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Deliverability Output curve linearization Analysis: Matching the Power Equation with the Offset Elliptical Equation

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ABSTRACT

It has been observed that the Deliverability curve equation (Power equation) obtained by means Linearization analysis overestimates production rate at low wellhead pressure; in order to improve the forecasting it has been matched the Power Equation with the Offset Elliptical Equation, in that way the Linearization analysis is a helpful tool for determining the Offset elliptical equation parameters. Synthetic data based on a new super big bore New Zealand geothermal well it has been utilized in order to show this procedure.

1. INTRODUCTION

The purpose of deliverability testing is to determine well production capacity curve, it can be estimated by measuring the stabilized well head pressure at different flow rate spending a long time, each flow rate usually is in succession without any intermediate shut in period. Deliverability production curve is determined plotting Flow rate (*W*) versus Wellhead pressure (*WHP*); limitation of this test is the long time required to reach stabilization in low permeability reservoirs. If all production test data are in the steady state condition, the plot of production rate *Log* (*W*) versus pressure drop at wellhead conditions *Log* (*MDP–WHP*) for two phase geothermal wells should give a straight line [1] ; coefficients determined by linear least squared fitting will be used to get the Deliverability Output curve equation (Power equation). It has been observed that the extrapolation of data using the power equation at low wellhead pressure is overestimated, for that reason a matching with the offset elliptical curve is used in order to improve these forecast values.

2. DELIVERABILITY OUTPUT CURVE LINEARIZATION ANALYSIS

Some considerations have been necessary to do, it has been ignored the frictional pressure drop in the well and assume that well has zero length, the stable reservoir pressure (P_r) becomes equal the Maximum discharge pressure (*MDP*), the feeding point pressure (P_{wf}) is replaced by the well head pressure (*WHP*) to calculate the pressure drop at wellhead conditions. This analysis plot *Log* (*W*) versus *Log* (*MDP-WHP*) to linearize [1] the two phase geothermal wells Deliverability Output curve. If the measured data has reached the steady states condition, the plot should be a straight line or could be improved the linear correlation ignoring scattered data, using linear least squared fitting, the equation yielded is:

$$Log(W) = a_o + a_1 Log(MDP - WHP) \tag{1}$$

Appling Exponential in both sides

$$Exp[Log(W)] = Exp[a_o + a_1 Log(MDP - WHP)]$$

The following expression is yields:

$$W = 10^{a_o}(MDP - WHP)^{a_1} \tag{2}$$

If C and n values are determined by

$$C = 10^{a_o} \tag{3}$$

$$n = a_1 \tag{4}$$

Replacing values it yields the following equation:

$$W = C(MDP - WHP)^n \tag{5}$$

This equation is a general form at one proposed by Kjaran and Eliasson [2] for two phases geothermal well considering only turbulence flow regime at reservoir condition and given by:

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$$W = C(P_r - P_{wf})^{0.5} \tag{6}$$

Maximum Discharge Pressure is given by R. James equation [3].

$$\left(\frac{W}{W_{max}}\right)^2 + \left(\frac{WHP}{MDP}\right)^2 = 1 \tag{7}$$

Figure 1 shows the typical slope diagram of Linearized Deliverability Output curve

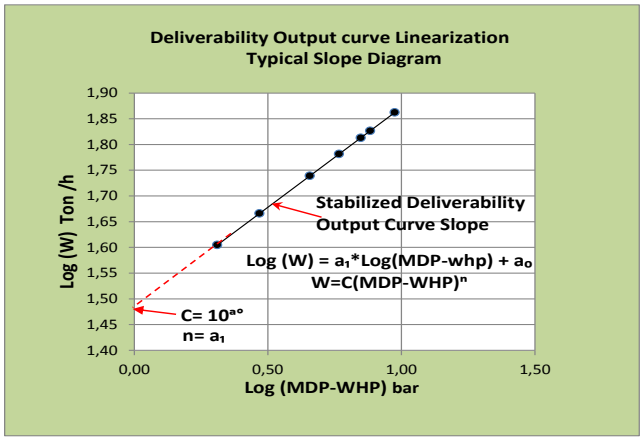

Figure 1. Typical Deliverability output curve linearization slope diagram.

