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RESEARCH PAPER

Sensitivity Analysis and Prediction of Gas Reservoirs Performance Supported by an Aquifer Based using Box-Behnken Design and Simulation Studies

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Abstract

Prediction of gas reservoir performance in some industrial cases requires costly and time-consuming simulation runs and a strong CPU must be involved in the simulation procedure. Many reservoir parameters conform to a strong aquifer behavior on gas reservoir performance. Effects of parameters, including reservoir permeability, aquifer permeability, initial reservoir pressure, brine water salinity, gas zone thickness, water zone thickness, temperature, tubing diameter, reservoir inclination, the effective intruding angle of the aquifer, and porosity were investigated using Tornado chart, and seven parameters were filtered. Response functions of aquifer productivity index, gas recovery factor, initial maximum gas production, water sweep efficiency, gas production rate, water breakthrough time, and water production were defined statistically, using Eclipse E100 and Box-Behnken design (BBD). According to the formulae generated by the BBD based on simulation runs, reservoir permeability, aquifer permeability, well-head pressure, and gas zone thickness are the most influencing parameters on the gas reservoir performance supported by the strong aquifer. The aquifer was found to be important especially due to its productivity index and sweep water efficiency. Validation of results given by the BBD through simulation runs showed response functions of aquifer productivity index, sweep water efficiency, maximum gas production, and recovery factor are of deviation percentages in the ranges of 10.61%, 6.302%, 3.958%, and 2.04%, respectively.

Keywords:
Aquifer,
Box-Behnken,
Gas Reservoir,
Gas Production
Permeability

Introduction

Although gas reservoirs are commonly suffered from fewer problems, there are still troubling issues related to gas production. The creation of condensate liquid, condensate blockage of the wellbore, and water aquifer are some of the frequent predicaments in the production from a gas reservoir [1]. The connection of the strong aquifer to the oil reservoirs increases the oil production recovery factor due to the supplement of reservoir production energy and pressure. In contrast to the oil reservoirs, the existence of aquifer makes some troubles in the gas production from gas reservoirs. The trapping of gas bubbles in the water phase, which was induced due to water flooding or aquifer encroachment, is the main reason for production reduction in gas reservoirs attached to the aquifer [2]. Based on the level of the pressure maintenance, aquifers could be divided into three categories of a) active water drive, b) partial water drive, and c) limited water drive. The degree of pressure maintenance decreases the classification, respectively [3].

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It is essential to produce carefully with a high level of monitoring in such sensitive reservoirs. The accurate simulation of these types of gas reservoir seems critical. Simulation costs, CPU requirements, and time-consuming runs are some common problems in the simulation of a huge reservoir or the heterogenic ones [4]. In the rest of the manuscript, after reviewing issues related to gas reservoirs connected to an aquifer, the Box-Behnken design (BBD) as a deployed method for the prediction of the gas reservoir performance will be discussed.

Li et al. [5] proposed a new methodology for the determination of the status of an aquifer supporting a gas reservoir. Their proposed methodology was based on the diagnostic curves determined by the flow rate and the pressure data of the gas production from a single well. The status of the aquifer was divided into sections of no aquifer influx period, early aquifer influx period, and middle-late aquifer influx period. Their new approach was validated according to the production data of a gas well in China.

The production from a gas reservoir connected to the aquifer leads to the invasion of the aquifer into the virgin gas zone. Water breakthrough in the production well increases the liquid phase near the wellbore region that results in the skin zone. Damage to the well, which is due to the liquid phase induced by the bottom water zone, has been surveyed via a mathematical model. Huang et al.[6] used the Forcheimer quadratic equation in conjugation with eight primary assumptions to propose a new model describing the damage to the well due to the aquifer water invasion. Any changes in the gas-water ratio strongly influence the gas open-flow capability, according to their research. The increment of water/gas ratio from 0.5 to 15 $m^3/10^4m^3$ resulted in a reduction of the gas well open-flow capability to 59% of the initial one. A logarithmic relationship between the gas well production capability and the water-gas ratio drop was reported.

Hashem et al. [7] have surveyed the effect of aquifer size on the performance of partial water drive gas reservoirs. They proposed a model to define the sensitivity of the gas reservoir performance, regarding the aquifer size, based on the gas material balance equation. The reservoir permeability is assumed to be 300 mD in all of the cases, and the gas-water contact is considered to be horizontal. They concluded that the impact of the aquifer on gas reservoir performance is negligible, where the ratio of aquifer radius to the radius of the reservoir is less than 0.2.

Geffen et al.[8] investigated the efficiency of gas displacement from porous media using liquid flooding. They surveyed the effects of water advance rate, static pressure, pressure, and temperature on gas displacement diving by the water force. They concluded that the gas saturation varies from 15 to 50 % for different sands at the end of the flooding.

Average gas reservoir pressures are used in the van Everdingen-Hurst unsteady state equation to compute water influx, and it may lead to a deviation from the real state when average input pressure is incorrect or even inaccurate. Saleh [9] employed a mathematical model that combines the material balance equation for a partial water-drive gas reservoir and the van Everdingen-Hurst unsteady state equation to investigate the error. Two cases of A and B are representations of using average reservoir pressures in the van Everdingen-Hurst unsteady state equation and method of using pressures at the original gas-water contact, respectively. The difference between the two cases considered to be the error. According to their results, the error, which is caused by the incorrect implementation of the average reservoir pressures in the van Everdingen-Hurst unsteady state, is significant and increases by increasing the aquifer size and permeability reduction.

Armenta et al. [10] attempted to solve the problem of the liquid loading in the gas wells caused by water coning, via a dual-completed well with a down-hole water sink (DWS) drainage and injection installation. The results of Eclipse simulation software showed a considerable advantage of dual completion over conventional wells in the low-pressure tight reservoirs, before killing the production well.

Li et al. [11]determined the aquifer activity level by using a new methodology. To define the status of the aquifer, a new parameter called "B," relative pressure, and degree of reserve recovery with different values have been introduced into calculations producing charts. According to the charts, they classified the water drive gas reservoirs into three types of active, moderately active, and inactive influx. It is possible to define the status of the aquifer regarding related characteristics by using the proposed charts.

Wang et al. [12] tried to use geological and production data to investigate the intensity of water influx based on water activity and reservoir types. According to their results, the H_2S production from each gas well increases as the pressure declines.

