

Enhancing Aramco GigaPOWERS Reservoir Simulator With Foam Modeling EOR Capabilities

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Abstract

Steam-foam flooding and aqueous foams are used in the oil and gas industry to control flow. By reducing mobility of the gas phase, the liquid production is increased and the encroaching of the gas-cap is deterred. In this paper, the implementation of foam EOR modeling based on the work of [1, 2] in Aramco in house reservoir simulator *GigaPOWERS* is discussed. Results for using foam EOR on large model cases is also reviewed. The low viscosity of CO_2 compared to other formation fluids will result in channeling and fingering which results in poor sweep-factor. The injection of foam helps in reducing the mobility of CO_2 , which helps in CO_2 sequestration and EOR applications.[3]

Keywords: foam modeling, EOR, gas mobility, mobility control, acid diversion

1 Introduction

The utilization of gas injection as a sweeping agent for EOR is impacted by how mobile gas is within the formation. To ensure a reasonable sweep efficiency, the gas mobility must be reduced so gas will not escape through high-permeability streaks or simply move to form or increase an already existing gas-cap. The reduced mobility will also ensure gas will not encroach production wells before oil. Another primary purpose to inject foam is to spread gas through large areas of reservoir to increase the chances of possible sweeps. The foam will generally reduce gas mobility by blocking a large number of pore throats and channels where gas may originally seep in.

2 Theoretical Background

There are multiple empirical and theoretical techniques to model foam in porous media. Theoretically based techniques include: population-balance, percolation models and fractional flow theory. Empirical techniques include: semi-empirical alteration of gas-phase mobilities. The technique most popular in industrial simulators is the semi-empirical technique originally implemented in [2]. Foam reduces gas mobility by generating a dispersed phase of lamellae (thin liquid films) that divide the gas into many disconnected bubbles. In the reservoir, this produces a gas mobility control effect: gas flows as a "bubble train" rather than a single continuous gas phase. The modeling of this bubble train can be carried out using *population-balance approach* [1].

2.1 Foam Quality And The Two Foam-Flow Regimes

Gas fractional flow is referred to in literature as *Foam Quality*, $f_g^* = \frac{Q_g}{Q_g + Q_l}$. The rates Q_g and Q_l refer to injection conditions. The flow of foam in porous media is dominated by two regimes: low-quality and high-quality regimes. In the low-quality regime (wet foam), liquid supply is abundant and lamella creation is easy, the creation of lamella is proportional to gas velocity.

The two flow regimes differ in how gas flow rate is depending on pressure gradient. In the low-quality regime, pressure gradient Δp is independent of liquid flow rate q_l , while in high-quality regime pressure gradient Δp is independent of gas flow rate q_g . These two flow regimes were introduced originally in [4], in a study to understand the minimum pressure gradient required to keep foams flowing in porous media.

In the low-quality regime, mobility reduction increases strongly with gas velocity, while in the high-quality regime foam stops getting stronger with more gas and mobility reduction becomes independent of further increasing in gas velocity.

2.2 Foam Adsorption And Decay

The specification of adsorption is supplied by a table of foam concentration in solution against adsorped foam concentration in rock. The mass of adsorped foam is: $V(\frac{1-\phi}{\phi})\rho_r C_f^a$.

2.3 General Formulation And Governing Equations

The mobility reduction is performed by reducing the relative permeability of gas by using the following equations:

$$K_{rg} = k_{rg}^o M_{rf} \quad (1)$$

$$M_{rf} = \frac{1}{1 + (M_r F_s F_w F_o F_c)} \quad (2)$$

Where:

- M_r : is the reference mobility reduction factor.
- F_s : is the mobility reduction factor component due to surfactant concentration.
- F_w : is the mobility reduction factor component due to water saturation.
- F_o : is the mobility reduction factor component due to oil saturation.
- F_c : is the mobility reduction factor component due to gas velocity (capillary number).

