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Application of Using Fuzzy Logic as an Artificial Intelligence Technique in the Screening Criteria of the EOR Technologies

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Abstract

Screening criteria stage for the EOR applications is useful for many candidate reservoirs before expensive reservoir descriptions and economic evaluations are done. This paper presents the application of using fuzzy logic as an artificial intelligence technique in the screening criteria of the EOR technologies. EOR screening criteria have been developed based on field results. The database of 347 successful EOR projects worldwide is used to carry out statistical analysis which resulted in determination of four critical values (minimum, maximum, r1, r2) for each fluid and rock property.

The determined values identify the suitable range of the rock and fluid properties and the screening criteria for each EOR method. In addition, these ranges can rate the properties of any field under study from 0 to 1 (through fuzzy logic membership functions). The minimum and the maximum values represent the successful boundaries of the fluid or rock properties for the studied EOR method; while r1 and r2 values represent the ranges with maximum rating (best conditions) for the fluid or the rock properties.

Not all fields are amenable to EOR processes. Effective screening practices must be employed to identify suitable candidates. In the developed screening tool, there are 15 inputs representing EOR screening criteria of the reservoir rock and fluid properties including: API, viscosity, depth, rock permeability, oil saturation, reservoir temperature, salinity, net thickness, Permeability variation coefficient (representing heterogeneity index), formation type, minimum miscibility pressure, initial reservoir pressure, current reservoir pressure, fracture pressure and option showing if the reservoir is dip or not.

The developed screening tool is characterized by an easily and friendly interface with additional options comparing to the other existing software or expert systems. The proposed tool can be used to support the decision making during the critical technology selection phase. Such study is an original contribution to achieve successful EOR applications.

Introduction

Planning of Enhanced Oil Recovery methods is a complex problem that requires an integrated approach for its solution. Although EOR is specific for specific reservoir, but EOR screening could be used as a guide or a first step in the implementation of a new EOR project. Prospects that pass this screening are candidates for further engineering and economic study. Most of early studies in the EOR selection were to establish the technical screening criteria of each EOR method (Taber and Martin, 1983; Goodlett *et al.*, 1986; Taber *et al.*, 1996a; Taber *et al.*, 1996b). Based on laboratory experiments and field experiences, the applicable ranges of the reservoir rock and fluid properties were presented in these studies.

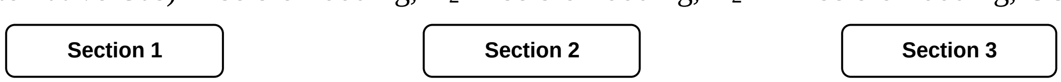
The large number of EOR projects (which have been utilized in many oil fields around the world) has led to an increased understanding of the selection and applicability of certain oil recovery methods, and that has ensured degree of technical and economical success. A.Aladasani proposed a new EOR selection criterion after a thorough analysis of EOR projects reported from 1998 through 2010. This criterion was based on dataset distribution, by detecting the ranges within which the majority of EOR projects fall. That will lead to more accurate results than using the average values of the reservoir and oil properties as a guide in EOR screening. The work in this paper used the new methodology of Aladasani to generate the fuzzy logic parameters required for the new developed screening tool.

Model Structure

The developed model used Fuzzy Logic (Fuzzy Inference System) as an Artificial Intelligence Technique in the EOR screening. The Fuzzy Inference System (FIS) of the developed model consists of three major sections as shown in Figure 1 (Input Section, Rule Editor Section, and Output Section).