A gas-condensate sandstone reservoir in Vietnam has been surveyed as a case study of reservoir performance regarding the bottom-water drive mechanism. All the parameters that influence the gas recovery factor, including gas production rate, completion length, aquifer size, horizontal reservoir permeability, and permeability anisotropy, have been investigated. According to their model, aquifer size has no impact on water breakthrough time in the gas condensate reservoir, but strongly influences the final recovery factor and the total water production [13]. In another case study, aquifers corresponded to Pliocene reservoirs of the North Adriatic were investigated by a developed integrating geological/geophysical interpretations, petrophysical data, and pressure/production ones. It was found that in the poorly consolidated reservoirs, the decrement of permeability with increasing net confining pressure comes to the reduction in the water permeability in the water-invaded zone [14].

Yu et al. [15] implemented three calculation methods of the Blasingame, the flowing material balance, and the Material balance equation to evaluate the aquifer influx for gas reservoirs with aquifer support. According to their results, the normalized data of the gas well, influenced by aquifers, can be subcategorized into three influx periods: no-aquifer, early-aquifer, and middle-late-aquifer influx period [15].

Kim et al. [16] proposed the Ensemble Kalman filter with covariance localization to characterize aquifer factors. They applied the covariance localization to take account of the adequate relationship between well production data and the grid properties. Hence, they could define permeability distribution and aquifer sizes by using production data.

Yue [17] performed a sensitivity analysis on a simplified model in Eclipse software regarding factors of reservoir pressure gradient, permeability, reservoir width, aquifer size, reservoir thickness, tubing size, tubing head pressure, and reservoir dip. The gas recovery factor, the water breakthrough time, the sweep efficiency, and the gas production rate parameters were all obtained through equations, derived by the BBD. Proposed equations that were functions of mentioned factors were validated by the Eclipse software at some random data points [17]. Authors think that other parameters, including aquifer permeability, and initial reservoir pressure, could strongly affect the performance of a gas reservoir attached to the aquifer. Fifty-seven simulation runs were performed using the Eclipse E100 to investigate the mentioned issue. Obtained results were used to find the sensitivity of the gas reservoir performance regarding each of the input factors. BBD was used to find sensitivity analysis of affecting factors. In the rest of the manuscript, the Eclipse model, input parameters, Tornado charts, response functions, final results, and model validation will be discussed.

Model Description

To investigate the sensitivity analysis and prediction of the gas reservoir performance under the influence of the strong aquifer, the Eclipse E100 software, and the BBD was implemented. The Eclipse software is used for simulation of the gas reservoirs under the desired circumstances defined by the BBD at three levels over seven factors. To do this, the aquifer productivity index, gas recovery factor, initial maximum gas production, and sweep efficiency of water were surveyed as the response functions. All of the independent parameters of the well radius, the thickness of aquifer zone, the effective inclination of water zone, permeability of water zone, reservoir inclination, production tube diameter, temperature, wellhead pressure, salinity, the thickness of gas zone, initial reservoir pressure, porosity, and reservoir permeability were all converted to a number between -1 to 1 using conversion functions. The effects of all the mentioned parameters were investigated through the tornado chart. The advantages of the mentioned conversion functions are ease of calculation and using the dimensionless form of the parameters.

Input data in the model

To construct the desired model, an aquifer that is overlaid by a gas zone was defined in a cubic medium with dimensions of 31×31×10 ft. The inclination of the model was 5-degree respect to the vertical direction, and the production well has been located at the center of the model. The reservoir rock and fluid properties are shown in Table 1.

Table 1. Reservoir rock and fluid properties used in the Eclipse model

Reservoir temperature (°F)	**220**
Porosity	0.11
Rock compressibility psi^{-1})	1.2×10^{-6}
Water compressibility (psi^{-1})	3×10^{-6}
Water density (Ib/ft^3)	62.4
The specific gravity of the gas	0.7

The gas viscosity was estimated using Lee and Gonzales correlation [18]. The deviation factor of gas was also correlated using Dranchuk and Abou Ghasem correlation [19]. Relative permeabilities of gas and water phases are shown in Table 2 which are selected from the experimental data of Chierici et al. [20].

Table 2. Relative permeability of gas and water used in Eclipse software

Sg	**K_{rg}**	**K_{rw}**	**Pc (atm)**
0.00	0.000	1.000	0.00
0.10	0.000	0.875	0.07
0.20	0.000	0.750	0.15
0.30	0.020	0.625	0.23
0.40	0.085	0.500	0.30
0.50	0.200	0.375	0.37
0.60	0.370	0.225	0.45
0.70	0.650	0.125	0.53
0.80	1.000	0.000	0.60

Tornado Chart

Many parameters are involved in the performance of the gas reservoirs, and some of them have a negligible effect on the gas reservoir performance. This could be detected using the tornado chart given by the design of experiment (DOE), based on the Eclipse results. The tornado chart, which was shown in Fig. 1, is a representation of a basis to select the more influencing parameters on a response surface. In another word, when the number of possible variables is large enough to make the response surface methodology (RSM) analysis difficult, DOE is implemented to reduce the number of the enormous variables to the ones that are mainly influencing the response function. The number of initial parameters, including brine water salinity, is thirteen. By elimination of less affecting parameters, the number of parameters is reduced to seven. The DOE defines the influencing degree of parameters by comparing the difference between the highest and the lowest values of each of them [21]. Thirteen affecting parameters of well-radius, the thickness of aquifer layer, the effective angle of aquifer layer, aquifer layer permeability, reservoir inclination, production tube diameter, temperature, wellhead pressure, brine water salinity, the thickness of gas column, initial reservoir pressure, porosity, and reservoir permeability were investigated in high, medium, and low levels to find their possible effect, while other parameters remain unchanged (Table 3).

Table 3. Three levels of under debated parameters used to find Tornado chart

Parameter/level	-1	0	1
Reservoir permeability (MD)	1	10	100
Aquifer permeability (MD)	1	10	100
Wellhead pressure (psi)	700	1000	1300
Temperature (°C)	60	100	140
Aquifer zone thickness (ft)	400	600	800
Effective aquifer intruding angle	120	240	360
Wellbore radius (ft)	2.2	3.5	4.8
The salinity of brine water (ppm)	100000	200000	300000
Reservoir inclination angle (degree)	0	45	90
Porosity (percent)	5	12.5	20
The thickness of the gas zone (ft)	200	300	400
Reservoir initial pressure (psi)	4300	4800	5300
Tubing diameter (in)	4	5.5	7

Reservoir permeability, initial reservoir pressure, gas column thickness, wellhead pressure, production tube diameter, aquifer layer permeability, and effective angle of the aquifer layer are conforming to the gas reservoir performance, according to the tornado chart. Removed parameters such as wellbore radius influence the simulation results. However, the difference between the highest and the lowest levels of the parameters indicates that it has a negligible effect concerning the other factors.

