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

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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.

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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.

$$M_{co_2} = Cc \int\int\int \o_{eff}(1 - SWirr)\rho_{co_2} dxdydz \quad \text{.....(1)}$$

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.

$$t = \frac{k}{\mu\left(\frac{Qmax*\dot{p}}{2\rho*H*A*FP}\right)^2} \quad \text{..................................(2)}$$

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% H_2O and 2% CO_2 as the targeted reservoir to store the CO_2 in Deep Saline Aquifer.

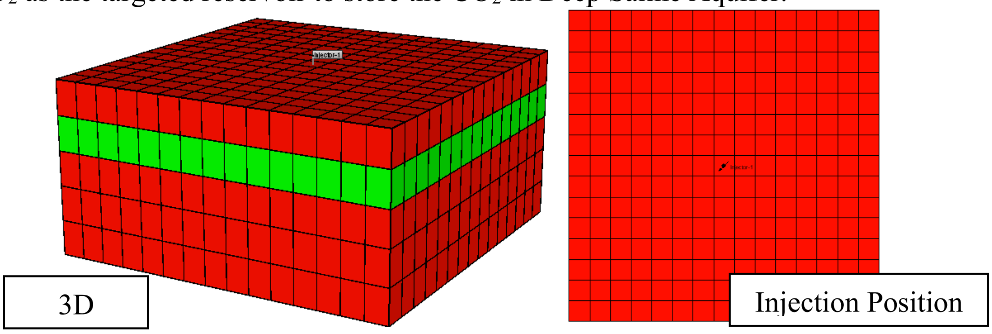

Figure 1 Reservoir Model

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.

Table 1 Parameter Range

No.	Parameter	Lower Limit	Upper Limit	Unit
1	CO_2 content	0.6275	1	%
2	Fracture pressure	1042	8000	psia
3	Permeability	20	400	mD

4	Porosity	0.1	0.528	frac.
5	Reservoir pressure	1091	8000	psia
6	Specific gravity	0.5	2	frac
7	Thickness	40	250	ft
8	Reservoir temperature	80	400	F
9	Area	40	60000	Acres
10	Injection duration/ project's lifetime	20	40	years
11	Irreducible water saturation	0.15	0.4	frac.

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

$$Storage\ Capacity\ (lb) = Coeff_1 * Term_1 + Coeff_2 * Term_2 \dots\dots.. + Coeff_n * Term_n \ldots\ldots\ldots\ldots (3)$$

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

Table 2 Term and Coefficient Storage Capacity

Term	Coefficient	Term	Coefficient
Intercept	2.1477E+11	Por*Por	-4.25632E+11
CO2Percentage	-1.0547E+11	Por*Pres	-9.21601E+07
Fracpres	-4.34664E+07	Por*Tres	4.21992E+08
Perm	-2.62375E+08	Por*ACRE	867216
Por	-1.6809E+11	Pres*Pres	1340.65
Pres	4.03745E+07	Pres*Thickness	-222813
Thickness	-3.95385E+08	Pres*Tres	53261
Tres	-1.78007E+08	Pres*ACRE	-1052.88
ACRE	-1.94064E+06	Pres*SWirr	-2.26283E+07
SWirr	4.11982E+09	Thickness*Thickness	-1.90654E+06
CO2Percentage*Tres	3.24801E+08	Thickness*ACRE	9425.35
Fracpres*Fracpres	-1613.64	Thickness*SWirr	4.73789E+08
Fracpres*Por	9.50941E+07	Tres*Tres	-830098
Fracpres*Thickness	249657	Tres*ACRE	1723.77
Fracpres*ACRE	961.434	ACRE*ACRE	-23.1227
Perm*Perm	-283645	Perm*Thickness	913964
Perm*Por	9.43819E+08	Perm*ACRE	5847.75
Perm*Pres	-20498.5		

$$Allowable\ Injection\ Time(month) = Coeff_1 * Term_1 + Coeff_2 * Term_2 \dots\dots + Coeff_n * Term_n \ldots(4)$$

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

Table 3 Term and Coefficient Allowable Injection Time

Term	Coefficient	Term	Coefficient
Intercept	238.156	Fracpres*Tres	6.01997E-05
CO2Percentage	-100.775	Fracpres*ACRE	-5.20313E-07
Fracpres	-0.034797	Perm*Perm	0.00182654
Perm	-1.22066	Perm*Por	-0.44554
Por	585.354	Perm*ACRE	-9.8006E-06
Pres	-0.00895164	Por*Tres	-0.9363
Specific_Gravity	25.4938	Por*ACRE	0.00639336
Thickness	0.243962	Por*DURATION	-6.71426
Tres	-0.0797618	Pres*ACRE	7.90001E-08
ACRE	0.00627766	CO2Percentage*DURATION	3.23769
DURATION	-1.83037	Fracpres*Perm	7.60457E-05

4.2. Eureqa Equation

Below is the generated equation from Eureqa for storage capacity:

$$SC' = 1.55 * 10^8 * k * ø + \frac{346*H*Por^3*A^2}{k} - [ø * A * H * (29.2 * Pres - 27.8 * FP)] \ldots\ldots (5)$$

$$Storage\ Capacity\ (lb) = 6.46 * 10^9 + \frac{(1.49*SC'*k)-(26.4*SC')}{k+(0.401*Pres*ø^2)} - (5.97 * 10^7 * k) \ldots\ldots (6)$$

The calculation is used two step equation, where the equation (5) is the first step equation and is 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:

$$Maximum\ Injection\ Time\ (month) = \frac{(8*10^5)+171*ø*A-13.4*k*Tres}{9.46*Tres+[FP*(1+0.0145*k])} \ldots\ldots (7)$$

4.3. *Case Study Result*

Both of the generated equation 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.

Table 4 Result Comparison between Eureqa and CMG-CMOST

	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.

Table 5 Case Study Storage Capacity Calculation Result

	East Natuna Field			**Snohvit Field**			**Southeast Queensland Field**		
Lyr.	**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	4.88	
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.

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