The reduction factors are given as bellow:

$$F_s = \left(\frac{C_s}{C_s^r}\right)^{e_s} \quad (3)$$

$$F_w = 0.5 + \frac{\arctan[f_w(S_w - S_w^l)]}{\pi} \quad (4)$$

$$F_o = \left(\frac{S_o^m - S_o}{S_o^m}\right)^{e_o} \quad (5)$$

$$F_c = \left(\frac{N_c^r}{N_c}\right)^{e_c} \quad (6)$$

$$N_c = \frac{K \nabla P}{\sigma_{wg}} \quad (7)$$

Where:

- C_s : is the effective surfactant concentration.
- C_s^r : is the reference surfactant concentration.
- e_s : controls the steepness of the transition about the limiting capillary pressure.
- f_w : Reference dry-out slope used in dimensionless foam dry-out calculation.
- S_w : Water saturation.
- S_w^l : Limiting water saturation.
- S_o : Oil saturation.
- S_o^m : Maximum oil saturation.
- e_o : controls the steepness of the transition about maximum oil saturation.
- N_c : is the capillary number.
- N_c^r : is the reference capillary number.
- e_c : controls the steepness of the transition about the reference capillary number.
- K : is the rock permeability.
- ∇P : is the pressure gradient.
- σ_{wg} : is the gas-water interfacial tension.

3 Simulation Results

3.1 This is an example for second level head—subsection head

3.1.1 This is an example for third level head—subsubsection head

Sample body text. Sample body text. Sample body text. Sample body text. Sample body text. Sample body text. Sample body text. Sample body text.

4 Equations

Equations in L^AT_EX can either be inline or on-a-line by itself (“display equations”). For inline equations use the `$...$` commands. E.g.: The equation $H\psi = E\psi$ is written via the command `$H \psi = E \psi$`.

For display equations (with auto generated equation numbers) one can use the `equation` or `align` environments:

$$\|\tilde{X}(k)\|^2 \leq \frac{\sum_{i=1}^p \|\tilde{Y}_i(k)\|^2 + \sum_{j=1}^q \|\tilde{Z}_j(k)\|^2}{p+q}. \quad (8)$$

where,

$$\begin{aligned} D_\mu &= \partial_\mu - ig \frac{\lambda^a}{2} A_\mu^a \\ F_{\mu\nu}^a &= \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + gf^{abc} A_\mu^b A_\nu^c \end{aligned} \quad (9)$$

Notice the use of `\nonumber` in the `align` environment at the end of each line, except the last, so as not to produce equation numbers on lines where no equation numbers are required. The `\label{}` command should only be used at the last line of an `align` environment where `\nonumber` is not used.

$$Y_\infty = \left(\frac{m}{\text{GeV}} \right)^{-3} \left[1 + \frac{3 \ln(m/\text{GeV})}{15} + \frac{\ln(c_2/5)}{15} \right] \quad (10)$$

The class file also supports the use of `\mathbb{}`, `\mathscr{}` and `\mathcal{}` commands. As such `\mathbb{R}`, `\mathscr{R}` and `\mathcal{R}` produces \mathbb{R} , \mathscr{R} and \mathcal{R} respectively (refer Subsubsection 3.1.1).

5 Tables

Tables can be inserted via the normal `table` and `tabular` environment. To put footnotes inside tables you should use `\footnotetext[]{\dots}` tag. The footnote appears just below the table itself (refer Tables 1 and 2). For the corresponding footnotemark use `\footnotemark[...]`

The input format for the above table is as follows:

```
\begin{table}[<placement-specifier>]
\caption{<table-caption>}\label{<table-label>}%
\begin{tabular}{@{}l l l l@{}}
\toprule
Column 1 & Column 2 & Column 3 & Column 4\\
\midrule
row 1 & data 1 & data 2 & data 3 \\
\end{tabular}
```

Table 1 Caption text

Column 1	Column 2	Column 3	Column 4
row 1	data 1	data 2	data 3
row 2	data 4	data 5 ¹	data 6
row 3	data 7	data 8	data 9 ²

Source: This is an example of table footnote. This is an example of table footnote.

¹Example for a first table footnote. This is an example of table footnote.

²Example for a second table footnote. This is an example of table footnote.

```
row 2 & data 4 & data 5\footnotemark[1] & data 6 \\  
row 3 & data 7 & data 8 & data 9\footnotemark[2]\\  
\botrule  
\end{tabular}  
\footnotetext{Source: This is an example of table footnote.  
This is an example of table footnote.}  
\footnotetext[1]{Example for a first table footnote.  
This is an example of table footnote.}  
\footnotetext[2]{Example for a second table footnote.  
This is an example of table footnote.}  
\end{table}
```

Table 2 Example of a lengthy table which is set to full textwidth

Project	Element 1 ¹			Element 2 ²		
	Energy	σ_{calc}	σ_{expt}	Energy	σ_{calc}	σ_{expt}
Element 3	990 A	1168	1547 ± 12	780 A	1166	1239 ± 100
Element 4	500 A	961	922 ± 10	900 A	1268	1092 ± 40

Note: This is an example of table footnote. This is an example of table footnote this is an example of table footnote this is an example of table footnote.