The first section is the inputs section, and it includes 15 inputs. In the developed screening tool, there are 15 inputs representing EOR screening criteria of the reservoir rock and fluid properties. These inputs are: API, viscosity, depth, rock permeability, oil saturation, reservoir temperature, salinity, net thickness, Permeability variation coefficient (representing heterogeneity index), formation type, minimum miscibility pressure, initial reservoir pressure, current reservoir pressure, fracture pressure and an option showing if the reservoir is dip or not. Each input of these inputs is represented by membership function which reflects its effect on each EOR method. Each input could be evaluated through its membership function. A membership function associated with a given fuzzy set maps an input value to its appropriate membership value. This section in fuzzy inference system allows the user to rate each input and output through the membership functions and it is the main idea in this current work. Through these membership functions, each input could be rated from 0 to 1 based on if the entered value lies on the feet of the membership function or it lies on its shoulder. There are different types of membership functions each type is characterized by its shape and its parameters.

The second section is the Rule Editor section. It controls the FIS by rules link between the inputs represented in (rock and fluid properties), and the outputs represented in EOR methods. There are 24 rules in this FIS. These rules form a condition through a relation between the different inputs which affect the outputs. Graphical User Interface (GUI) is constructed by use of “matlab 2008” to facilitate the process of entering inputs and reading outputs, to make the developed tool easier and friendly user. The third section is the output section, and it includes 14 outputs (EOR methods). The model outputs are represented in 14 EOR methods as follows: CO_2 miscible flooding, hydrocarbon miscible flooding, WAG (Water Alternative Gas) miscible flooding, N_2 miscible flooding, N_2 immiscible flooding, CO_2



