilot, a First *International Conference on Health, Safety and Environment in Oil and Gas Exploration and Production*.

[14] Rizzato P 2019 Dynamic Modeling of a High Temperature CO2-Rich Giant Gas Field with a Carbon Capture and Storage Strategy *SPE Reservoir Characterisation and Simulation Conference and Exhibition*

[15] Mishra G and Kumar 2019 Planning India's First CO2-EOR Project as Carbon Capture Utilization Storage: A Step Towards Sustainable Growth *SPE Oil and Gas India Conference and Exhibition*, India