¹Example for a first table footnote.

²Example for a second table footnote.

In case of double column layout, tables which do not fit in single column width should be set to full text width. For this, you need to use `\begin{table*}` ... `\end{table*}` instead of `\begin{table}` ... `\end{table}` environment. Lengthy tables which do not fit in textwidth should be set as rotated table. For this, you need to use `\begin{sidewaystable}` ... `\end{sidewaystable}` instead of `\begin{table*}`

... `\end{table*}` environment. This environment puts tables rotated to single column width. For tables rotated to double column width, use `\begin{sidewaystable*}` ... `\end{sidewaystable*}`.

6 Figures

As per the \LaTeX standards you need to use eps images for \LaTeX compilation and pdf/jpg/png images for PDF \LaTeX compilation. This is one of the major difference between \LaTeX and PDF \LaTeX . Each image should be from a single input .eps/vector image file. Avoid using subfigures. The command for inserting images for \LaTeX and PDF \LaTeX can be generalized. The package used to insert images in \LaTeX /PDF \LaTeX is the graphicx package. Figures can be inserted via the normal figure environment as shown in the below example:

```
\begin{figure}[<placement-specifier>]
\centering
\includegraphics{<eps-file>}
\caption{<figure-caption>}\label{<figure-label>}
\end{figure}
```



Fig. 1 This is a widefig. This is an example of long caption this is an example of long caption this is an example of long caption this is an example of long caption

In case of double column layout, the above format puts figure captions/images to single column width. To get spanned images, we need to provide `\begin{figure*}` ... `\end{figure*}`.

For sample purpose, we have included the width of images in the optional argument of `\includegraphics` tag. Please ignore this.

7 Algorithms, Program codes and Listings

Packages `algorithm`, `algorithmicx` and `algpseudocode` are used for setting algorithms in \LaTeX using the format:

```
\begin{algorithm}
\caption{<alg-caption>}\label{<alg-label>}
```

Table 3 Tables which are too long to fit, should be written using the “sidewaystable” environment as shown here

Projectile	Element 1 ¹			Element ²		
	Energy	σ_{calc}	σ_{expt}	Energy	σ_{calc}	σ_{expt}
Element 3	990 A	1168	1547 \pm 12	780 A	1166	1239 \pm 100
Element 4	500 A	961	922 \pm 10	900 A	1268	1092 \pm 40
Element 5	990 A	1168	1547 \pm 12	780 A	1166	1239 \pm 100
Element 6	500 A	961	922 \pm 10	900 A	1268	1092 \pm 40

Note: This is an example of table footnote this is an example of table footnote this is an example of table footnote
this is an example of table footnote.

¹ This is an example of table footnote.

```

\begin{algorithmic}[1]
. . .
\end{algorithmic}
\end{algorithm}

```

You may refer above listed package documentations for more details before setting `algorithm` environment. For program codes, the “`verbatim`” package is required and the command to be used is `\begin{verbatim} ... \end{verbatim}`.

Similarly, for listings, use the `listings` package. `\begin{lstlisting} ... \end{lstlisting}` is used to set environments similar to `verbatim` environment. Refer to the `lstlisting` package documentation for more details.

A fast exponentiation procedure:

```

begin
  for i:=1 to 10 step 1 do
    expt(2,i);
    newline() od
where
proc expt(x,n) ≡
  z:=1;
  do if n=0 then exit fi;
  do if odd(n) then exit fi;
    comment: This is a comment statement;
    n:=n/2; x:=x*x od;
  { n>0 };
  n:=n-1; z:=z*x od;
  print(z).
end

```

Comments will be set flush to the right margin

```

for i:=maxint to 0 do
begin
{ do nothing }
end;
Write( 'Case-insensitive-');
Write( 'Pascal-keywords.' );

```

8 Cross referencing

Environments such as `figure`, `table`, `equation` and `align` can have a label declared via the `\label{#label}` command. For figures and table environments use the `\label{}` command inside or just below the `\caption{}` command. You can then use the `\ref{#label}` command to cross-reference them. As an example, consider the label declared for Figure 1 which is `\label{fig1}`. To cross-reference it, use the command `Figure \ref{fig1}`, for which it comes up as “Figure 1”.