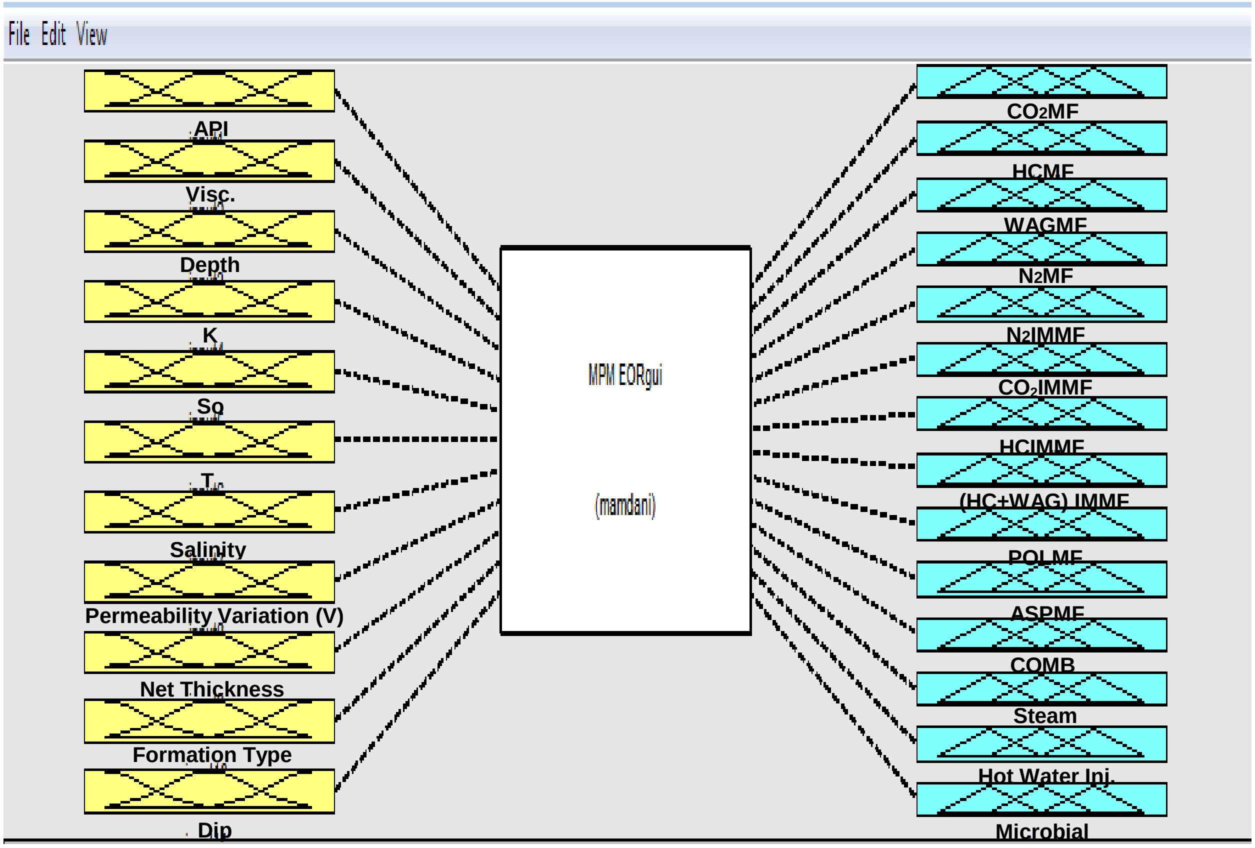


Figure 1-Fuzzy inference system editor

immiscible flooding, hydrocarbon immiscible flooding, immiscible flooding of hydrocarbon in addition to WAG, polymer flooding, ASP (Alkaline-Surfactant Polymer) flooding, in-situ combustion, steam injection, hot water injection, and microbial. Because of the sensitivity of each EOR method toward certain parameters, the weights for the inputs in the evaluation are not the same. Those critical parameters for each EOR method have a greater weight than other parameters. The process of putting weight for each input is implemented through the rule editor section.

Data Preparation and Analyses

This section shows the approach and the methodology used to generate the fuzzy logic parameters of each EOR method in the developed screening tool. An EOR database comprising of 347 projects is built to carry out statistical analysis. The data related to each EOR method is cleaned to remove inconsistent data or unsuccessful projects. Then, the data of the successful projects related to each EOR method is used to generate a new EOR screening methodology. That will be represented in the rules of the new EOR screening fuzzy model.

A dataset was created by collecting the data of EOR projects from the "2010, 2012, and 2014 Worldwide *Oil & Gas Journal* EOR Survey". The total number of EOR projects in the dataset was 347 projects subdivided into seven categories, namely, steam, in-situ combustion, CO_2 miscible, CO_2 immiscible, hydrocarbon miscible, chemical methods, and others. The next step was separating the data related to each EOR method to make the analysis related to each rock/fluid property for each EOR method.

EOR screening parameters in the developed screening tool are very sensitive to the results of these analyses, so checking the quality of the data is very important to avoid misleading results. The problems encountered in the EOR survey data are: missing data, inconsistent data, data related to unsuccessful and discouraging projects, and finally data related to too early to tell (TETT) projects. TETT projects refer to new projects that can't be evaluated at the current time. So data cleaning is essential to remove the effect of these invalid data.

The next step of analysis is representing the distribution of the reservoir and fluid properties for each EOR method. Then the minimum and the maximum values for each property against each EOR method are detected. Also the property range (through which the maximum number of EOR projects had been applied (r1&r2)) for each EOR method is detected. Finally the results of the current work are compared to Aladasani work (Aladasani, 2010) and Taber work (Taber, 1997) to be validated. A.Aladasani summarized his work results on only r1 and r2 values. Taber summarized his work results with only three values: minimum, maximum and one average value. Taber work was updated (by A.Aladasani) in 2010 to include EOR survey reports submitted from 1998 through 2010, and to include also the new categories and sub categories of EOR methods.

Analyses of Other EOR Methods

Fuzzy Logic parameters for EOR methods with either no data or not sufficient data for analyses are extracted from literature ((Taber, 1997) & (Aladasani, 2010)). Table 1 showes the summary of fuzzy logic parameters (for all EOR methods) used in the new developed screening tool. The number of projects in prackets (red coloured) is the number of projects used in the analyses of the current work, while the number without prackets is the number of projects used in literature (Updated Taber Screening Criteria by Aladasani). The same for the values of the parameters, the values between prackets represnt the values of the current work, while that without prackets represent the values from literature (Taber and Updated Taber Screening Criteria).

