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Annular Pressure Losses Prediction Using Power-Law Model with Polymer Water-Base Mud

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Abstract

Bottomhole Pressure (BHP) determination is quite crucial in the success of the drilling operations, especially on tight-drilling window environment. The calculation becomes much more critical when drilling with near-balance bottomhole pressure on the unconventional drilling techniques like Managed Pressure Drilling (MPD). Although Pressure-While-Drilling (PWD) technology can provide measured values of Bottomhole Pressure, it is so expensive and needs circulation to convey readings. Also, in case of tool failure, it consumes a lot of time to trip out of hole in order to change the tool, especially on deep-well drilling. On this paper, Bingham, Power-Law, Herschel-Bulkley and API RP13D rheological models have been utilized to calculate the Annular Pressure Loss (APL) on a deep well with polymer Water-Base Mud (WBM). A comparative study between model-calculated and PWD-measured values of APL for 15 points along the wellbore was conducted on the calculation of Annular Pressure Loss. Power-Law model was found the most optimum rheological model for polymer Water-Base Mud, due to exhibiting no Yield Stress. Power-law model gave 35 psi average error which can be tolerated most of the time during drilling operations.

Keywords

Bottomhole Pressure ;Calculation; Rheological models; Power-Law model; Polymer Water-Base Mud

Introduction

Managed Pressure Drilling (MPD) Technology

On tight-drilling window environments or when Managed Pressure Drilling (MPD) is applied, the importance of real-time prediction of Bottomhole Pressure (BHP) cannot be overemphasized. The increase or decrease of BHP might easily result in Non-Productive Time (NPT) by inducing formation breakdown or getting influx. In order to mitigate such incidents, BHP should be controlled and monitored at all time of the operations. Bottomhole Pressure is the summation of the hydrostatic pressure of the mud ($P_{hyd.}$), the Annular Friction Pressure of the flow (APF) and the Surface Back-Pressure (SBP) in case of MPD as shown in the following equation:

$$BHP = P_{hyd.} + AFP + SBP$$

Hydrostatic Pressure of the mud is simply calculated with the Mud Weight (MW) and True Vertical Depth (TVD), however along the deep wellbore, MW will be considerably variant but this point is out of the paper scope. The Annular Pressure Loss (APL) is considered the most difficult term as the drilling fluids are non-Newtonian fluids at which the viscosity of the fluid depends on the temperature and

the shear rate. To describe the thixotropic, pseudo-plastic behavior of the drilling fluid, different rheological models are utilized where different assumptions are postulated.

Pressure-While-Drilling (PWD) is a recent technology that gives us continuous reading of BHP that allows to optimize the drilling operations and calibrate the rheological models. However, it is an expensive technology, doesn't work on connection and could cost a trip in case of tool failure which is quite frequent.

Tazhong Field Overview

The Tazhong field is located in the Tarim Basin, in the central part of Taklimakan Desert, Xinjiang Uyghur autonomous region of Northwest China. Since 1989, The Tarim field has grown to be a crucial hydrocarbon, especially gas field for China[1] with 27 oil/gas discovered fields[2] and total area of 560 thousands km2. The basin consists of a Paleozoic marine cratonic basin and a Meso-Cenozoic continental foreland basin. In the Tazhong Uplift, there are three sets of oil and gas stratum systems, of which the Ordovician traps are the largest in size and close to the oil-source beds with the most favorable conditions to form

largescale oil and gas fields [3]. The structure is composed of 4 producing blocks with large networks of fractures which make drilling within this environment difficult. The well within this study was drilled in the eastern side of this structure which is a reef flat-lithology trap where the productive zone is the Ordovician fractured limestone. Table 1 shows the characteristics of the reservoir, while Figure 1 shows the location map for Tarim basin at Taklimakan desert in the north of China.

Table 1 Reservoir Characteristics [3]

Reservoir Pressure (SG)	1.11 – 1.20
Reservoir Temperature (^{0}C)	130 – 140
Gas Density (SG)	0.61 – 0.64
CO2 Percentage	1.6 – 3.2 %
H2S (ppm)	11 – 33,000

Figure 1 Tarim Basin, Taklamakan Desert Location Map.