The primary purpose of using the BBD is the reduction of simulation time duration and lowering its related costs. Using numerous parameters in the simulation without considering their affecting level misleads the primary goal. Therefore, six parameters of well-radius, the thickness of the aquifer layer, temperature, salinity, reservoir dip angle, and porosity, which have a weaker impact on the gas reservoir performance, were removed from the input parameters in the BBD. The procedure for the selection of appropriate parameters was based on the tornado chart, which is shown in Fig. 1.

Table 4. Parameters involved in the prediction of gas reservoir performance with corresponding conversion functions

Factor	Parameter	Coded parameter	Level			Conversion function
Reservoir permeability	K_{res}(MD)	X_1	1	10	100	Log(K_{res})-1
Initial reservoir pressure	P_i(psi)	X_2	4300	4800	5300	$\frac{P_i - 4800}{500}$
Gas column thickness	H_{gas}(ft)	X_3	200	300	400	$\frac{H_{gas} - 300}{100}$
Wellhead pressure	P_{wh}(psi)	X_4	700	1000	1300	$\frac{P_{wh} - 1000}{300}$
Production tube diameter	D_t(in)	X_5	4	5.5	7	$\frac{D_t - 5.5}{1.5}$
Aquifer zone permeability	K_{aq}(MD)	X_6	1	10	100	Log(K_{res})-1
Effective aquifer intruding angle	IA(degree)	X_7	120	240	360	$\frac{IA - 240}{120}$

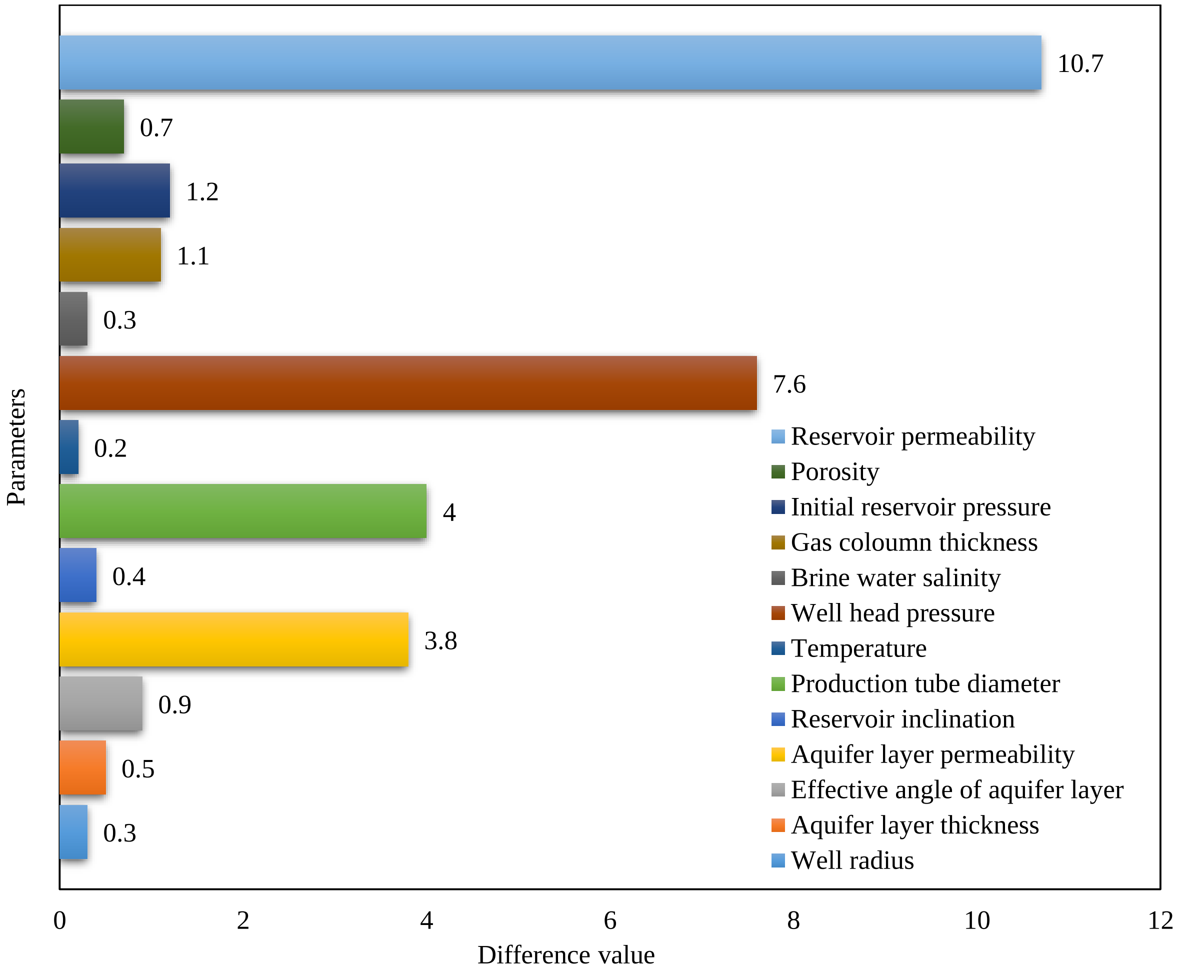

Fig. 1. Tornado chart: influencing level of parameters

In the cases where the wellbore radius was 0.2 and 1 ft, the difference between the gas recovery factors was 0.3 %. Just 0.5% deviation obtained via simulation runs where the thickness of the aquifer column was identical and it was five folds of the gas zone thickness. The difference obtained by the simulation in two cases of 0 and 90-degree inclination of the reservoir was 0.4%. By changing the temperature from 150 to 70 C, the difference between the gas recoveries obtained to be 0.2%. By changing the salinity from 150000 ppm to 300000 ppm, the recovery factor changed by 0.3 %. The difference between the gas recoveries was only 0.3% when the wellbore radii were 0.2 and 1 ft. Table 4 shows investigated parameters besides their conversion functions.

According to the BBD, 57 simulation runs are required to investigate the effects of seven factors on the water aquifer over three levels.

