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The Feasibility of Multiphase Flow Models Application to the First Horizontal Well Drilled Underbalanced in the Gulf of Suez, Egypt : A Case Study

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Abstract

Underbalanced drilling (UBD) is one of the unconventional drilling techniques, which exhibits effective solution to conventional drilling problems, such as low rate of penetration, high formation damage, differential pipe sticking, lost circulation, and short bit life. Low density fluids, such as air, mist, foam, or aerated mud are used to achieve bottomhole circulating pressures (BHCP) lower than pore pressure of the formation being drilled. The successful application of UBD depends on two main factors : controlling wellbore pressure to be maintained lower than formation pore pressure and wellbore stability. In this paper, the first horizontal well drilled underbalanced using aerated liquid in the Gulf of Suez in Egypt have been analyzed to evaluate the feasibility of different multiphase flow models application in predicting BHCP, standpipe pressure, and the minimum liquid annular velocity required for hole cleaning. The appropriate multiphase flow model which gives the most accurate results of the previous hydraulics calculations is determined. UBD operating envelope for this well is constructed and the optimum operating condition to ensure a successful and safe UBD operation is recommended.

Keywords: *Underbalanced drilling; Aerated mud; Horizontal drilling; Multiphase flow models; Gasified liquid drilling; Operating envelope;Hole cleaning.*

1. Introduction

The economics of exploration and exploitation of oil and gas fields continue to encourage the use of new drilling techniques to reduce conventional drilling technique problems and costs. Underbalanced drilling (UBD) is one such technique, which is defined as a drilling operation utilizing appropriate equipment where the wellbore pressure exerted is intentionally less than the pore pressure in any part of the exposed formations with the intention of producing formation fluids during drilling. There are five techniques of UBD according to the UBD fluid system : gas drilling (dry air, nitrogen, or natural gas), mist drilling, foam drilling, gasified (aerated) liquid drilling, and flowdrilling (single phase liquid drilling) [1-2].

1.1. Benefits of drilling underbalanced

Recently, UBD has been used with increasing frequency to minimize or mitigate problems associated with conventional drilling or overbalanced drilling (OBD). The benefits of UBD generally fall into two categories:

Cost reduction: including mitigation of OBD problems as low penetration rate, formation damage, lost circulation, differential sticking, short bit life.

Value adding: including productivity improvement due to the lower formation damage, earlier production, increase in ultimate recovery, and real-time formation evaluation and reservoir characterization while drilling [3-4]. As the majority of hydrocarbons being exploited today are produced from mature fields and pressure depleted reservoirs, this is where UBD technology recommended to be utilized. Soon, UBD will become the standard drilling technique for field development, both onshore and offshore, if the geology and reservoir are suitable [5].

1.2. Gasified liquid drilling

Gasified or aerated liquids are the predominant underbalanced drilling fluids used all over the world [1]. The liquid phase is normally water or crude oil gasified with nitrogen to reduce the hydrostatic pressure exerted by the liquid phase. The created equivalent circulating densities (ECD) usually range from 4 to 7 ppg. There are two main types of gasification techniques: drillpipe injection through the standpipe and annulus injection through completion, parasite tubing string, or parasite casing string, as shown in Figure 1.

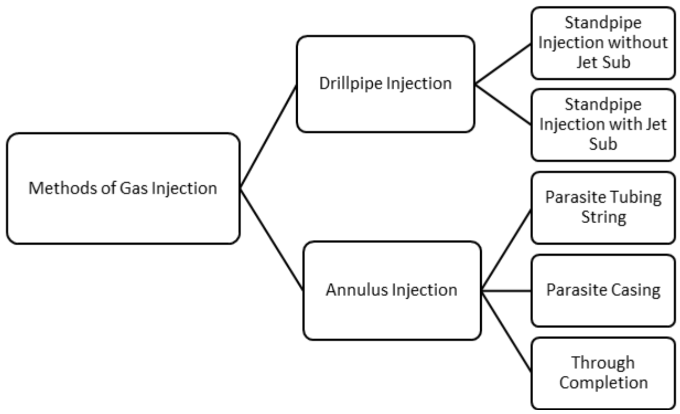

Fig. 1. The different gasification techniques.

UBD is one of the effective solutions used in a pay zone to prevent formation damage particularly in horizontal wells because they are more vulnerable to formation damage than vertical wells due to the producing intervals and the exposure time of these intervals to the drilling fluids are longer than that in vertical wells. In addition, stimulation of horizontal wells to overcome formation damage caused by OBD is expensive and difficult [6] .

There are two main practical challenges limit on how long a horizontal section can be drilled and maintain underbalanced, the first is maintaining the circulating pressure underbalanced although the horizontal section acts as a long separator [7]. The second challenge is wellbore instability particularly in unconsolidated or highly depleted reservoir [8].