The objectives for utilizing MPD technology on the well of the study were to drill and complete a 6'' lateral from 6539 m MD/ 6516 m TVD to 7149 m MD horizontally within the Ordovician Limestone reservoir with minimal losses and no serious well control situations. The objectives of this well were almost met because TD was called earlier than expected with only 79 m at 7070 m MD where they encountered huge mud losses that couldn't be handled via MPD.

Materials and Methodology

On an ultra-deep, recent horizontal well in China, Pressure-While-Drilling (PWD) technology was applied to get the actual measurement of BHP. The operator utilized Polymer Water-Base Mud (WBM) to reach the Cambrian reservoir. In addition, Bingham, Power-law, Herschel-Bulkley and API RP13D rheological models are utilized to predict the Annular Pressure Loss (APL) at 15 different points along the wellbore in addition to the Newtonian assumption for reference purpose.

The results from the different models were cross-plotted versus the actual values that are measured by PWD. Analysis for the cross-plot was performed and the different statistical values were calculated for each model.

This study has been done on a well drilled in China few years ago. The section on focus is 6'' sidetrack which was kicked off at 5585 m and reached Total Depth (TD) at 6647 m in the Cambrian dolomite reservoir sections. Polymer Water-Base Mud (WBM) was utilized to drill this section. Different mud weights have been used during the drilling of this section based on the well events. Tables 2, 3 and 4 are the input data utilized in calculating Annular Pressure Loss (APL) using the various rheological models. Table 2 shows the well configuration including the different casing strings with their setting depth.

Table 2 Well Configuration.

Interval (m)	Bit size (mm)	Casing size (mm)	Casing depth (m)
0-500	444.5	339.7	500
500-3900	311.2	244.5 (273)	3900
3900-5570	215.9	177.8	5572
5570-6000	152.4	127	6000
6000-6647	152.4	114.30 (Liner)	6647

Table 3 shows the mud properties of different mud weights used along the target section of the well. Mud rheological properties help calculating the friction pressure along the annulus. The thicker the mud, the higher the pressure loss, however viscosity is required to enhance the cutting lifting capacity of the mud and the well hole cleaning.

Table 3 Mud Properties of the Well.

Name	Value			
Mud Weight (g/cc)	1.18	1.22	1.27	1.33
Funnel Viscosity (s)	50	49	46-54	46-56
Plastic Viscosity (MPa.s)	20	20	20	20-21
Yield Point (Pa)	6	6	6-8	8-9
Fann Readings	52	52	52-56	56-60
	32	32	32-36	36-39
	24	24	26-29	29-31
	15	15	17-19	18-20
	3	3	4	5-6
	2	2	3	4-5

Table 4 shows the Bottomhole Assembly (BHA) of the drill string during drilling the highlighted section. Well Sketch along with the BHA defines the annular

clearance of the drilling fluid path. The cross-sectional area is critical for the annular velocity and the annular pressure losses.

Table 4 Bottomhole Assembly (BHA) of the Well

Section (m)		5983 - 6378		Mud Weight g/cm3 = 1.27-1.40	
BHA	Name × specs	OD (Inch / mm)	ID (Inch/mm)	Length (m)	Total Length (m)
	594 x DP x S135 I	3.5 / 88.9	2.6 / 66.09	5812.36	6378
	39 x HWDP×S135 I	3.5 / 88.9	2.13 / 54	363.15	565.64
	18 x DP×S135 I	3.5 / 88.9	2.6 / 66.09	173.22	202.49
	NMDC×S135	4.75 / 120.7	2.2 / 56	9.30	29.27
	MWD	4.75 / 120.7	2.2 / 56	5.12	19.97
	HCIM	4.75 / 120.7	2.2 / 56	3.80	14.85
	PWD	4.75 / 120.7	2.63 / 67	2.8	11.05
	Float sub	4.8 / 122	2.25 / 57.2	2.78	8.25
	1.25°Motor	4.75 / 1200	2.2 / 56	5.22	5.47
	PDC Bit	6 / 152.4		0.25	0.25

The following tables (Table 5 & 6 & 7) show the relevant inputs and Pressure-While-Drilling (PWD) readings of 15 different points along the wellbore. The bottomhole pressure is recorded by PWD, and then the annular pressure losses are derived from the recorded data. Annular Pressure Losses are also calculated using data like BHA, well sketch and mud properties via four different rheological models. Then the calculated and the measured data are compared so as to explore the best rheological model that could describe the behavior of the mud rheology during drilling this well.