Response functions

BBD is one of the response surface methods (RSM) which are implemented in researches where the number of variables increases. RSM refers to statistical methods defining the relationships between a target parameter and dependant variables. Eq. 1 could be used to explain the RSM.

$$y = f\ (\alpha_1, \alpha_2, \alpha_3, \dots) + \varepsilon \tag{1}$$

In Eq. 1, α_i, ε, and y stand for independent variables, the error caused by the difference between actual and predicted response and dependant target parameter. It is common to convert the natural parameters of α to a dimensionless one. Hence, a new dimensionless equation could be described as Eq. 2.

$$y = f\ (x_1, x_2, x_3, \dots) + \varepsilon \tag{2}$$

Due to more flexibility and using the least squared method, quadratic functions were used in this research. Therefore, the general form of the quadratic equations could be described as Eq. 3 [21].

$$\eta = \beta o + \sum_{j=1}^{k} \beta_j\, x_j + \sum_{j=1}^{k} \beta jj\, x_j^2 + \sum_{i<} \sum_{j=2}^{k} \beta_{ij} xi\, xj \tag{3}$$

As mentioned before, the performance of gas reservoirs could be assessed by the evaluation of P/z at each pressure. It could be found in Eq. 4[3].

$$\frac{\mathrm{P}}{\mathrm{z}} = \frac{\frac{\mathrm{P_i}}{\mathrm{z_i}}\left(1 - \frac{\mathrm{G_p}}{\mathrm{G}}\right)}{1 - \frac{\mathrm{P_i z_{sc} T_{sc}}}{\mathrm{G P_{sc} z_i T}}\left(\mathrm{W_e} - \mathrm{W_p B_w}\right)} \tag{4}$$

The performance of the gas reservoir and initial gas in place could be approximated by obtaining values of G_p, W_e, and W_p. As a whole, understanding the parameters in Eq. 4 helps engineers to gain a more accurate site from the gas reservoir. To find the mentioned parameters, six response functions of f_1 to f_6 were employed to define aquifer productivity index, water production, gas recovery factor, sweep water efficiency, initial maximum gas production, the breakthrough time, and its related constants ("a" and "b"). "a" and "b" should be known to estimate water encroachment. It should be mentioned that all of the response functions are linear and nonlinear functions of parameters were filtered through the tornado chart. According to the BBD, 57 simulation runs are required to find the response functions.

Result and Discussion

Aquifer Productivity Index

The aquifer productivity index (J_w) is used to explain the water influx volume into the reservoir in a specific pressure drop. This index is a function of all under-debated parameters selected in the tornado chart.

$$\mathrm{J_w} = \mathrm{f_1}(\mathrm{x_1.x_2.x_3.x_4.x_5.x_6.x_7}) \tag{5}$$

Using the BBD, the productivity index of the aquifer predicted is reported as Eq. 6.

$$\begin{aligned}\mathrm{J_w} = 7.933 + 16.32\mathrm{K_{res}} + 1.59\mathrm{P_i} + 1.15\mathrm{H_{gas}} + 7.15\ \mathrm{P_{wh}} + 2.54\ \mathrm{D}_{\mathrm{t}} + 9.77{\mathrm{K_{res}}}^2 \\ + 3.36\ \mathrm{K_{res}H_{gas}} + 11.74\ \mathrm{K_{res}}\ \mathrm{P_{wh}} + 3.7\mathrm{K_{res}}\ \mathrm{D_t}\end{aligned} \tag{6}$$

All of the parameters in Eq. 6 are of positive coefficients, and it means that the increment of all the parameters comes to increase the aquifer productivity index. The reservoir permeability and wellhead pressure affect stronger water productivity index, from a statistical point of view. All the multiplied coefficients of each parameter, standard error, and "t" values of Eq. 6 are shown in Table 5. Besides, Table 6 shows the variance analysis of the aquifer productivity index equation. Both R^2 and re-adjusted R^2 of aquifer productivity indexes were reported 0.9531 and 0.9441, respectively.

Table 5. Multiplied coefficients of each parameter, standard error, and "t" value of aquifer productivity index

Factor	coefficient	Standard error	t value
Average	7.933	0.5733	13.83
K_{res}	16.132	0.6723	23.99
H_{gas}	1.595	0.6723	2.372
D_t	7.157	0.6723	1.722
K_{aq}	9.771	0.6723	10.646
IA	2.549	0.6723	3.792
$K_{res} \times K_{res}$	9.771	0.8835	11.059
$K_{res} \times D_t$	3.360	1.1644	2.886
$K_{res} \times K_{aq}$	11.740	1.1644	10.082
$K_{res} \times$ IA	3.707	1.1644	3.182

Table 6. Variance analysis of aquifer productivity index

Source	Degree of freedom	SS	MS	F	
Model	9	10353.9	1150.43	106.06	<0.0001
Error	47	509.8	10.85		
Summation	56	10863.7			

Fig. 2 shows a sensitivity analysis of the aquifer productivity index for aquifer and reservoir permeability. It reveals that the aquifer productivity index increases drastically as both reservoir and aquifer permeability increase. Besides, the increment of reservoir permeability has more influence than the aquifer one.

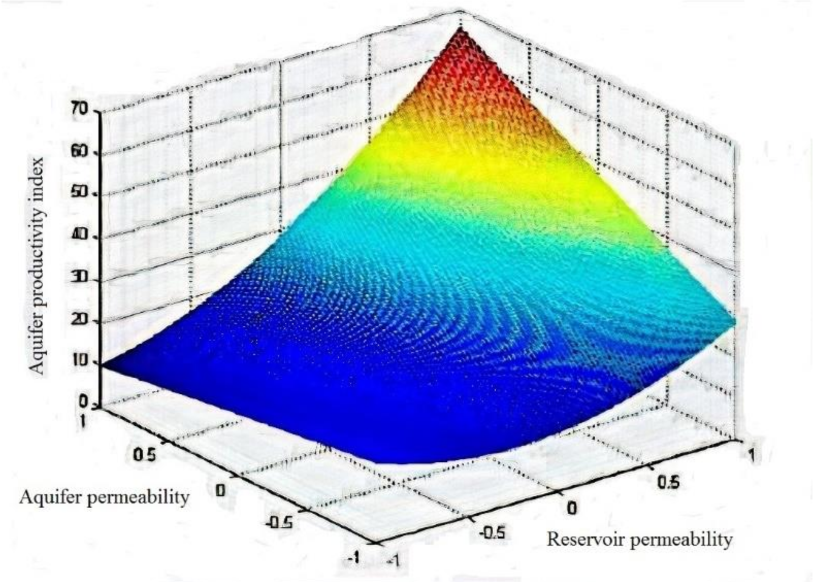

Fig. 2. Sensitivity analysis of aquifer productivity index respect to aquifer and reservoir permeability

Water Production

Water production is zero before the breakthrough of the waterfront. After reaching breakthrough time, related production rate and cumulative water production could be calculated, using Eq. 6 and Eq. 11, as a quadratic equation, respectively. The quadratic equation constants will be discussed by equations given by the BBD after running all simulation cases. Theoretically, the integration of the water production rate during production time is equal to water encroachment. The breakthrough time could be evaluated as following statistical points of view through Eq. 12.