3. MATCHING POWER EQUATION TO OFFSET ELLIPTICAL EQUATION

The deliverability output curve is elliptical in appearance [3], in order to improve the Deliverability Output curve; offset elliptical equation in both axes will be used, that is given by the following expression:

$$\left[\frac{(W-W_o)}{(W_{max}-W_0)}\right]^2 + \left[\frac{(WHP-P_o)}{(MDP-P_0)}\right]^2 = 1 \tag{8}$$

Then the flow rate is gotten by the following equation:

$$W = \sqrt{\left(1 - \frac{(WHP-P_o)^2}{(MDP-P_o)^2}\right)(W_{max} - W_o)^2} + W_o \tag{9}$$

R. James suggests [3] which optimum pressure for single stage flashing is 1/6 of the maximum wellhead pressure (*MDP*).

$$P_o = \left(\frac{1}{6}\right) MDP \tag{10}$$

W_{max} and W_0 values will be determined by trial and error.

Graphical procedure is shown in Figure 2. The Deliverability Output curve gotten with the Linearization analysis equation (5) will be matched with the offset elliptical curve equation (9) in all the production test data, the extrapolated point to low wellhead pressure will be determined using the offset elliptical curve equation.

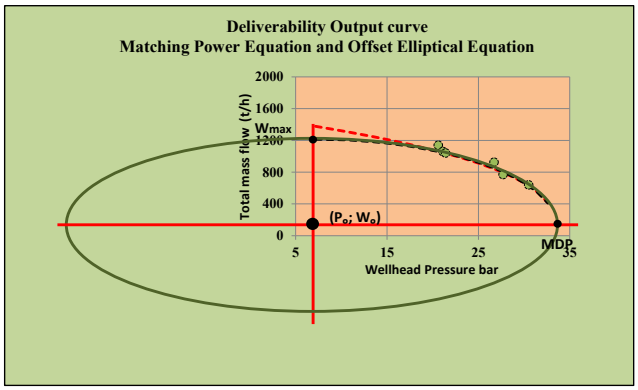

Figure 2. Matching the Power and Offset Elliptical Deliverability Output curve equation.

4. STUDY CASE

Synthetic data has been deduced from the production test graph presented by Quinao, J. J.et al. [4], which correspond to one super big bore geothermal well operated by Mighty River Power in New Zealand, the deliverability output curve is shown in Figure 3.

Data deduced from the graph has been analyzed in two ways:

1) Analyzing all the data from the Deliverability Output curve production test, and
2) Selecting data in order to improve the linear correlation