Table 5 shows the measured depth, mud weight, flow rate and PWD-measured bottomhole pressure for each of the 15 points along the wellbore

Table 6 shows how to process the PWD-measured bottomhole pressure so as to calculate the measured Annular Pressure Losses. The hydrostatic pressure for each point is calculated based on the True Vertical Depth (TVD). The Wellhead Pressure (WHP) applied by

the Managed Pressure Drilling choke is also taken into consideration when calculating the Annular Pressure Losses. Then the summation of WHP and hydrostatic head is subtracted from the total bottomhole pressure to get the annular friction loss.

Table 7 shows some remarks that have been taken during drilling the section. The remarks are mainly the Total Gas percentage during drilling these different points. The gas is a different phase that enters the continuous drilling fluid phase. This gas might lead to different annular pressure losses due to the different flow regime and friction pressure calculations for the gaseous fluids. The gas would also be a special consideration in case of Oil-Base Mud (OBM) because of its ability to dissolve and hide up within the solution and sudden break out on surface. Usually higher gases along the annulus would give less friction pressure in the annulus.

Table 5 Measured data (Depth, Mud weight, Flow rate & BHP)

	#	Depth		Mud Weight		Flow Rate		BHP	
		m	ft	sg	ppg	liter/sec	gpm	Mpa	psi
BHA#1	1	5740	18832	1.18	9.8	9	143	68.9	9993
	2	5770	18930	1.18	9.8	9	143	69	10008
	3	5800	19029	1.18	9.8	9	143	69.1	10022
	4	5840	19160	1.18	9.8	8.8	139	69.2	10037
	5	5868	19252	1.18	9.8	9	143	69.4	10066
BHA#2	6	5880	19291	1.22	10.2	8.2	130	73.6	10675
	7	5950	19521	1.27	10.6	8	127	76.4	11081
	8	6020	19751	1.27	10.6	8	127	76.3	11066
	9	6090	19980	1.27	10.6	8	127	76.4	11081
	10	6130	20112	1.27	10.6	8	127	77	11168
BHA#3	11	6200	20341	1.33	11.1	8	127	79.5	11531
	12	6240	20472	1.33	11.1	8	127	79.9	11581
	13	6280	20604	1.34	11.2	8	127	80	11603
	14	6340	20801	1.34	11.2	8	127	79.9	11589
BHA#4	15	6370	20899	1.4	11.7	7.8	124	83.5	12111

Table 6 Processing Measured data (Depth, WHP, ECD, TVD, Hydrostatic Pressure. and APL)

	#	Depth		WHP		ECD		TVD	Hyd. Pressure	APL
		m	ft	Mpa	psi	ppg	sg	ft	psi	psi
BHA#1	1	5740	18832	0.7	102	10.20	1.23	18832	9626	266
	2	5770	18930	0.8	116	10.21	1.23	18855	9638	254
	3	5800	19029	0.9	131	10.21	1.23	18879	9650	242
	4	5840	19160	1.7	247	10.21	1.23	18910	9665	125
	5	5868	19252	1.8	261	10.22	1.23	18932	9677	128
BHA#2	6	5880	19291	2.2	319	10.84	1.30	18941	10010	346
	7	5950	19521	2.5	363	11.22	1.35	18996	10450	268
	8	6020	19751	2.2	319	11.19	1.34	19012	10459	288
	9	6090	19980	2.1	305	11.20	1.34	19029	10468	308
	10	6130	20112	3.4	493	11.28	1.35	19038	10473	202
BHA#3	11	6200	20341	1.2	174	11.64	1.40	19055	10977	379
	12	6240	20472	1.7	247	11.68	1.40	19064	10983	352
	13	6280	20604	1.3	189	11.70	1.40	19073	11071	344
	14	6340	20801	1	145	11.68	1.40	19087	11079	365
BHA#4	15	6370	20899	0.8	116	12.20	1.46	19094	11579	416

Table 7 Operation Remarks at different points.