$$t_b = f2(x_1.x_2.x_3.x_4.x_5.x_6.x_7) \tag{7}$$

$$Q_w = a(t - t_b) + b(t - t_b)^2 \tag{8}$$

$$a = f_3(x_1.x_2.x_3.x_4.x_5.x_6.x_7) \tag{9}$$

$$b = f_4(x_1.x_2.x_3.x_4.x_5.x_6.x_7) \tag{10}$$

$$W_p = \int Q_w dt = \int [a(t - t_{bt}) + b(t - t_b)^2]dt \tag{11}$$

Functions of a, b, and t_b obtained with the BBD are as follows:

$$t_b = 3.01940 - 11.6633K_{res} - 1.93521P_i - 2.04521H_{gas} + 0.717500\,P_{wh} - 1.04542\,D_t + 9.97029{K_{res}}^2 + 0.893415{D_t}^2 + 3.64625K_{res}P_i + 4.70125K_{res}H_{gas} - 1.71625K_{res}\,P_{wh} \tag{12}$$

$$a = f_3 = 0.005221 + 0.037023K_{res} + 0.019897\,D_t - 0.004583P_{wh} + 0.03195{K_{res}}^2 + 0.009347{D_t}^2 + 0.00955{K_{aq}}^2 + 0.054059\,K_{res}\,D_t - 0.012875K_{res}\,K_{aq} \tag{13}$$

$$b = f_4 = 2.9924 + 5.8154K_{res} + 1.0135P_i + 0.8367H_{gas} + 1.6345\,D_t + 3.1650{K_{res}}^2 + 1.1463K_{res}P_i + 4.1463K_{res}\,D_t + 0.9727H_{gas}\,D_t \tag{14}$$

As could be seen from Eq. 12, reservoir permeability, initial pressure, gas zone thickness, and tubing diameter influence the breakthrough time, negatively. It means that the increment of the mentioned parameters come to the retardation of breakthrough time. Some parameters, including tubing diameter, may have no impact on breakthrough time theoretically, but from the statistical point of view, this parameter is of a negative effect on response function based on simulation runs. However, it could be seen that the coefficient corresponded to the tubing diameter is negligible. Similar to breakthrough time, reservoir permeability has more effect on breakthrough time. The next affecting parameter is gas zone thickness. The R^2 and re-adjusted R^2 of water breakthrough time were 0.9693 and 0.9626, respectively. Hence, Eq. 12 seems adaptive to simulation results. Response functions of "a" and "b" are related to water encroachment, and increasing each of them results in increasing water encroachment. Table 7 represents multiplied coefficients, standard error, and "t" value of parameters involved in Eq. 12. Moreover, Table 8 shows the variance analysis of the breakthrough time equation.

Table 7. Multiplied coefficients related to water production equation, corresponded standard error, and “t” value

Factor	coefficient	Standard error	t value
Average	3.0194	0.4114	34.7
K_{res}	-11.663	0.384	-30.309
P_i	-1.9352	0.384	-5.029
H_{gas}	-2.0452	0.384	-5.315
P_{wh}	0.7175	0.384	1.865
D_t	-1.045	0.3848	-2.717
$K_{res} \times K_{res}$	9.9703	0.5117	19.486
$Dt \times D_t$	0.8934	0.5117	1.746
$k_{aq} \times p_i$	3.6462	0.6645	5.471
$K_{res} \times H_{gas}$	4.701	0.6645	7.053
$K_{res} \times p_{wh}$	-1.7162	0.6645	-2.575

Table 8. Variance analysis of water breakthrough time

Source	Degree of freedom	SS	MS	F	
Model	10	5155.21	515.52	145.22	<1.1111
Error	46	163.48	3.55		
Summation	56	5318.69			

Fig. 3 shows the sensitivity analysis of the water breakthrough time with respect to gas zone thickness and reservoir permeability. Breakthrough time decreases with increasing reservoir permeability.

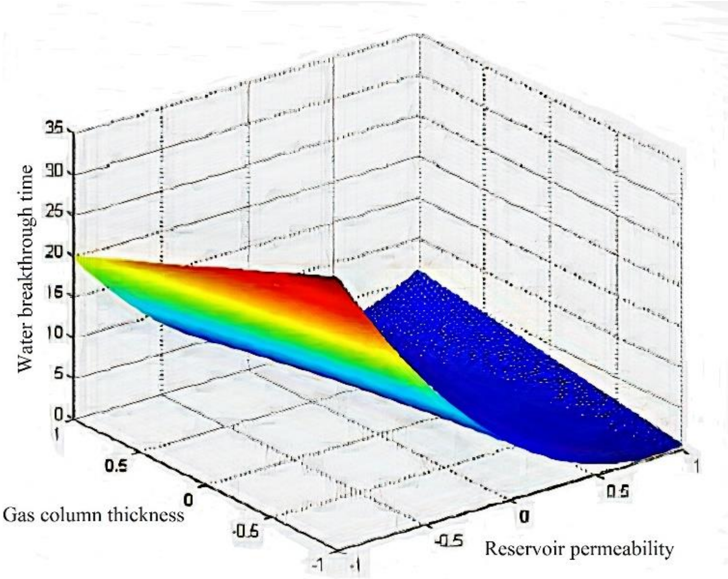

Fig. 3. Sensitivity analysis of water breakthrough time respect to gas zone thickness and reservoir permeability

Gas Recovery Factor

Cumulative gas production could be found, by integrating the gas production equation concerning elapsed time, theoretically. Also, the gas recovery factor could be assessed by knowing the initial gas in place [3].

$$G_p = \int Q_g dt = \int \{\frac{kh}{1422T(0.5\ln\frac{4A}{\gamma C_A {r_w}^2} + S)}[m(p) - m(p_{wf})]\}dt \tag{15}$$

Indeed, the gas recovery factor equation will be found according to Eq.16 statistically. According to Eq. 17 that is derived from the BBD, the gas recovery factor depends strongly on reservoir permeability and wellhead pressure. Aquifer permeability and tubing diameter are other affecting parameters in the lower level. Reservoir and aquifer permeabilities increase the gas recovery factor. On another hand, tubing diameter and wellhead pressure reduce the gas recovery factor when they increase.

$$RF = f5(x_1.x_2.x_3.x_4.x_5.x_6.x_7) \tag{16}$$

$$\begin{aligned} RF = 60.2011 &+ 5.76958K_{res} + 0.608750\,P_i + 0.312917\,H_{gas} - 4.27792\,P_{wh} \\ &- 2.04708\,D_t + 2.27208\,K_{aq} + 0.536250\,IA + 1.82465{K_{res}}^2 \\ &- 0.584097\,P_{wh}^2 + 0.455903\,{D_t}^2 - 1.41285{K_{aq}}^2 \\ &- 0.902500K_{res}\,P_{wh} - 2.15875K_{res}\,D_t + 0.482500K_{res}\,K_{aq} \\ &+ 0.44000\,P_i\,P_{wh} + 0.456250P_i\,K_{aq} - 0.782500\,K_{aq}\,IA \end{aligned} \tag{17}$$

Multiplying coefficients of all influencing parameters in Eq. 14 are listed in Table 9. According to Table 10, the R^2 and re-adjusted R^2 of water breakthrough time were 0.98870 and 0.98370, respectively. Therefore, the proposed equation from the BBD has a high level of adaption to Eclipse responses.