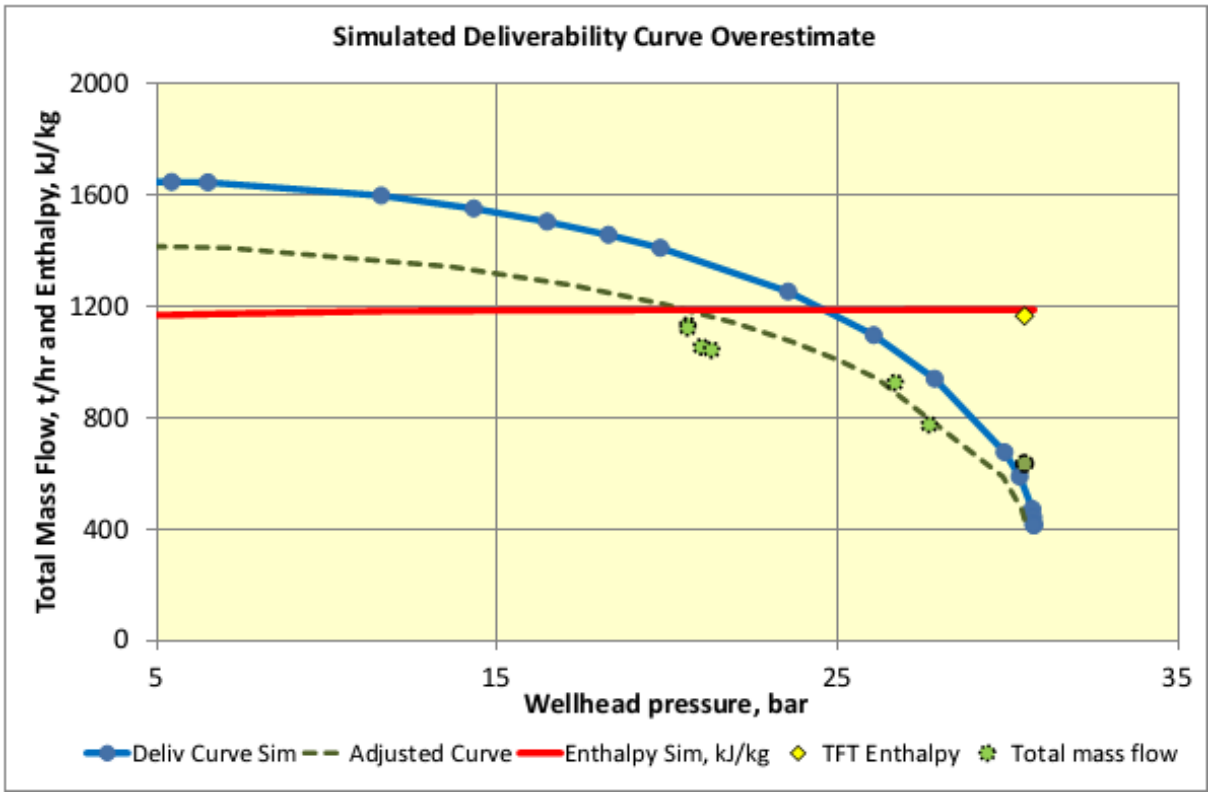

Figure 3. Deliverability Output curve Geothermal Super big bore. (From Quinao et al. [4])

4.1 All data analysis from the Deliverability Output curve production test

Table 1 shows the worksheet with the analysis procedure, *MDP* was determined using equation (7) and taking the production data at the wellhead pressure of 21.4 and 30.5 bar, it was gotten a value of 34.9016 bar; P_0 has a value of 7.4340 bars. Coefficients determined by linear least squared fitting from the Linearization analysis plot (Figure 4) has been used to get C y n with values of 327.8687 and 0.4561 respectively using equation (3) and (4) linear correlation is 0.9552 and deliverability output curve (Power equation) is given by:

$$W = 327.8687(34.9016 - WHP)^{0.4561} \quad \text{tons/h}$$

W_{max} and W_0 values were determined by means trial and error given values of 1256.18 and 6.352 T/h respectively, offset elliptical equation is given by the following expression:

$$W = \sqrt{\left(1 - \frac{(WHP - 7.434)^2}{(27.4676)^2}\right)(1249.82)^2} + 6.352 \quad \text{tons/h}$$

Deliverability Output curve considering all data is shown in Figure 5, offset elliptical equation give conservative extrapolated flow rate values at low wellhead pressure than power equation, maximum flow rate with offset elliptical and power equation are 1256.18 and 1485.75 tons/h respectively, the power equation give with an overestimated of 18.28% respect to the offset elliptical equation.

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Table 1. Linearization analysis considering all data

WHP	W	MDP-WHP	Log(1)	Log(W)	W (T/h)		Comparison
Bar	T/h	(1)		●	(C,n)	Elliptical Eq.	%
7,434		27,4676	1,4388		1485,75	1256,18	18,28
10,700		24,2016	1,3838		1402,40	1247,31	12,43
13,450		21,4516	1,3315		1327,33	1225,83	8,28
15,000		19,90	1,2989		1282,69	1207,83	6,20
17,500		17,40	1,2406		1206,52	1169,23	3,19
20,600	1140	14,30	1,1554	3,0569	1103,24	1103,24	0,00
21,100	1060	13,80	1,1399	3,0253	1085,48	1090,51	-0,46
21,400	1040	13,50	1,1304	3,0170	1074,65	1082,56	-0,73
23,000		11,90	1,0756		1014,57	1036,11	-2,08
25,000		9,90	0,9957		932,91	967,19	-3,54
26,700	925	8,20	0,9139	2,9661	856,11	897,18	-4,58
27,700	770	7,20	0,8574	2,8865	806,81	849,99	-5,08
29,200		5,70	0,7560		725,29	768,71	-5,65
30,500	640	4,40	0,6436	2,8062	644,54	684,97	-5,90
31,500		3,40	0,5317		573,06	608,79	-5,87
32,570		2,33			482,38	510,27	-5,47
33,000		1,90			439,55	463,30	-5,13
33,500		1,40			382,45	400,50	-4,51
34,000		0,90			312,74	323,94	-3,46
34,500		0,40			216,27	219,29	-1,38
34,700		0,20			157,94	157,50	0,28
34,852		0,05			83,32	81,43	2,31
34,892		0,01			39,40	39,40	0,00
MDP	34,9016			a_o	2,5157		
P_o	7,4340			a_1	0,4561		
Wmax	1256,18			n	0,4561		
W_o	6,352			C	327,8687		