Algorithm 1 Calculate $y = x^n$

Require: $n \geq 0 \vee x \neq 0$ **Ensure:** $y = x^n$

```
1:  $y \leftarrow 1$ 
2: if  $n < 0$  then
3:    $X \leftarrow 1/x$ 
4:    $N \leftarrow -n$ 
5: else
6:    $X \leftarrow x$ 
7:    $N \leftarrow n$ 
8: end if
9: while  $N \neq 0$  do
10:  if  $N$  is even then
11:     $X \leftarrow X \times X$ 
12:     $N \leftarrow N/2$ 
13:  else [ $N$  is odd]
14:     $y \leftarrow y \times X$ 
15:     $N \leftarrow N - 1$ 
16:  end if
17: end while
```

To reference line numbers in an algorithm, consider the label declared for the line number 2 of Algorithm 1 is `\label{algl n2}`. To cross-reference it, use the command `\ref{algl n2}` for which it comes up as line 2 of Algorithm 1.

8.1 Details on reference citations

Standard L^AT_EX permits only numerical citations. To support both numerical and author-year citations this template uses natbib L^AT_EX package. For style guidance please refer to the template user manual.

Here is an example for `\cite{...}`: [?]. Another example for `\citep{...}`: [?]. For author-year citation mode, `\cite{...}` prints Jones et al. (1990) and `\citep{...}` prints (Jones et al., 1990).

All cited bib entries are printed at the end of this article: [?], [?], [?], [?], [?], [?], [?], [?], [?], [?], [?] and [?].

9 Examples for theorem like environments

For theorem like environments, we require amsthm package. There are three types of predefined theorem styles exists—`thmstyleone`, `thmstyletwo` and `thmstylethree`

<code>thmstyleone</code>	Numbered, theorem head in bold font and theorem text in italic style
<code>thmstyletwo</code>	Numbered, theorem head in roman font and theorem text in italic style
<code>thmstylethree</code>	Numbered, theorem head in bold font and theorem text in roman style

For mathematics journals, theorem styles can be included as shown in the following examples:

Theorem 1 (Theorem subhead) *Example theorem text. Example theorem text. Example theorem text. Example theorem text. Example theorem text. Example theorem text. Example theorem text. Example theorem text. Example theorem text. Example theorem text.*

Sample body text. Sample body text. Sample body text. Sample body text. Sample body text. Sample body text. Sample body text. Sample body text.

Proposition 2 *Example proposition text. Example proposition text. Example proposition text. Example proposition text. Example proposition text. Example proposition text. Example proposition text. Example proposition text. Example proposition text.*

Sample body text. Sample body text. Sample body text. Sample body text. Sample body text. Sample body text. Sample body text. Sample body text.

Example 1 Phasellus adipiscing semper elit. Proin fermentum massa ac quam. Sed diam turpis, molestie vitae, placerat a, molestie nec, leo. Maecenas lacinia. Nam ipsum ligula, eleifend at, accumsan nec, suscipit a, ipsum. Morbi blandit ligula feugiat magna. Nunc eleifend consequat lorem.

Sample body text. Sample body text. Sample body text. Sample body text. Sample body text. Sample body text. Sample body text. Sample body text.

Remark 1 Phasellus adipiscing semper elit. Proin fermentum massa ac quam. Sed diam turpis, molestie vitae, placerat a, molestie nec, leo. Maecenas lacinia. Nam ipsum ligula, eleifend at, accumsan nec, suscipit a, ipsum. Morbi blandit ligula feugiat magna. Nunc eleifend consequat lorem.

Sample body text. Sample body text. Sample body text. Sample body text. Sample body text. Sample body text. Sample body text. Sample body text.

Definition 1 (Definition sub head) Example definition text. Example definition text. Example definition text. Example definition text. Example definition text. Example definition text. Example definition text.

Additionally a predefined “proof” environment is available: `\begin{proof} ... \end{proof}`. This prints a “Proof” head in italic font style and the “body text” in roman font style with an open square at the end of each proof environment.