Table 9. Multiplying coefficients of all of influencing parameters in the gas recovery with related standard error and "t" value

Factor	coefficient	Standard error	t value
Average	69.201	0.2305	30.148
K_{res}	5.7697	0.1412	40.868
P_i	0.6087	0.1412	4.312
H_{gas}	0.3129	0.1412	2.216
$\mathrm{P_{wh}}$	-4.2779	0.1412	-30.302
$\mathrm{D_t}$	2.0471	0.1412	-14.5
k_{aq}	2.2721	0.1412	16.094
IA	0.5362	0.1412	3.798
$K_{res} \times K_{res}$	1.8247	0.1955	9.336
$P_{wh} \times P_{wh}$	-0.5841	0.1955	-2.988
$Dt \times \mathrm{D_t}$	0.4559	0.1955	2.333
$k_{aq} \times k_{aq}$	-1.4128	0.1955	-7.229
$k_{res} \times p_{wh}$	-0.9025	0.2445	-3.691
$K_{res} \times \mathrm{D_t}$	-2.1588	0.2445	-8.828
$K_{res} \times k_{aq}$	0.4828	0.2445	1.973
$P_i \times \mathrm{P_{wh}}$	40.4	0.2445	1.799
$P_i \times k_{aq}$	0.4563	0.2445	1.866
$k_{aq} \times IA$	-0.7825	0.2445	-3.2

Table 10. Variance analysis of gas recovery factor equation

Source	Degree of freedom	SS	MS	F	
Model	17	1628.34	95.875	200.58	<1.1111
Error	39	18.66	0.478		
Summation	56	1646.99			

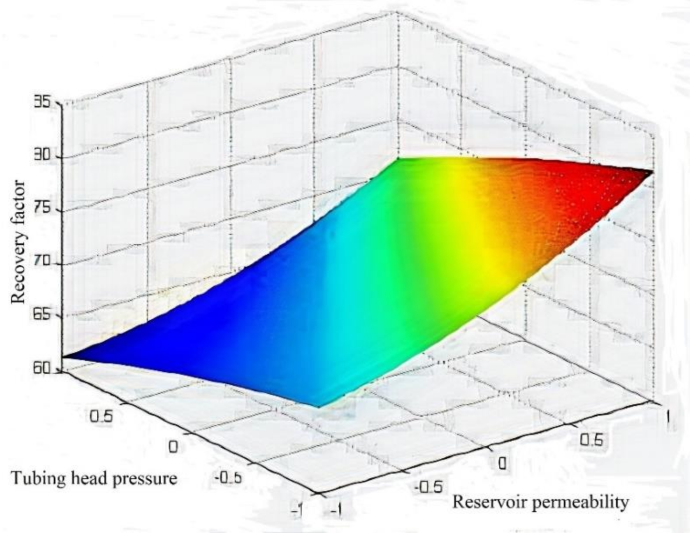

Fig. 4. Sensitivity analysis of gas recovery factor respect to reservoir permeability and wellhead pressure

Fig. 4 shows the sensitivity analysis of gas recovery factor with respect to reservoir permeability and wellhead pressure that are the two most affecting parameters on gas recovery factor, according to Eq. 17. According to Fig. 4 and Eq. 14, the gas recovery factor increases as the reservoir permeability increases wellhead pressure decreases.

Sweep Water Efficiency

From the theoretical point of view $f_6(x_1.x_2.x_3.x_4.x_5.x_6.x_7)$, as sweep efficiency parameter, must be known to determine other parameters like original gas in place or G in Eq. 18 [3].

$$\frac{P}{z}=\frac{\frac{P_i}{z_i}(1-\frac{G_p}{G})}{f_6[\frac{S_{gr}}{S_g}+\frac{1-f_6}{f_6}]} \tag{18}$$

$$Ev=f_6(x_1.x_2.x_3.x_4.x_5.x_6.x_7) \tag{19}$$

Sweep efficiency is given by the BBD, as Eq. 20.

$$\begin{gathered}Ev=60.2011+5.76958K_{res}+\ 0.608750P_i+\ 0.312917H_{gas}-4.27792P_{wh}\\ -2.04708D_t+2.27208\ K_{aq}+0.53650\ IA+\ 1.82465{K_{res}}^2-\ 0.58409{P_{wh}}^2+\\ 0.455903D_t^2-1.412850\ {K_{aq}}^2-0.902500\ K_{res}\ P_{wh}-2.15875\ K_{res}\ D_t\ +\\ 0.482500K_{res}\ P_{wh}+0.44000P_i\ P_{wh}+0.45625P_i\ K_{aq}-0.782500\ K_{aq}\ (IA)\end{gathered} \tag{20}$$

The sweep water efficiency depends on reservoir permeability, aquifer permeability, wellhead pressure, and tubing diameter, according to Eq. 20. It could be dedicated that both reservoir and wellhead pressures are primary and secondary affecting parameters on sweep water efficiency. Increasing reservoir permeability increases sweep efficiency, in contrast to wellhead pressure that causes the reduction in response function when it increases. Multiplying coefficients of all influencing parameters in Eq. 20 are listed in Table 11. According to Tables 10 and 12, the R^2 and re-adjusted R^2 related to sweep water efficiency is calculated to be 0.9556 and 0.9408, respectively.

The sensitivity analysis of sweep water efficiency is visually shown in Fig. 5. Aquifer permeability and reservoir permeability have consistent effects on response functions, and both of them cause an increase in the sweep efficiency.