Simulation of the multiphase flow in gasified horizontal UBD is principal to create the preliminary design and to optimize of underbalanced drilling parameters to overcome the previous practical challenges. Multiphase flow is studied in various petroleum engineering disciplines particularly production engineering because wells normally produce a mixture of gas and liquids. In production engineering, multiphase flow generally prevails in a tubing or pipe. However, in drilling engineering the multiphase flow prevails in the annulus as well as the drillstring. The initial software utilized for gasified and mist drilling simulation was production software [7]. In recent years, unconventional drilling techniques such as underbalanced drilling and managed pressure drilling (MPD) has become more widespread so that many commercial drilling simulators of multiphase flow models for drilling operations have been produced by oil and gas companies.

Appropriate multiphase flow model can help to predict the bottomhole pressure, standpipe pressure, cutting transport ratio, and hole cleaning with high accuracy which enables the operators to optimize the liquid and gas injection rates, choke back pressure, the wellbore geometry, and design the UBD operating envelope. Guo *et al.* [9] developed a computer simulation for aerated mud, results found differences between the predicted and measured standpipe pressure (SPP) about 10 % when drilling at depths from 3000 ft to 7000 ft. Smith *et al.* [10] applied different multiphase flow models to three oil wells and one gas well in Western Canada drilled underbalanced with coiled tubing to evaluate the application of pressure loss calculation using different multiphase flow models. According to results the appropriate multiphase flow model for oil wells and gas well is recommended with a standard deviation of predicted bottomhole circulating pressure (BHCP) ranges from 5.5 % to 7.4 %.

2. Overview of UBD operations

112-78H was the first horizontal well drilled Underbalanced in Gulf of Suez in Egypt. The 6" horizontal section was drilled Underbalanced using nitrified diesel by injection of the nitrogen gas to the diesel liquid through the standpipe and hence down to the drillstring therefore the nitrogen gas supply must be able to overcome the standpipe pressure which will be predicted in this paper. In gasified drilling technique, the target underbalanced pressure must be at least 500 psi lower than the formation pressure to minimize the effect of pressure fluctuation during tripping or making connections [1]. For safety considerations, Weatherford as the contractor of UBD operation of this well recommended for the drilling crew to take 5 to 15 minutes before breaking open the joint during making connections to bleed down the pressure in the drillstring through the standpipe bypass line. Two float valves have been utilized within the drillstring, sometimes a third float is set near to the surface to reduce the bleed down time of the string.

In addition to the standard drilling equipment, additional equipment required for underbalanced drilling operations of 112-78H well :

- Nitrogen pumping unit.
- Rotating control head.
- Dedicated underbalanced drilling choke manifold.
- 4-Phase horizontal separator.
- Tank system to store produced fluids.
- Fluid management equipment.
- Drillstring floats, either wireline retrievable or standard non-retrievable.

The rotating control head and choke manifold system provide primary well control during UBD operations. Drillstring floats are used to prevent flow up inside the drillstring during tripping and connections. The 4-phase separator separates the returns from the well into solid, gas, water, and hydrocarbon liquid phases. In addition to the active drilling fluid system, a tank system is required to store produced fluids. The fluid management equipment, such as transfer pumps, piping, and valving, control the shipping of the fluids between the separator, the active mud systems and the storage tanks. The separated gas phase is typically sent to flare, but depending on the production rate, it may also be economical to recompress the gas and inject it into a near-by gas pipeline.

3. Study methodology

To achieve the objectives of the underbalanced well, the design of UBD operations should consider the following criteria:

- Selecting compatible drilling fluids based on drilling and reservoir considerations.
- Maintaining the wellbore pressure low enough to create a sufficient drawdown but it must be high enough to prevent any open hole collapse.
- Maintaining an annular liquid velocity higher than or at least equal to the minimum annular liquid velocity required for hole cleaning.
- The equivalent liquid rate (ELR) at any operating point of liquid and gas injection rates must be within the operating range of mud motor.
- Controlling the reservoir fluid influx to ensure that the surface separating equipment capacities and pressure rating can accommodate the production while drilling and pressure at the surface.

Based on the previous criteria, the successful application of gasified liquid drilling mainly depends on determination of the appropriate multiphase flow model which predicts the hydraulics calculations with minimum mean absolute error (MAE). The predicted BHCP is compared with the measured one using pressure while drilling (PWD) tool, and the predicted SPP is compared with the measured one from the standpipe gauge at the surface. The minimum annular liquid velocity required for hole cleaning can be predicted using WellPlan™ software algorithm.