Proof Example for proof text. Example for proof text. Example for proof text. Example for proof text. Example for proof text. Example for proof text. Example for proof text. Example for proof text. Example for proof text. Example for proof text. \square

Sample body text. Sample body text. Sample body text. Sample body text. Sample body text. Sample body text. Sample body text. Sample body text.

Proof of Theorem 1 Example for proof text. Example for proof text. Example for proof text. Example for proof text. Example for proof text. Example for proof text. Example for proof text. Example for proof text. Example for proof text. Example for proof text. \square

For a quote environment, use `\begin{quote}...\end{quote}`

Quoted text example. Aliquam porttitor quam a lacus. Praesent vel arcu ut tortor cursus volutpat. In vitae pede quis diam bibendum placerat. Fusce elementum convallis neque. Sed dolor orci, scelerisque ac, dapibus nec, ultricies ut, mi. Duis nec dui quis leo sagittis commodo.

Sample body text. Sample body text. Sample body text. Sample body text. Sample body text (refer Figure 1). Sample body text. Sample body text. Sample body text (refer Table 3).

10 Methods

Topical subheadings are allowed. Authors must ensure that their Methods section includes adequate experimental and characterization data necessary for others in the field to reproduce their work. Authors are encouraged to include RIIDs where appropriate.

Ethical approval declarations (only required where applicable) Any article reporting experiment/s carried out on (i) live vertebrate (or higher invertebrates), (ii) humans or (iii) human samples must include an unambiguous statement within the methods section that meets the following requirements:

1. Approval: a statement which confirms that all experimental protocols were approved by a named institutional and/or licensing committee. Please identify the approving body in the methods section
2. Accordance: a statement explicitly saying that the methods were carried out in accordance with the relevant guidelines and regulations
3. Informed consent (for experiments involving humans or human tissue samples): include a statement confirming that informed consent was obtained from all participants and/or their legal guardian/s

If your manuscript includes potentially identifying patient/participant information, or if it describes human transplantation research, or if it reports results of a clinical trial then additional information will be required. Please visit (<https://www.nature.com/nature-research/editorial-policies>) for Nature Portfolio journals, (<https://www.springer.com/gp/authors-editors/journal-author/journal-author-helpdesk/publishing-ethics/14214>) for Springer Nature journals, or (<https://www.biomedcentral.com/getpublished/editorial-policies#ethics+and+consent>) for BMC.

11 Discussion

Discussions should be brief and focused. In some disciplines use of Discussion or ‘Conclusion’ is interchangeable. It is not mandatory to use both. Some journals prefer a section ‘Results and Discussion’ followed by a section ‘Conclusion’. Please refer to Journal-level guidance for any specific requirements.

12 Conclusion

Conclusions may be used to restate your hypothesis or research question, restate your major findings, explain the relevance and the added value of your work, highlight any limitations of your study, describe future directions for research and recommendations.

In some disciplines use of Discussion or ‘Conclusion’ is interchangeable. It is not mandatory to use both. Please refer to Journal-level guidance for any specific requirements.

Supplementary information. If your article has accompanying supplementary file/s please state so here.

Authors reporting data from electrophoretic gels and blots should supply the full unprocessed scans for key as part of their Supplementary information. This may be requested by the editorial team/s if it is missing.

Please refer to Journal-level guidance for any specific requirements.

Acknowledgements. Acknowledgements are not compulsory. Where included they should be brief. Grant or contribution numbers may be acknowledged.

Please refer to Journal-level guidance for any specific requirements.

Declarations

Some journals require declarations to be submitted in a standardised format. Please check the Instructions for Authors of the journal to which you are submitting to see if you need to complete this section. If yes, your manuscript must contain the following sections under the heading ‘Declarations’:

- Funding
- Conflict of interest/Competing interests (check journal-specific guidelines for which heading to use)
- Ethics approval and consent to participate

- Consent for publication
- Data availability
- Materials availability
- Code availability
- Author contribution

If any of the sections are not relevant to your manuscript, please include the heading and write ‘Not applicable’ for that section.

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Springer journals and proceedings: <https://www.springer.com/gp/editorial-policies>

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BMC journals: <https://www.biomedcentral.com/getpublished/editorial-policies>

Appendix A Section title of first appendix

An appendix contains supplementary information that is not an essential part of the text itself but which may be helpful in providing a more comprehensive understanding of the research problem or it is information that is too cumbersome to be included in the body of the paper.

References

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