Table 11. Multiplying coefficients of all of influencing parameters in sweep water efficiency with related standard error and "t" value

Factor	Coefficient	Standard error	't' value
Average	40.54	0.8312	48.782
K_{res}	5.14	0.6303	8.17
P_i	2.87	0.6303	4.558
H_{gas}	-1.102	0.6303	-1.749
P_{wh}	-4.434	0.6303	-7.035
D_t	-5.238	0.6303	-8.311
k_{aq}	13.06	0.6303	20.73
IA	4.234	0.6303	6.718
$K_{res} \times K_{res}$	3.61	0.8517	4.249
$Dt \times D_t$	1.953	0.8517	2.293
$k_{aq} \times k_{aq}$	-4.486	0.8517	-5.267
$k_{res} \times p_{wh}$	-2.499	1.0917	-2.289
$K_{res} \times D_t$	-8.248	1.0917	-7.555
$K_{res} \times k_{aq}$	10.46	1.0917	9.585
$H_{gas} \times k_{aq}$	2.143	1.0917	1.963

Table 12. Variance analysis of sweep water efficiency

Source	Degree of freedom	SS	MS	F	
Model	14	8618.15	615.58	64.59	<1.1111
Error	42	400.42	9.53		
Sum	56	9018.57			

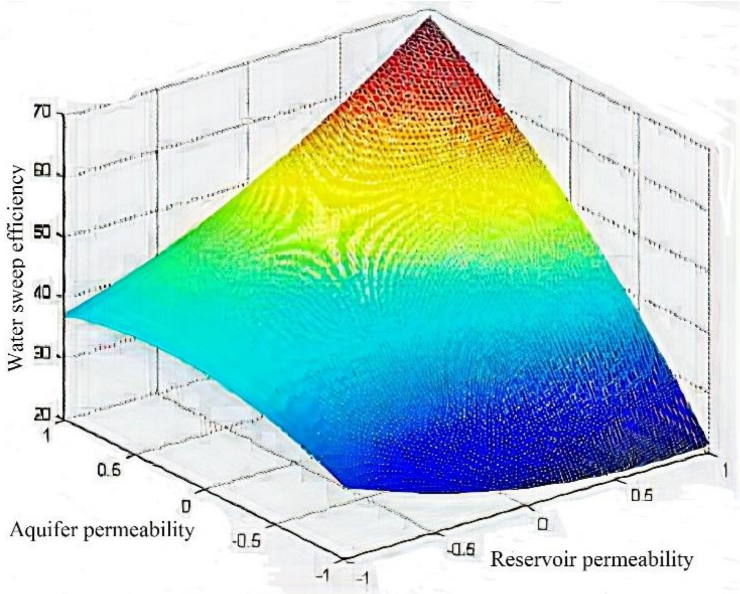

Fig. 5. Sensitivity analysis of sweep water efficiency with respect to aquifer and reservoir permeability

Initial Maximum Gas Production

Gas production at the pseudo-steady state could be evaluated through Eq. 21 theoretically [3].

$$Q_g = \frac{kh}{1422T(0.5\ln\frac{4A}{\gamma C_A {r_w}^2 + S})}[m(p) - m(p_{wf})] \tag{21}$$

The equation that is proposed by the BBD could approximate the dependency of gas recovery factor regarding maximum initial gas production rate.

$$Q_g = 70.368 + 20.363K_{res} + 1.882P_i + 3.66H_{gas} + 4.61\, P_{wh} + 10.49{K_{res}}^2 + 3.77K_{res}H_{gas} + 11.82K_{res}\, P_{wh} + 3.26H_{gas}\, P_{wh} \tag{22}$$

Table 13. Multiplying coefficients of all of influencing parameters in maximum initial gas production with related standard error and "t" value

Factor	Coefficient	Standard error	‘t’ value
Average	70.368	0.7792	90.308
K_{res}	20.363	0.9137	22.287
P_i	1.882	0.9137	2.06
H_{gas}	3.664	0.9137	4.01
D_t	4.614	0.9137	5.05
$K_{res} \times K_{res}$	10.498	1.2008	8.742
$K_{res} \times H_{gas}$	3.773	1.5836	2.384
$K_{res} \times D_t$	11.827	1.5826	7.473
$H_{gas} \times D_t$	3.261	1.5826	2.061

Table 14. Variance analysis of the maximum Initial gas production rate

Source	Degree of freedom	SS	MS	F	
Model	8	13718.9	1714.86	85.57	<1.1111
Error	48	961.7	20.04		
Sum	56	14680.6			

According to Eq. 22 the maximum initial gas production rate of a gas reservoir, connected to an aquifer, highly depends on reservoir permeability. The wellhead pressure and gas zone thickness could be considered as affecting parameters in the lower level of influence. Increment of reservoir permeability, initial pressure, gas zone thickness, and wellhead pressure increase the initial gas production rate. Table 13. shows multiplying coefficients, standard errors, and "t" values. According to Table 14, the R^2 and re-adjusted R^2 of maximum initial gas production are 0.9345 and 0.9236, respectively.

Fig. 6 is a representation of the sensitivity analysis of the maximum initial gas production rate regarding reservoir permeability and tubing diameter. As could be seen in Fig. 6 an increase of reservoir permeability, strongly enhances the initial production rate. The effect of tubing diameter is more noticeable when reservoir permeability is high.

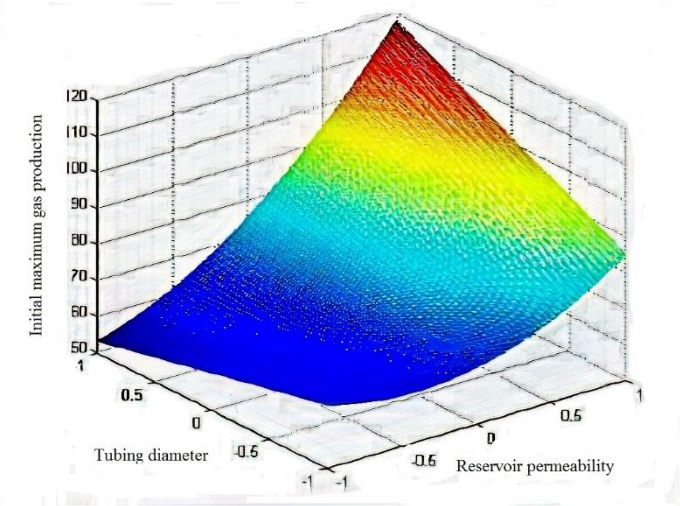

Fig. 6. Sensitivity analysis of maximum initial gas production rate respect to reservoir permeability and tubing diameter

Validation of Proposed Models

All of the mentioned obtained response functions have high R^2 and readjusted R^2. Hence, they are adapted to the input data. To survey the validity of proposed relations for response functions, the authors selected five data points to check if there is consistency between Eclipse software results and the BBD outcomes. Five data points that are used for the validation are shown in Table 15. Table 16 represents that the results of the Eclipse software and response functions of the aquifer productivity index, sweep water efficiency, water production, gas recovery factor, and maximum initial gas production rate have excellent consistency. To visualize the deviation of the RSM model from simulation results, an arithmetic average from data points are shown in Fig. 6. According to Table 16, the response functions of breakthrough time show very poor adaption in comparison with Eclipse software results, similar to 'a' and 'b. It may be an indication of the other possible affecting parameters requirement that has not been taken into account to predict the breakthrough time. As could be seen from Fig. 7, the response functions of aquifer productivity index, sweep water efficiency, maximum gas production, and recovery factor are of deviation percentages in the ranges of 10.61%, 6.302%, 3.958%, and 2.04% respectively. In contrast, water breakthrough time, which has a deviation percentage of 63.07%, was poorly fitted with simulation results. The best adaption was found to be the recovery factor, and the worst one is the breakthrough time.