There are two methods to predict the pressure gradient in multiphase flow systems, the two methods are empirical correlations and mechanistic models. Duns and Ros model [11], Hagedorn and Brown model [12], Beggs and Brill model [13], and Gray model [14] are empirical correlations whereas Hassan and Kabir model [15] is considered one of the mechanistic models. Underbalanced hydraulics module in WellPlan™ software from Halliburton Landmark provides the hydraulic calculations of aerated liquid drilling using all the previous multiphase flow models.

The liquid phase of drilling fluid is selected to be diesel oil with density of 7.25 ppg (specific gravity = 0.87) to minimize any possibility of formation damage due to spontaneous imbibition. Nitrogen is selected as the gas phase to eliminate the possibility of downhole fire and minimize the corrosion rate. Figure 2 shows the flowchart of the methodology that has been discussed previously.

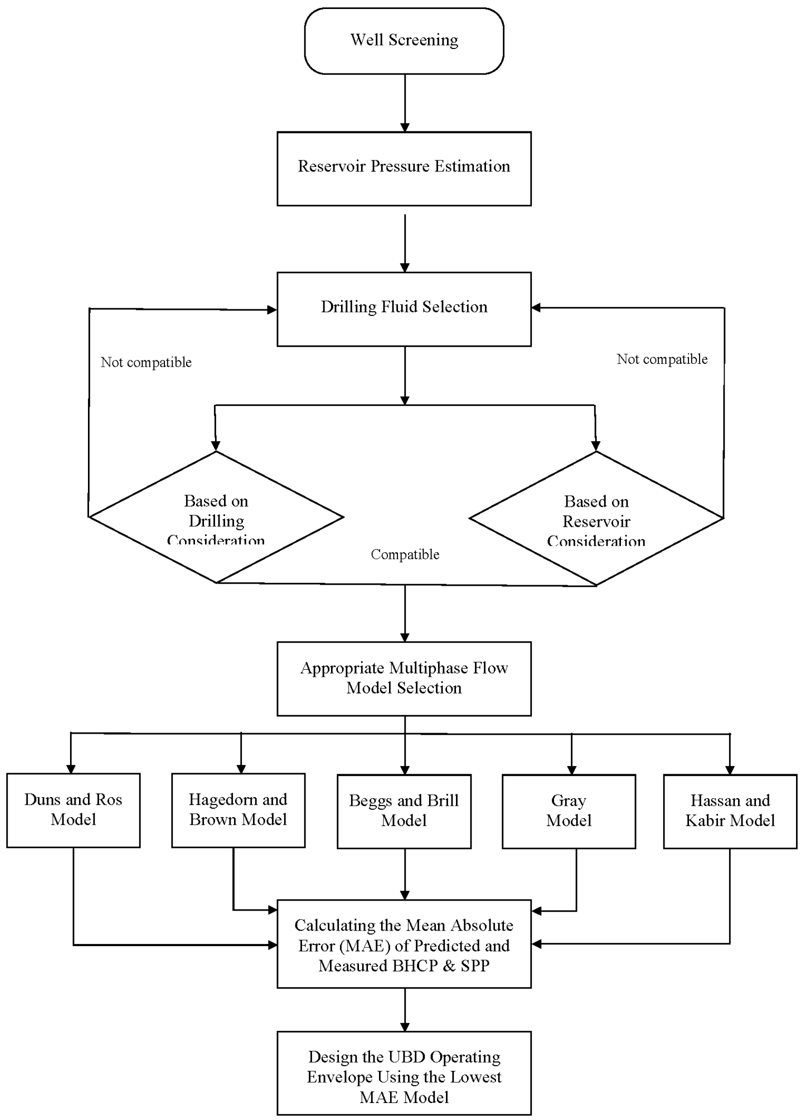

Fig. 2. Methodology flowchart.

4. UBD operating envelope and optimum rate

The behavior of multiphase flow in the well bore during horizontal underbalanced drilling is very complex. To avoid the problems of breaking the target underbalanced condition, the downhole conditions response to the changes in liquid injection rate, gas injection rate, choke back pressure, hole cleaning, drillstring washout, drill bit nozzles plugging, should be predicted before beginning the UBD operation. UBD operating envelope is a closed area by four constraints :

1. Target wellbore pressure
2. The maximum and the minimum mud motor ELR
3. Minimum annular liquid velocity for hole cleaning
4. The maximum allowable drawdown according to wellbore stability and surface equipment capacity and pressure rating or the minimum injected liquid rate.

These constraints are constructed on the pressure performance curves resulting from the plot of BHCP vs. gas injection rate. Any operating condition of underbalanced well must be selected to be inside the well operating envelope.