	#	Depth		Operation Remarks
		m	ft	
BHA#1	1	5740	18832	TG < 5%
	2	5770	18930	
	3	5800	19029	
	4	5840	19160	TG=47%
	5	5868	19252	TG=52%
BHA#2	6	5880	19291	TG=25%
	7	5950	19521	TG < 20% and Intermittent PWD data all the time
	8	6020	19751	
	9	6090	19980	
	10	6130	20112	
BHA#3	11	6200	20341	TG < 10% and intermittent PWD data
	12	6240	20472	
	13	6280	20604	
	14	6340	20801	
BHA#4	15	6370	20899	

Results

The following tables (Table 8 and 9) show the results of Annular Pressure Loss calculation via Newtonian-fluid assumptions besides four different rheological models (Bingham, Power-law, Herschel-Bulkley and API RP13D) for 15 points at different depths. The PWD-measured values are mentioned so as to calculate the error and the error percentage. The PWD-measured values were used as references for the results of the model-calculated values.

Bingham model postulates a linear stress-strain behavior of viscosity with a departure from the origin, usually called "Yield Point". Bingham model doesn't take into consideration "shear thinning" effect where the fluid viscosity decreases at higher strain rates. Power-Law model on the other hand stresses the shear thinning effect without any Yield limit. The shear thinning behavior is expressed with a power function of two parameters: "Flow Behavior Index" and "Consistency Constant".

Table 8 shows the Annular Pressure loss values as they were calculated by Bingham model and Power-Law model. The error was calculated by subtracting the calculated value from the PWD-measured value. Then the error percentage was calculated by dividing the error by the PWD-measured value. Newtonian assumption is pressure friction calculation based on a single-value viscosity that keeps constant regardless of the strain rate. It is the same as Bingham model without Yield Point. Herschel-Bulkley model is believed to be the most accurate model as it combines the features of Bingham Yield Point with Power-Law shear thinning behavior. API RP13D model tried to make a better use of the six-theta readings via utilizing the low-strain readings in the low shear region and the high-strain readings in the high shear region.

Table 9 shows the Annular Pressure loss values as they were calculated by the Newtonian-assumption, Herschel-Bulkley model and API RP13D model. The error was calculated by subtracting the calculated value from the PWD-measured value. Then the error percentage was calculated by dividing the error by the PWD-measured value.

Figure 2 is a cross-plot between the calculated and the measured values of the Annular Pressure Loss for the different models. On the cross-plot, the points are staked together because the depth differences weren't that much.

The cross-plot shows Bingham model huge offset from the PWD-measured values which is referred to the much higher than reality plastic viscosity values of Bingham which lead to higher calculated friction losses. The Newtonian assumption gives the lowest values on the plot which are much lower than the actual PWD-measured values. That is referred to the ignoring of the pseudo-plastic behavior of the drilling fluid. It is pretty much clear that the closest values to the PWD-measured values are Power-Law model and Herschel-Bulkley model values.

percentages are the only positive values as the calculated pressure loss is always less than the measured value due to ignoring the pseudo-plasticity. The 4th and 5th points had huge error percentage as big Total Gas percentages were out during drilling these points as per Table-7. The high gas cut led to lower actual pressure losses while the calculating models don't take into consideration the gas effect. Along the rest of the points, there is an average amount of error that differs from each model to the other. This residual error is maybe due to the combination of cutting effect, drill string rotating effect, thermal effect and/or pipe eccentricity effect.

Table 8 Bingham & Power law APL compared to measured values

#	Measured	Bingham			Power Law		
	APL	Error %	Error	APL	Error %	Error	APL
1	266	-94	-249	515	-23	-61	327
2	254	-104	-264	518	-30	-75	329
3	242	-115	-279	521	-37	-89	331
4	125	-319	-398	522	-163	-202	327
5	128	-313	-400	528	-162	-207	335
6	346	-50	-172	518	9	31	315
7	268	-94	-253	522	-32	-86	354
8	288	-83	-240	528	-24	-70	358
9	308	-74	-227	535	-18	-55	363
10	202	-167	-337	539	-82	-164	366
11	379	-92	-347	726	2	8	371
12	352	-108	-379	731	-6	-22	374
13	344	-114	-393	736	-9	-32	376
14	365	-104	-379	744	-4	-15	380
15	416	-80	-332	748	10	40	376