Model Verification and Validation

To test the reliability and consistency of the new developed screening tool, the results of the tool is compared with the results of commercial EOR software (EORgui). The properties of some of the Egyptian Oil Reservoirs (which is summarized in Table 2) are used as inputs for both of them. The results of the screening for both of them are summarized in Table 3. The differences noticed in the results of the two tools are mainly due to updating the screening criteria of EOR methods. EORgui uses the screening criteria of Taber, Martin, and Seright; while the new tool uses the updated screening criteria of Taber represented in Table 1. For Example, Steam Injection is seen to be applicable in reservoirs X2 and X3 by the new developed tool, while it is not applicable by EORgui. That is because EORgui excluded Steam Injection only beacause the reservoir permeability is less than 200 md. The new developed tool showed that Steam Injection is applicable because many successful EOR projects are implemented with reservoir permeability below this limit, and hence the screening criteria is updated to include range of the successful EOR projects. The same for In-Situ Combustion and Polymer results for Reservoir X3. After updating the permeability range for In-Situ Combustion and the oil saturation range for Polymer, both of them will be applicable.The main difference in the screening of the Western Desert resrvoirs (group 2) is that EORgui didn’t take into consideration MMP, so it showed that miscible injection methods are applicable for all of the Western Desert reservoirs (group 2) . The new developed tool showed that miscible injection methods are not applicable for most of the Western Desert reservoirs because the miscibility conditions are not achieved. The new developed tool showed that Polymer is applicable for all Western Desert reservoirs in Table 2, ASP is applicable for reservoir X13, and In-Situ Combustion is

Table 1- Summary of fuzzy logic parameters used in the new developed screening tool