5. Case study

Belayim Petroleum Company, one of the major petroleum companies in Egypt, decided in 2002 to drill the first horizontal underbalanced well in the Gulf of Suez in Egypt. Weatherford prepared the preliminary study of the well. The well target is the sand body of Zone-III of Belayim formation whose thickness ranges from 13 to 36 ft at a true vertical depth of 7644 ft and measured depth of 8196 ft. The well will be drilled laterally for 1148 ft with an average inclination of 85°. The kickoff point is at 6151 ft. The reservoir pressure was estimated to be 3000 psi. The 6″ horizontal section was drilled underbalanced from the 7″ liner shoe at 8435 ft MD (7664 ft TVD) to 9364 ft MD (7799 ft TVD). The well profile is shown in figure 3.

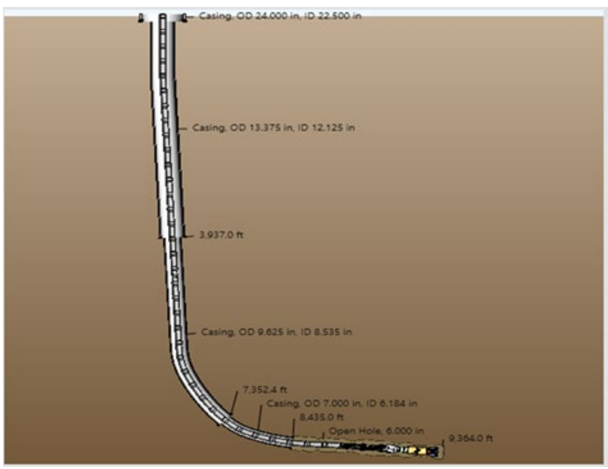

Fig. 3. 112-78H well diagram.

The type of the installed positive displacement motor is PowerPak steerable motor XP (Extra Power) extended power sections that provide higher torque output, with OD of 4¾″, 4 : 5 lobes, 6 stages, oil bearing section, and flow rate range from 100 to 250 gpm. A 12/32 bypass motor nozzle is installed to increase the maximum flow rate from 250 to 320 gpm. Conventional measurement while drilling (MWD) / PWD / logging while drilling (LWD) tools have been used in the horizontal section which confronted by the attenuation of pressure pulses generated to convey their signals to the MWD pressure sensor on the standpipe at the surface due to the exist of compressible fluid in the drillstring.

The primary driver for drilling this well underbalanced is to reduce or eliminate the formation damage that is caused during conventional drilling operations. Additional benefits include reducing the occurrence of stuck pipe and other lost time incidents and improving overall drilling performance.

6. Results and discussion

6.1. Bottomhole circulating pressure prediction

The predicted BHCP from each model is compared to the measured bottomhole pressure using PWD tool, six values of the measured bottomhole pressure at different operating conditions have been recorded during drilling the lateral section from 8793 ft MD to 8986 ft MD. Table 1. and Table 2. show the comparison of BHCP prediction accuracy of various multiphase flow models.

Table 1. Comparison of BHCP prediction accuracy of the first three multiphase flow models.

			Multiphase flow model					
			Hassan & Kabir Model		Beggs & Brill Model		Duns & Ros Model	
q_L, gpm	qg, scfm	PWD, psi	BHCP, psi	Error %	BHCP, psi	Error %	BHCP, psi	Error %
250	250	2887	2833	1.87	2789	3.4	2803	2.91
250	500	2660	2710	-1.88	2672	-0.45	2642	0.68
240	500	2652	2702	-1.89	2675	-0.87	2634	0.68
230	500	2620	2697	-2.94	2677	-2.18	2622	-0.08
210	500	2590	2680	-3.47	2679	-3.44	2599	-0.35
180	500	2549	2658	-4.28	2677	-5.02	2565	-0.63
MAE				2.72		2.56		0.89

Table 2. Comparison of BHCP prediction accuracy of the other two multiphase flow models.

			Multiphase flow model			
			Gray model		Hagedorn & Brown Model	
q_L, gpm	qg, scfm	PWD, psi	BHCP, psi	Error %	BHCP, psi	Error %
250	250	2887	2573	10.88	2592	10.22
250	500	2660	2214	16.77	2180	18.05
240	500	2652	2186	17.57	2150	18.93
230	500	2620	2155	17.75	2117	19.2
210	500	2590	2088	19.38	2038	21.31
180	500	2549	1972	22.64	1900	25.46
MAE				2.72		2.56

According to 112-78H well data simulated on WellPlan ™ software, Duns and Ros model shows the lowest mean absolute error (MAE = 0.89 %) of BHCP prediction so that it is the most accurate multiphase flow model to predict BHCP of this well, Figure 4 illustrates the measured values of wellbore pressure using PWD tool versus the predicted BHCP using Duns and Ros model. The second and third most accurate models are Beggs and Brill model (MAE = 2.56 %) and Hassan and Kabir model (MAE = 2.72 %) respectively, Figure 5 illustrates the measured values of wellbore pressure using PWD tool versus the predicted BHCP using Hassan and Kabir model.