Table 9 Newtonian, Herschel-Bulkley & API RP13D APL compared to measured values

| #	Measured	Newtonian Fluid			Herschel-Bulkley			API RP13D		
	APL	Error %	Error	APL	Error %	Error	APL	Error %	Error	APL
1	266	62	166	100	-17	-45	311	-34	-90	356
2	254	60	153	101	-23	-59	313	-41	-104	358
3	242	58	140	102	-30	-73	315	-49	-119	361
4	125	20	25	100	-150	-187	312	-187	-233	358
5	128	19	25	103	-149	-191	319	-185	-237	365
6	346	73	252	94	13	45	301	0	-1	347
7	268	65	175	93	-35	-95	363	-54	-144	412
8	288	67	194	94	-28	-79	368	-53	-152	440
9	308	69	212	96	-21	-64	373	-45	-138	446
10	202	52	106	96	-86	-174	375	-123	-247	449
11	379	74	281	98	-14	-52	431	-35	-131	510
12	352	72	254	98	-23	-82	434	-46	-162	514
13	344	71	245	99	-27	-94	438	-51	-174	518
14	365	73	265	100	-21	-77	442	-43	-158	523
15	416	76	318	98	-6	-23	439	-25	-105	521
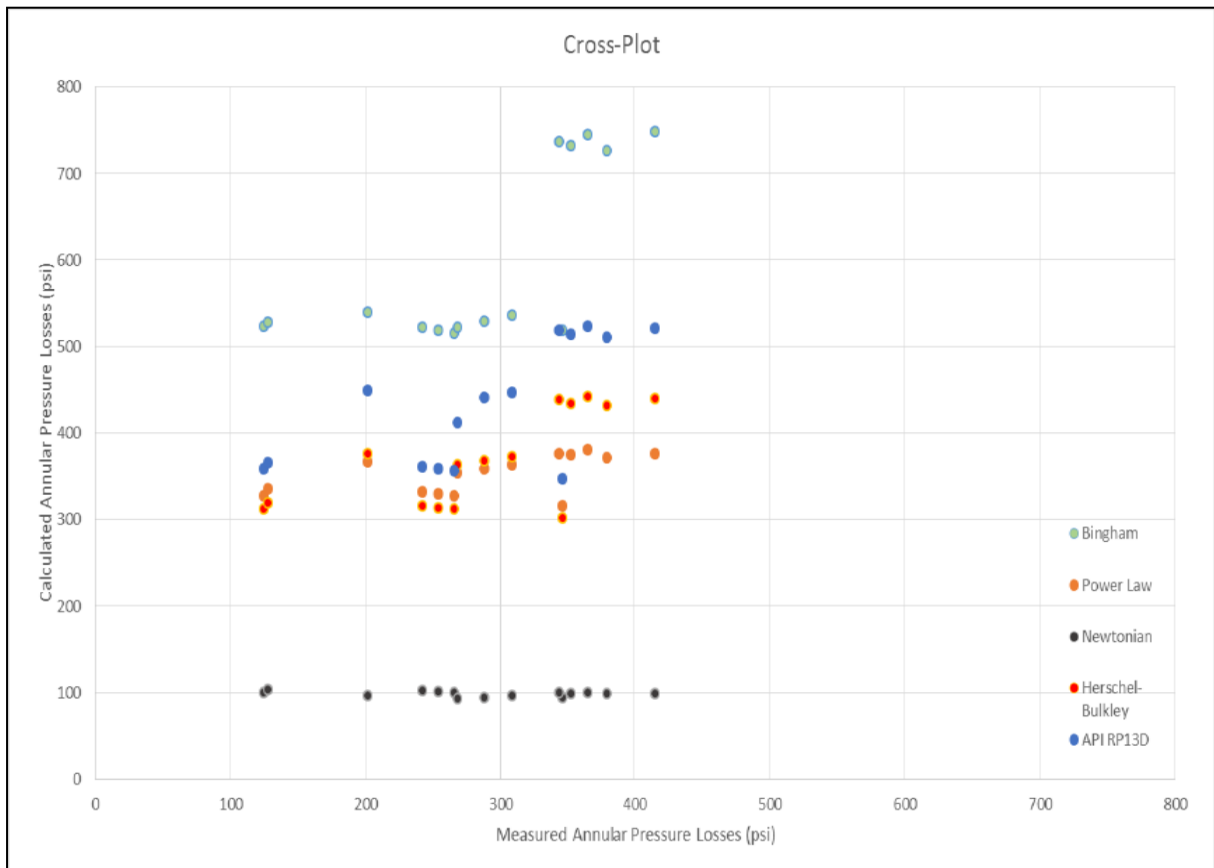
Figure 2 a cross-plot between the calculated and the measured values of the Annular Pressure Loss for the different models.
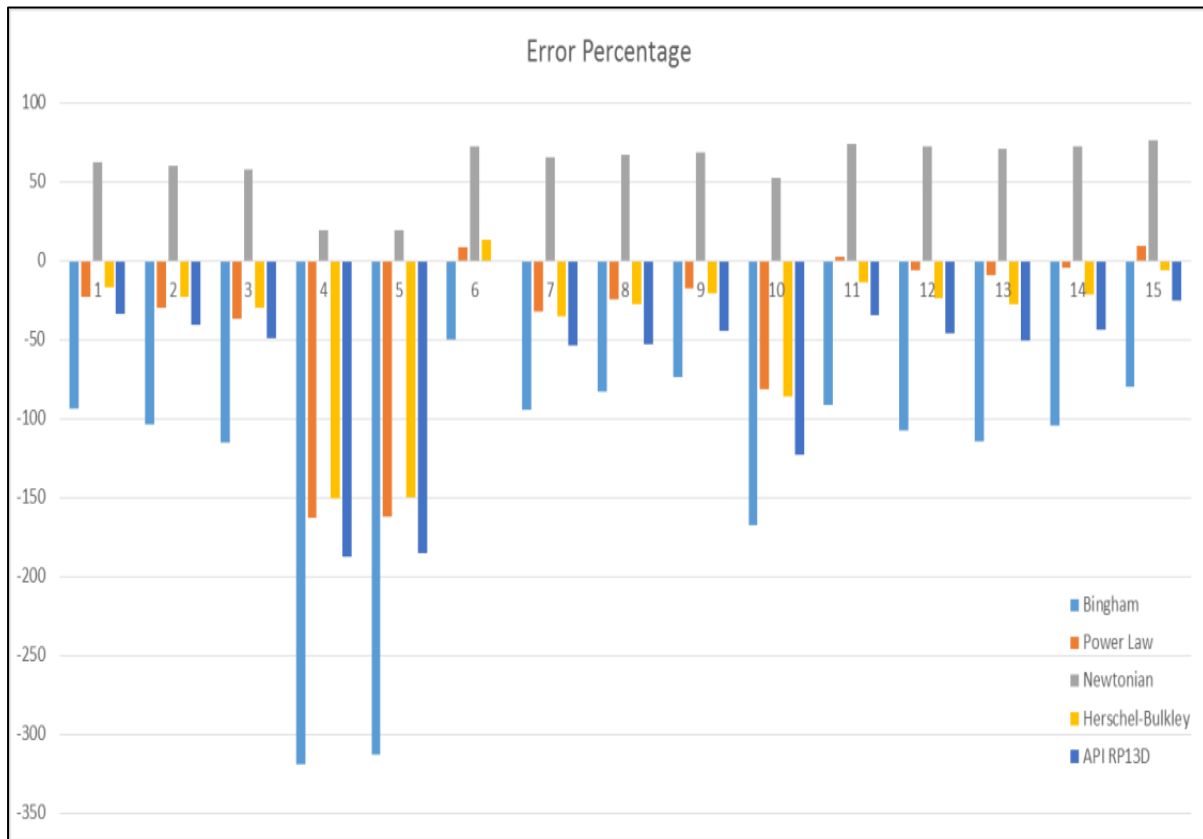
Figure 2 Error percentage graph for different rheological models.