S N	EOR Method	# Projects	Gravity (^{0}API)	Viscosity (cp)	Oil Satura-tion (% PV)	Formation Type	Permeabil-ity (md)	Net Thick-ness (ft)	Depth (ft)	Temperture (^{0}F)	Salinity (PPM)
Miscible Gas Injection											
1	CO_2	153 **(135)**	22-45 **(31-42)**	0-35 **(0.4-1.4)**	15-89 **(38-55)**	Sand-stone or Car-bonate	1.5-4500 **(2-70)**	[Wide Range]	1500-13365 **(4500-6500)**	82-257 **(100-150)**	……
2	Hydrocarbon	67 **(37)**	23-57 **(38-44)**	0.04-18000 **(0.3-0.5)**	30-98 **(70-93)**	Sand-stone or Car-bonate	0.1-5000 **(20-300)**	[Thin unless dipping]	4040[4000] -15900 **(4250-6750)**	85-329 **(185-200)**	……
3	WAG	3	33-39 Avg. 35.6	0.3-0.9 Avg. 0.6	……..	Sand-stone	130-1000 Avg. 1043.3	[NC*]	7545-8887 Avg. 8216.8	194-253 Avg. 229.4	……
4	Nitrogen	3	38[35]-54 Avg. 47.6	0-0.4 **(0.07-0.2)**	0.76[0.4]-0.8 Avg. 0.78	Sand-stone or Car-bonate	0.2-35 Avg. 15.0	[Thin unless dipping]	10000[6000]-18500 Avg. 14633.3	190-325 Avg. 266.6	……
Immiscible Gas Injection											
5	Nitrogen	8	16-54 Avg. 34.6	0-18000 Avg. 2256.8	47-98.5 Avg. 71	Sand-stone	3-8000 Avg. 1041.7	……	1700-18500 Avg. 7914.2	82-325 Avg. 173.1	……
6	CO_2	16 **(16)**	11-35 **(23-35)**	0.6-592 **(6-18)**	30-78 **(30-60)**	Sand-stone or Car-bonate	30-1000 **(60-300)**	……	1150-8500 **(2350-5150)**	82-198 **(120-170)**	……
7	Hydrocarbon	2	22-48 Avg. 35	0.25-4 Avg. 2.1	75-83 Avg. 79	Sand-stone	40-1000 Avg. 520	……	6000-7000 Avg. 6500	170-180 Avg. 175	……
8	Hydrocarbon + WAG	14	9.3-41 Avg. 31	0.17-16000 Avg. 3948.2	Avg. 88	Sand-stone or Car-bonate	100-6600 Avg. 2392	……	2650 -9199 Avg. 7218.71	131-267 Avg. 198.7	……
Chemical Methods											
9	Polymer	53	[13-26.5] MF(S)**	[123.2-4000] MF(Z)***	[34-64] MF(S)	Sand-stone Preferred	[1.8-834.1] MF (S)	[NC]	[4221.9-9460] MF (Z)	[167-237.2] MF (Z)	[100000-200000] MF (Z)
10	Alkaline Sur-factant Poly-mer (ASP)	13	[20-35] MF(S)	[875.8-6500] MF(Z)	[35-74] MF(S)	Sand-stone Preferred	[10-450] MF (S)	[NC]	[2984.5-9000] MF (Z)	[121.6-200] MF (Z)	[70000-200000] MF (Z)
Thermal/Mechanical Methods											
12	Combustion	27 **(13)**	10-38 **(19-33)**	1.44-2770 **(1.44-2)**	50-94 **(50-55)**	Sand-stone or Car-bonate [Prefera-bly Car-bonate]	10 -15000 **(10-650)**	**[>10]** MF(S) **[10-15]**	400-11300 **(400-8450)**	64.4-230 **(200-215)**	……
13	Steam	274 **(126)**	8-33 **(10-15)**	3-5000000 **(200-10000)**	35-90 **(50-85)**	Sand-stone	1-15000 **(1000-3000)**	**[>20]** MF(S) **[20-30]**	200-9000 **(1000-1800)**	10-350 **(80-130)**	……
14	Hot Water	10	12-25 Avg. 18.6	170-8000 Avg. 2002	15-85 Avg. 58.5	Sand-stone	900-6000 Avg. 3346	-	500-2950 Avg. 1942	75-135 Avg. 98.5	……
Microbial											
16	Microbial	4	12-33 Avg. 26.6	1.7-8900 Avg. 2977.5	55-65 Avg. 60	Sand-stone	180-200 Avg. 190	-	1572-3464 Avg. 2445.3	86-90 Avg. 88	[70000-200000] MF (Z)

NC: Not Critical** ****MF (S): S Shape Membership Function.** ** MF (Z): Z Shape Membership Function**

Table 2- Rock and fluid properties for some of the Egyptian Oil Reservoirs

Group	Reservoir	API	Viscosity	Depth	Permeability, K	Oil sat.	Res. Temp	Salinity	Permeability Variation, V	Net Thickness, h	Formation Type	MMP	Initial Res. P.	Current Res. P.	DIP
			CP	ft	md	%	°F	PPM	fraction	ft		Psia	Psia	Psia	
Group 1	X1	16	30	3937	5635	69	164	200000	0.63	151	Sandstone	2053	1849	1550	yes
	X2	19	24.8	3241	193	61	150	220000	0.65	134.5	Sandstone	1885	1529	1220	yes
	X3	21.4	17	2920	27	67	148	100000	0.5	134.5	Sandstone	1860	1314	700	yes
	X4	19.5	16	2800	60	69	131	160000	0.84	98.4	Carbonate	1645	1300	870	yes
	X5	21.9	12.2	2582	84	65	124	160000	0.8	46	Carbonate	1548	1264	650	yes
	X6	21	13	2582	189	64	128	160000	0.85	46	Carbonate	1604	1220	550	yes
Group 2	X7	37.3	0.48	5597	237	52	163	No Aquifer	0.5	18	Sandstone	2042	2325	1750	yes
	X8	37	0.43	5938	35	48	172	98000	0.6	21.3	Carbonate	2150	2444	2112	yes
	X9	36	1.4	6050	307	62	180	80000	0.8	24.8	Sandstone	2234	2700	1400	No
	X10	37	3.7	5490	107	74	178	80000	0.74	18	Sandstone	2220	2600	1430	No
	X11	40.5	1.6	6530	88	64	190	80000	0.78	17	Sandstone	2364	2650	1500	No
	X12	42.7	0.8	6880	5	67	187	80000	0.8	14	Sandstone	2330	2800	1600	No
	X13	41	0.5	7700	18	53	198	80000	0.69	20	Sandstone	3115	2720	1550	No
	X14	39.6	1.6	8850	88	64	223	80000	0.75	11	Sandstone	3770	2840	1520	No
	X15	40	1.6	6750	7	64	186	80000	0.73	26	Sandstone	2320	2630	1500	No