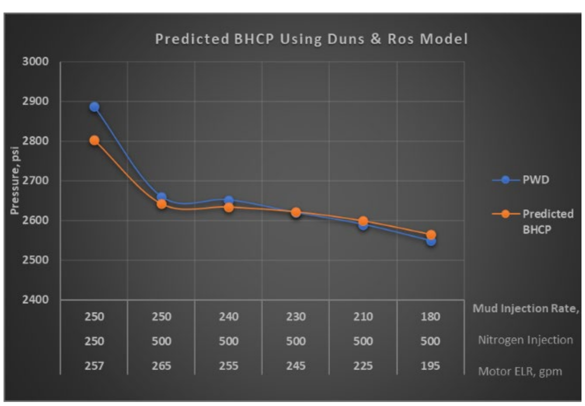

Fig. 4. Measured wellbore pressure vs. predicted BHCP using Duns and Ros model.

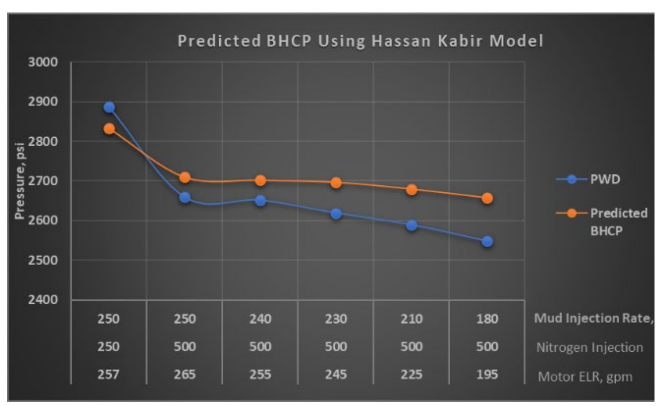

Fig. 5. Measured wellbore pressure vs. predicted BHCP using Hassan & Kabir model.

6.2. Standpipe pressure prediction

SPP is the total frictional pressure drop in the drilling fluid circulating system, it is an important drilling parameter that must be predicted with an adequate accuracy because the continuous monitoring of SPP helps in identifying downhole problems such as drillstring or bit nozzles washout, broken drill string, plugged drill bit, inadequate hole cleaning, worn pump packing, lost returns due to formation fracture, and an increase in mud density or viscosity. Drilling using compressible fluids as aerated liquid makes the prediction of SPP more complicated than incompressible used in conventional drilling.

For the same operating conditions at which the bottomhole pressure was measured using PWD tool, SPP has been recorded at each operating condition. Table 3. and table 4. show the comparison of SPP prediction accuracy of various multiphase flow models.

Table 3. Comparison of SPP prediction accuracy of the first three multiphase flow models

			Multiphase flow model					
			Hassan & Kabir Model		Beggs & Brill Model		Duns & Ros Model	
q_L, gpm	qg, scfm	Recorded SPP, psi	BHCP, psi	Error %	BHCP, psi	Error %	BHCP, psi	Error %
250	250	2887	1930	14.22	2764	-22.84	1969	12.49
250	500	2660	1916	6.54	2764	-34.83	1909	6.88
240	500	2652	1804	-0.22	2612	-45.11	1791	0.5
230	500	2620	1700	-6.25	2464	-54	1675	-4.69
210	500	2590	1499	-3.38	2187	-50.83	1458	-0.55
180	500	2549	1239	-10.63	1814	-61.96	1173	-4.73
MAE				2.72		MAE	6.87	

Table 4. Comparison of SPP prediction accuracy of the other two multiphase flow models

			Multiphase flow model			
			Gray model		Hagedorn & Brown Model	
q_L, gpm	qg, scfm	Recorded SPP, psi	BHCP, psi	Error %	BHCP, psi	Error %
250	250	2887	1700	24.44	1797	20.13
250	500	2660	1428	30.34	1563	23.76
240	500	2652	1299	27.83	1433	20.39
230	500	2620	1175	26.56	1308	18.25
210	500	2590	946	34.76	1069	26.28
180	500	2549	656	41.43	625	44.2
MAE				30.89		25.50

Although the Duns and Ros correlation is a result of an extensive laboratory study on two-phase flow tests conducted in vertical flow loop, it shows the lowest mean absolute error (MAE = 4.97 %) in predicting SPP, figure 6 illustrates the measured values of SPP versus the predicted values of SPP using Duns and Ros model.

The second most accurate model in predicting SPP is the Hassan and Kabir model (MAE = 6.87 %), Figure 7 illustrates the measured values of SPP versus the predicted values of SPP using Hassan and Kabir model.