The authors tried to show that using Box- Behnken design is feasible for describing phenomena related to a gas reservoir supported by an active aquifer. The actual models used in the oil and gas industry are probably comprised of plenty of faults, discontinuities, inhomogeneities, uncertainties, and other possible complexities. Running a thorough individual simulation to predict the response of the reservoir in each production scenario might induce a high cost. In another word, modellers might study the aquifer of a gas reservoir by performing a thorough qualified RSM model, and use it instead of performing expensive simulations. The authors think this study could be considered as a benchmark for further detailed studies in the future.

Table 15. Data points used to validate the proposed model given by the BBD

Points	K_{res}	P_i	H_{gas}	P_{wh}	D_t	K_{aq}	IA
P_1	5	5200	350	1150	7	8	130
P_2	23	5000	245	1250	5.5	16	200
P_3	48	4700	210	950	4	54	190
P_4	69	4500	290	1100	5.5	28	300
P_5	82	4400	230	1200	4	93	350

Table 16. Results of the simulation run and the BBD

	P_1		P_2		P_3		P_4		P_5	
	DOE	SIM	DOE	SIM	DOE	SIM	DOE	SIM	DOE	SIM
J_w	3.24	3.98	15.2	15.22	27.56	28.87	38.61	43.7	48.250	58.98
RF	64.54	65.40	67.85	64.07	79.46	77.80	73.98	73.73	76.62	77.33
Q_{max}	70.64	68	77.09	83	73.39	75	93.03	97	78.12	76
E_v	33.44	35.09	41.79	31.45	69.16	68.76	54.51	53.98	77.13	76.72
a	0.0099	0.001	0.021	0.019	0.017	0.011	0.049	0.009	0.019	0.006
b	3.293	2.228	5.685	5.452	3.693	3.979	8.701	8.904	3.786	3.352
t_{bt}	3.742	3.43	0.129	1.82	0.564	4.01	0.853	1.44	0.634	5.05

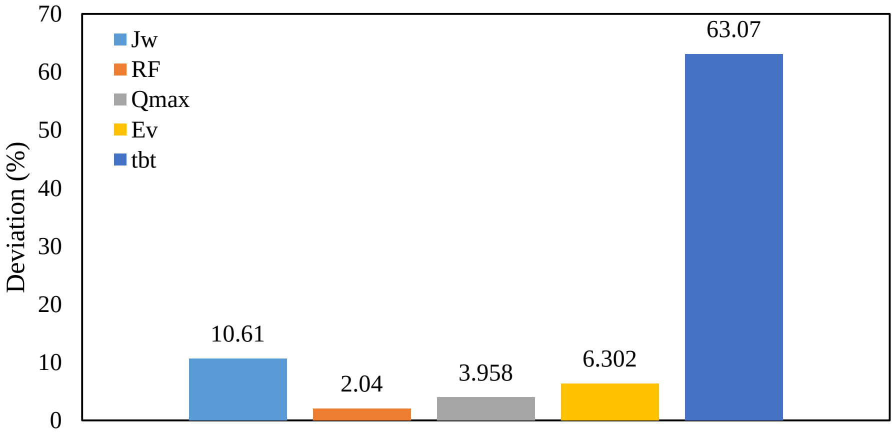

Fig. 7. Deviation percentages of response functions given by the BBD

The input variables in the study performed by Yue [17] were including reservoir width which was considered constant in this study. Instead, this study distinguishes between reservoir permeability and aquifer permeability. It was shown that the aquifer permeability is the second most important parameter in determining the aquifer productivity index and water sweep efficiency.

Conclusion

The simulation results show that all of the factors including reservoir permeability, maximum initial reservoir pressure, gas column thickness, wellhead pressure, production tube diameter, aquifer zone permeability, and effective aquifer intruding angle influence the performance of the gas reservoir supported by the strong aquifer. Reservoir and aquifer permeability are the two most influencing parameters in the productivity index prediction of aquifer supporting the gas reservoir.

Reservoir permeability and gas zone thickness are two affecting parameters in the prediction of water breakthrough time. Increasing both of them comes to the reduction of breakthrough time.

Reservoir permeability and wellhead pressure are of the highest impact on the recovery factor of the gas reservoir supported by a strong water aquifer. In contrast to the reservoir permeability factor, the increase of the wellhead pressure leads to a reduction in the recovery factor.

Unlike all other factors, reservoir permeability is not the most affecting parameter in the prediction of sweep water efficiency. The aquifer permeability was found to be the most influencing parameter in the prediction of the sweep efficiency equation given by the BBD.

According to equations derived by the BBD, reservoir permeability, and the thickness of the gas zone are the most affecting parameters in the prediction of the initial gas flow rate.

The main target of using the BBD is to manage the time duration of the simulation, high costs, and CPU requirements. Conventional reservoir models in the gas industry are not as simple as the mentioned cubic simple model used in this research. The simulation of gas reservoirs with a high degree of heterogeneity requires time-consuming and costly simulations. It seems reasonable to perform a similar statistical procedure for each gas reservoir supported by the strong aquifer. Every statistical scenario must be examined using other data point results given by Eclipse software or history match of reservoir production data.

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Nomenclature

P	Pressure, psi
P_{sc}	Pressure at standard condition (14.7 psi)
C_A	Shape factor
Gp	Cumulative gas production, MSCF
G	Initial gas in place, MSCF
B_w	Water formation factor, bbl/STB
γ	1.78
Z	Compressibility factor, dimensionless
k	Permeability, Darcy
T	Temperature (R)
A	Reservoir area, across
S_{gr}	residual gas saturation, dimensionless
$m(p)$	Pseudo-pressure
S	Skin factor, dimensionless
T_{sc}	Temperature and standard condition, R
We	Cumulative water influx, bbl
S_g	Gas saturation
h	Reservoir thickness, ft
Q_g	Gas flow rate, Scf

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