applicable for reservoir X15; while EORgui excluded these EOR methods from the results of those reservoirs. That is due to updating the screening criteria for these methods as mentioned above. Although EORgui showed that In-Situ Combustion is applicable in both of X7 and X9 reservoirs, the new developed tool showed that In-Situ Combustion is not applicable in both of them, because viscosity is out of range (based on the updated screening criteria).

Application of the New Developed Screening Tool on Some of the Egyptian Oil Reservoirs

To check the applicability of the new developed screening tool, some of the Egyptian oil reservoirs whose properties summarized in Table 2 are considered as case studies. The reservoirs investigated here are assumed to be produced to their economic limit and are potential candidate for EOR processes. The results of the screening for the reservoirs under study are summarized in Table3. Based on the data avilable and the screening results, some notes concluded will be illustrated:

Steam injection method is not seen to be applied in Western Desert resrvoirs (group 2), because the viscosity is out of range in some fields, and thickness in addition to viscousity and API are out of range in other fields. However, Steam injection could be applied in some of the Eastern Desert reservoirs (group 1), and it is very good candidate in other reservoirs.

In-Situ Combustion is the most suitable EOR method for Eastern Desert reservoirs (group 1). It is not applicable in some of the Western Desert resrvoirs (group 2) because of the reservoir thickness, however there is a possibility of applying this technique in reservoirs X11, X14, X15. In-Situ Combustion is the most suitable EOR method for reservoir X10 in group 2.

Table 3- Summary of the screening results

Reservoir	EORgui	New Developed Screening Tool
X1	IMM (83%), ST (80%), COMB (67%).	COMB (83.81%), ST (80.85%)
X2	IMM (83%), COMB (83%).	COMB (83.99%), CO_2IMMF (81.93%), ST (80.82%), N_2IMMF (80.5%).
X3	IMM (83%), SP/ASP (73%).	COMB (83.98%), POL (83.75%), ASP (83.23%), ST (80.74%), N_2IMMF (80.5%)
X4	IMM (83%), COMB (58%).	COMB (83.75%), CO_2IMMF (80.5%).
X5	IMM (83%, COMB (58%).	COMB (83.99%), CO_2IMMF (81.68%).
X6	IMM (83%), COMB (58%).	COMB (83.75%), CO_2IMMF (80.65%).
X7	SP/ASP (91%), IMM (83%), COMB (75%), HCMF (70%), CO_2MF (67%).	POL (83.85%), ASP (82.6%), N_2IMMF (80.5%).
X8	IMM (83%), HCMF (70%), CO_2MF (67%).	CO_2MF (85.27%), HCMF (84.42%).
X9	SP/ASP (91%), COMB (75%), CO_2MF (67%), IMM (67%), HCMF (50%).	POL (83.71%), ASP (81%), N_2IMMF (80.5%).
X10	IMM (100%), SP/ASP (100%), COMB (83%), CO_2MF (67%).	COMB (83.75%), POL (83.72%), ASP (81%), N_2IMMF (80.5%).
X11	SP/ASP (91%), IMM (83%), COMB (75%), CO_2MF (67%), HCMF (60%).	POL (83.47%), ASP (80.56%), N_2IMMF (80.5%), COMB (68.5%).
X12	IMM (83%), CO_2MF (78%), HCMF (70%).	POL (83.6%), N_2IMMF (80.5%).
X13	IMM (83%), CO_2MF (67%), HCMF (60%).	POL (83%), ASP (80.5%), N_2IMMF (80.5%),
X14	IMM (83%), COMB (75%), CO_2MF (67%), HCMF (60%).	POL (80.79%), N_2IMMF (80.5%), COMB (65.5%).
X15	CO_2MF (67%), IMM (67%), HCMF (50%).	POL (83.6%), N_2IMMF (80.5%), COMB (68.5%).