The previous results of BHCP and SPP prediction indicate that the Duns and Ros model is more accurate than the Hassan and Kabir model and Beggs and Brill model although the last two were developed to predict the flow behavior in directional and horizontal wells. To explain the reason of this contradiction, the multiphase flow concepts must be well understood. The accuracy of pressure gradient prediction in multiphase flow models relies on other parameters beside the well profile or well path such as flow pattern prediction which affects the calculated friction factor and the liquid hold up which affects the traveling velocities of each phase and the physical properties of gas-liquid mixtures. Table 5. illustrates the available flow patterns of each multiphase flow model used.

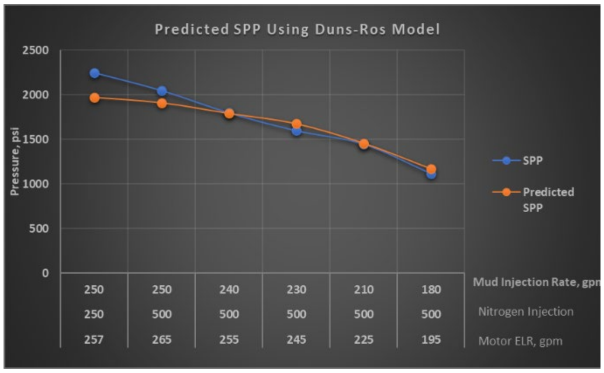

Fig. 6. Measured SPP vs. predicted SPP using Duns and Ros model.

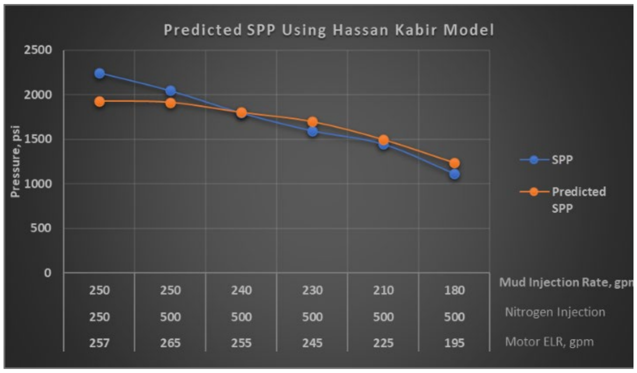

Fig. 7. Measured SPP vs. predicted SPP using Hassan and Kabir model.

Table 5. The available flow patterns depending on the selected multi-phase flow model.

Pattern	Beggs-Brill	Duns-Ros	Gray and Hasan Kabir	Hagedorn-Brown
Liquid	X	X	X	X
Gas	X	X	X	X
Segregated	X			
Intermittent	X			
Distributed	X			
Transition	X	X		
Bubble		X	X	X
Slug		X	X	X
Mist		X		
Annular			X	
Dispersed bubble			X	

6.3. UBD operating envelope of well 112-78H

The Duns and Ros model is utilized to construct the UBD operating envelope of well 112-78H because this model gives the most accurate results of multiphase flow behavior. The minimum vertical annulus liquid velocity required for efficient hole cleaning selected to be 70 ft / min, this value is the maximum vertical annulus liquid velocity that could be selected according to the mud motor operational specifications. The corresponding minimum horizontal annulus liquid velocity predicted to be 320 ft / min at 8772 ft MD, If the annular velocity is not adequate for efficient hole cleaning, liquid phase viscosity should be increased to provide sufficient cutting transport capacity. Although a significant formation fluid produced during UBD may improve cuttings transport but in the UBD operating envelope design, the effect of produced formation fluid was neglected considering the worst-case scenario and no production while drilling, results are demonstrated graphically in Figure 8.

6.4. Recommended operating condition

A comparison between the different operating conditions was carried out to determine the optimum liquid and gas rate, and results are demonstrated graphically in Figure 9.

From Fig. 9 the recommended liquid injection rate is 280 gpm and gas injection rate is 800 scfm at which the motor equivalent liquid rate is equal to 305 gpm (lower than the maximum operating rate), the drawdown at this condition is 500 psi to minimize the effect of pressure fluctuation, and the minimum vertical and horizontal annulus velocity are 70 ft / min and 320 ft/min respectively. Cutting transport ratio should be checked to ensure that there are no issues with hole cleaning at this annular liquid velocity in the lateral and vertical sections.