Table 10 Statistics of the results (Points #4, #5 & #10 are excluded due to unreliable PWD readings)

Model	Newtonian	Bingham	Power Law	Herschel-Bulkley	API RP13D
Average Error	221.2	-292.9	-35.5	-58.3	-123.1
Average Error Percentage	68.5	-92.6	-13.5	-19.4	-39.6
Mean Absolute Error (MAE)	221.2	292.9	48.7	65.8	123.1
Mean Absolute Percentage Error	68.5	92.6	17.0	21.5	39.6
Mean Square Error (MSE)	51825	90461	3074	4765	17134
Root Mean Square Deviation (RMSD) / Standard Deviation (SD)	227.7	300.8	55.4	69.0	130.9
Normalized Root-Mean-Square Deviation / Coefficient of Variation of the RMSD, CV(RMSD)	1.282	1.361	0.431	0.494	0.755

Table 10 shows the statistical parameters for the different models results. It is pretty clear that Power-Law model is the best fitting model with the measured values with an average error of – 35 psi (35 psi higher than the measured value) and an average error percentage of – 13.5%. Herschel-Bulkley model comes second in terms of matching with the PWD-measured data with an average error of – 58 psi and an average error percentage of – 19.4%.

Discussion

Several observations can be noticed from the output tables and graphs. Many of the observations can be explained in the light of each model assumptions while other needs a review for the drilling conditions. The following items are the observation along with its possible explanation:

- Newtonian assumption give the lowest estimation at all points (average error= 221 psi & average error percentage= 68.5%). That is because most of drilling fluids are non-Newtonian fluids which show different effective viscosities with different strain rate. It is just calculated for referencing.

- Bingham models outputs are too much higher than the measured values which the highest error percentage (average error= -293 psi & average error percentage= -92.6%). Bingham model by assumptions, doesn't take shear-thinning effect into consideration. This makes Bingham model values of APL are always higher than the actual

values due to the higher apparent viscosity of Bingham model.

- Newtonian values and Bingham values are the lower and higher limits of prediction, respectively. Newtonian hypothesis gives the lowest values as it doesn't take "yielding limit" or "Shear-thinning" into consideration so it uses always much lower values for apparent viscosity, while Bingham model gives the higher values due to assuming much higher apparent viscosity and yield point[4].

- API 13D model gives values less than Bingham but with high error percentages (average error= -123 psi & average error percentage= -39.6%). API 13D model always gives values higher than Power law as it is using the lowest readings of viscometer so in this readings shear-thinning effect is much less than the higher values.

- Power law values and Herschel-Bulkley values are the best readings (Average error percentage of Power-law is -13.5% while of Herschel-Bulkley is -19.4%). In the first 5 points Power law values are higher, and then it starts to give lower values than Herschel-Bulkley values. In the first 5 points, Power law values were higher than Herschel-Bulkley values and less accurate because flow rate was high and then Power Law values became lower than Herschel-Bulkley at the rest of points.

- Large percentage of error in all models in points #4 and #5 because high gas percentages adversely affected PWD readings. PWD measurement wasn't reliable at point #10.

- Surprisingly, Power-law model was the best matching model while Herschel-Bulkley model (the widely-accepted and most commonly-used model in drilling industry all over the world) came second in accuracy. This proves that Polymer Water-Base Mud exhibits no Yield Stress.

- The constant amount of error that appears in all points is due to the effects of combination of factors like:
    a. It was found that the drillstring rotation raises the bottomhole pressure. It means that an extra friction pressure is added due to the drillstring rotation [5]. Rotation of drillstring is not considered in any model till the moment; however it has an effect on the bottomhole pressure. (almost 1 psi pressure loss per 1 rpm)
    b. Drilling was proceeding with less than 3 meter per hour ROP which doesn't provide any considerable amount of cuttings to increase APL.
    c. The hole TVD was deep enough to make the downhole temperature too high. In Higher temperature, the viscosity drops which leads to the pressure losses reduction [6].
    d. The consistent amount of gases during drilling causes annular pressure losses to be lower than expected.

- The high error in points #4 & #5 is due to the amount of gases came out of the well. Gas was around 50% during drilling of this interval. At point #10, PWD reading was unreasonable due to possible instantaneous malfunction or some other event during drilling.

Conclusions

Power-law model was found the best matching with Pressure-While-Drilling measured data with 35 psi average error (14%) in Annular Pressure Loss calculation with Polymer Water-Base Mud. Herschel-Bulkley model came second in accuracy with average error 58 psi average error (20%). Both of the models take into consideration the shear-thinning effect of the non-Newtonian fluids as a power function, however Power-Law model doesn't assume a Yield Stress meanwhile Herschel-Bulkley model assumes it. This leads to different indexes and consistency coefficients for each model of them. Polymer Water-Base Mud doesn't exhibit Yield Stress.

It is evident too that even with the best matching model; there is always a residual error that offsets the modelled value from the measured one. This residual error is attributed to many of the classical assumptions of the rheological models such as stationary, well-centered drillstring and isothermal assumptions. To drill, drillstring rotation is necessary which approximately adds 1 psi extra pressure loss per each rpm. The high temperature, encountered when drilling a deep reservoir (which is our case), changes the mud effective weight and rheology relevantly.

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