IMM: Immiscible EOR method ST: Steam Injection COMB: In-Situ Combustion CO_2IMMF: CO2 Immiscible Flooding
N_2IMMF: N_2 Immiscible Flooding SP: Surfactant-Polymer ASP: Alkaline-Surfactant-Polymer POL: Polymer Flooding
HCMF: Hydrocarbon Miscible Flooding CO_2MF: CO_2 Miscible Flooding

Chemical EOR methods are applicable in most of the Western Desert reservoirs (group 2), but they have limited applications in eastern desert reservoirs (group 1) due to high formation water salinity, and heterogenous carbonate formations.

Egyptian oil reservoirs are good candidate for immiscible gas injection. Nitrogen Immiscible Injection (N_2IMMF) is applicable in most of the western desert reservoirs and could be applied in some of the eastern desert reservoirs. Carbon Dioxide Immiscible Injection (CO_2IMMF) is applicable for most of eastern desert reservoirs, but there is a restriction on its source.

Miscible methods are not seen to be applied in most of the Egyptian oil reservoirs, because the MMP is greater than the current reservoir pressure (there is a great difference), and most of these reservoirs are depleted. Both of Miscible Carbon Dioxide injection (CO_2MF) and Miscible Hydrocarbon Injection (HCMF) is applicable for reservoir X8 in Western Desert (group 2).

The results of the studied fields, verifies that the developed software is reliable and consistent. It is confirmed also through a human expert who obtained results by a sensitivity analysis of EOR screening criteria.

Conclusions

The new developed tool presented in this paper executes screening criteria of fifteen EOR methods (through artificial fuzzy logic) based on the new screening methodology generated from statistical analysis of the EOR database. The screening results for some of the Egyptian oil reservoirs showed that In-Situ Combustion is the most suitable EOR method followed by Immiscible Gas Injection and Chemical EOR methods.

Nomenclature

AI = Artificial Intelliegence.
ASP = Alkaline Surfactant Polymer.
CO_2MF = CO_2 Miscible Flooding.
CO_2IMMF = CO_2 Immiscible Flooding.
COMB = In-Situ Combustion.
EOR = Enhanced Oil Recovery.
FIS = Fuzzy Inference System.
GUI = Graphical User Interface.
HCMF = Hydrocarbon Miscible Flooding.
IMM = Immiscible EOR Method.
MF = Membership Function.
MF (S) = S Shape Membership Function.
MF (Z) = Z Shape Memebership Function.
MMP = Minimum Miscibility Pressure.
N_2IMMF = N_2 Immiscible Flooding.
POL = Polymer Flooding.
R1 = the lower boundary of the range through which the maximum number of successful EOR projects had been applied.
R2 = the upper boundary of the range through which the maximum number of successful EOR projects had been applied.
SP = Surfactant-Polymer.
ST = Steam Injection.
TETT = To Early To Tell.
WAG = Water Alternative Gas.

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