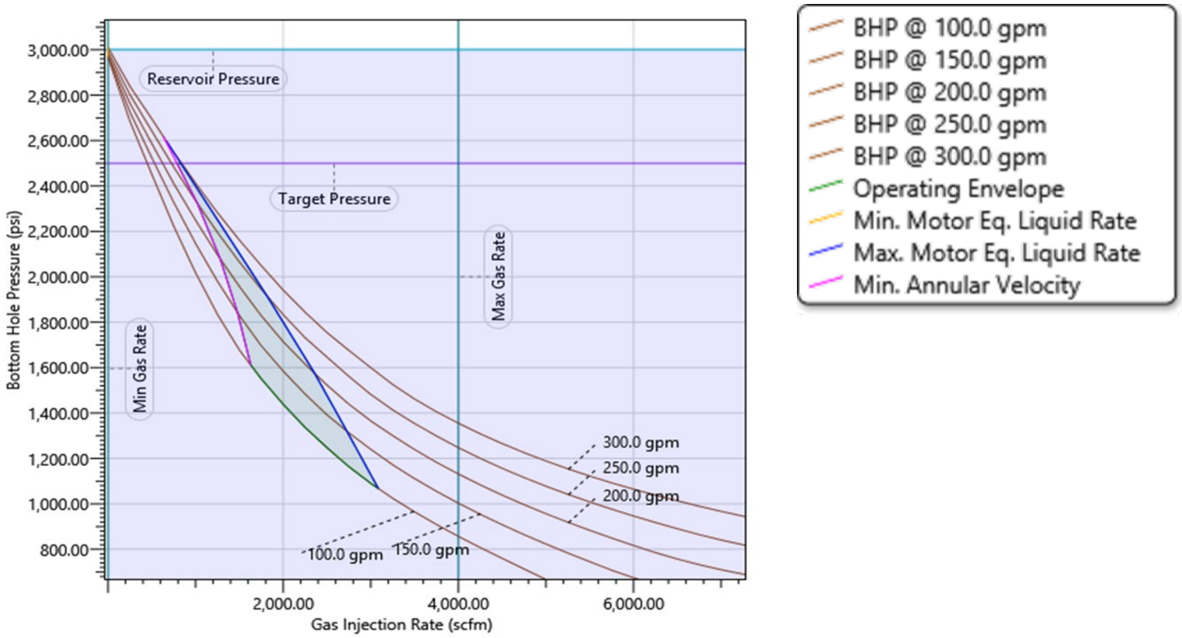

Fig. 8. UBD operating envelope of well 112-78H.

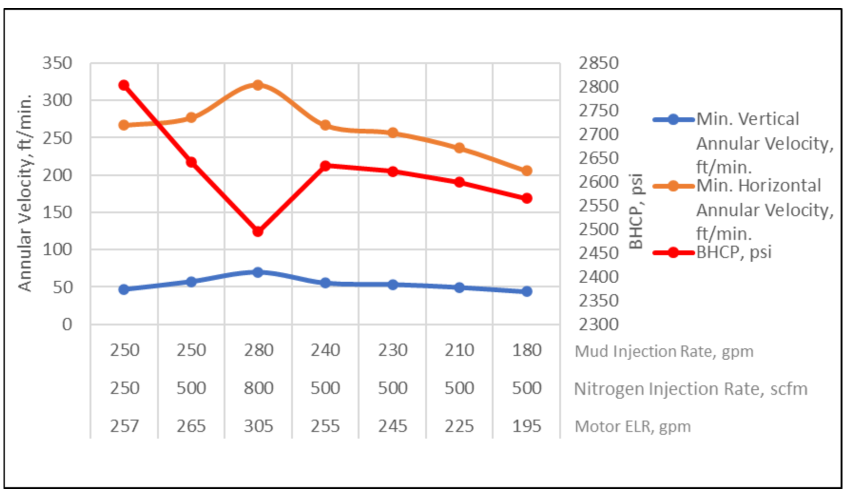

Fig. 9. Comparison of different operating conditions of well 112-78H.

Cutting transport ratio is defined as the cuttings velocity divided by the mean annular liquid velocity. Positive cuttings transport ratios means that cuttings will be transported to the surface with more or less transport efficiency. Negative cuttings transport ratios means that cuttings will be accumulated in the annulus. It is a good measurement of the carrying capacity of the drilling fluid. As illustrated in figure 10, the cutting transport ratio at the recommended operating condition and zero choke back pressure indicated that there is no hole cleaning problem. To show the effect of applied choke back pressure on the cutting transport ratio and hole cleaning, 100 psi back pressure is applied to the annulus during drilling at the same recommended liquid and gas injection rate as shown Figure 11.

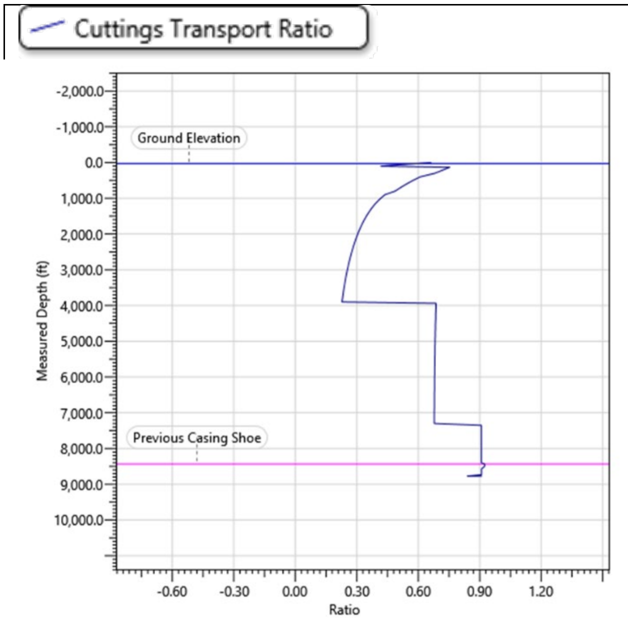

Fig. 10. Cutting transport ratio at the recommended operating condition and zero choke back pressure.

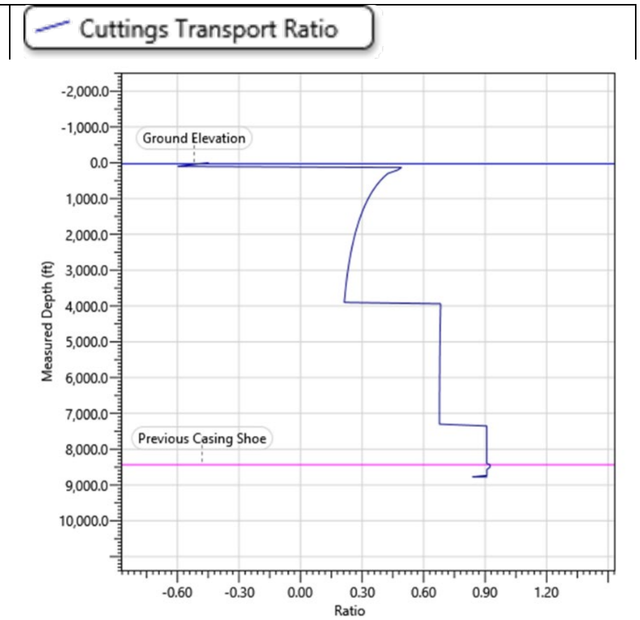

Fig. 11. Cutting transport ratio at the recommended operating condition and 100 psi choke back pressure.

7. Conclusions

Well 112-78H was drilled successfully to the total depth achieving an initial production rate of 750 bbl./day higher than the initial production rates of offset wells without any stimulation operations. There were no lost time incidents encountered neither due to pipe sticking nor due to loss of circulation while drilling the lateral section underbalanced. The rate of penetration enhanced, and the drill bit footage increased.

The application of different multiphase flow models to the first horizontal underbalanced well in the Gulf of Suez, Egypt have been evaluated. Based on the results, flow pattern and liquid hold up prediction have a significant effect on the multiphase flow model behavior. The Duns and Ros model and Hassan and Kabir model gave the most accurate hydraulic calculations of well 112-78H.

In aerated liquid drilling, the increase of gas injection rate enhances the hole cleaning because the occurrence of turbulent flow. On the contrary, applying choke back pressure to the annulus during aerated liquid drilling to increase BHCP and control formation fluids reduces the cutting transport ratio and hole cleaning.

8. Recommendations

Duns and Ros model and Hassan and Kabir model are recommended multiphase flow models to be used in similar cases for simulation the multiphase flow behavior in horizontal underbalanced wells and design the UBD operating envelope.

It is recommended to use additional pressure loss caused by bottomhole assembly such as MWD/PWD/LWD tools and mud motor. 400 psi has been used as an additional pressure loss in hydraulic calculations of well 112-78H, this value should be increased if the operating range of liquid and gas injection rates have been increased.

Electromagnetic measurement while drilling (EMWD) is recommended to be used in gasified liquid drilling using drillstring gas injection because the compressible fluid in the drillstring greatly attenuates the pressure pulses generated to convey the MWD signals to the surface particularly with high concentrations of injection gas.

To accelerate the tripping operation and avoid killing the well during UBD in the pay zone to minimize the possibility of formation damage, downhole deployment valve (DDV) is recommended to be used particularly if the well completely drilled underbalanced.

Nomenclature

UBD	*Underbalanced drilling*
BHCP	*Bottomhole circulating pressure*
SPP	*Standpipe pressure*
ECD	*Equivalent circulating density*
MPD	*Managed pressure drilling*
MD	*Measured depth*
TVD	*True vertical depth*
MWD	*Measurement while drilling*
PWD	*Pressure while drilling*
LWD	*Logging while drilling*
ELR	*Equivalent liquid rate*
MAE	*Mean absolute error*
EMWD	*Electromagnetic measurement while drilling*

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