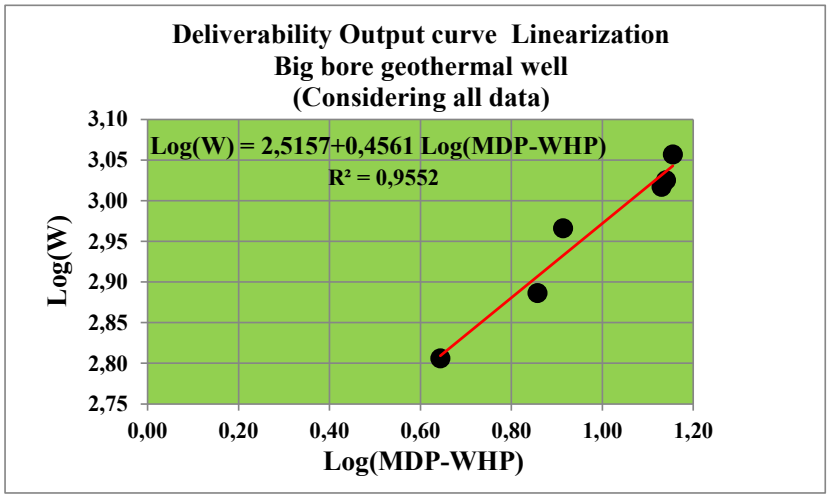

Figure 4. Deliverability Output curve linearization analysis considering all production data.

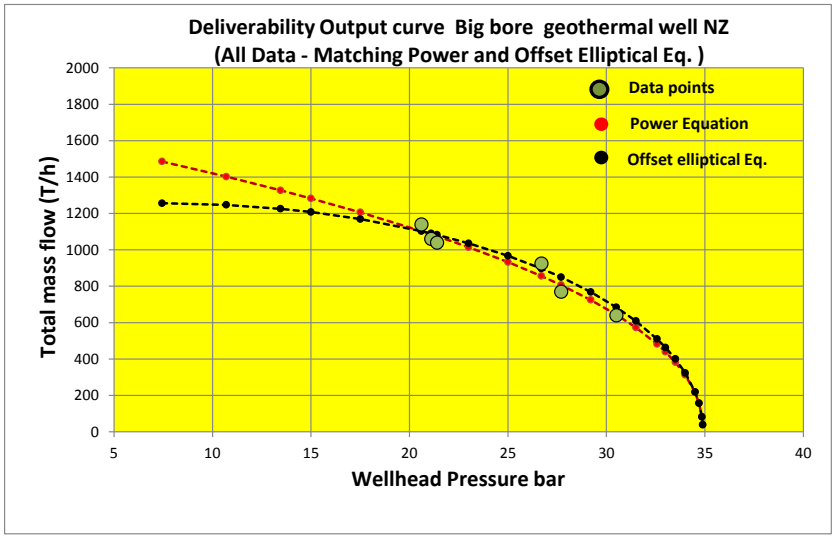

Figure 5. Deliverability Output curve (All production data - Matching power and offset elliptical equation).

4.2 Selected data analysis

It has been considered which data from 20.6 and 26.7 bars have not reaches the steady state condition for that reason have been excluded from the analysis.

Table 2 present the worksheet with the analysis, the previous value of *MDP* has been used in this section, coefficients determined by linear least squared fitting from the Linearization analysis plot (Figure 6) has been used to get C y n with values of 327.3407 and 0.4441 by means equation (3) and (4) respectively, linear correlation is 0.9961 and deliverability output curve equation (Power equation) is given by:

$$W = 327.3407(34.9016 - WHP)^{0.4441}$$

W_{max} and W_0 values were determined by means trial and error given values of 1214.23 and 9.849 Ton/h respectively, the offset elliptical equation is given by the following expression:

$$W = \sqrt{\left(1 - \frac{(WHP - 7.434)^2}{(27.4676)^2}\right)(1204.38)^2} + 9.849$$

Deliverability Output curve with selected data analysis is shown in Figure 7, offset elliptical equation give conservative flow rate values at low wellhead pressure than power equation, maximum flow rate with offset elliptical and power equation are 1214.23 and 1425.54 Ton/h respectively with an overestimated of 17.40% respect to the offset elliptical equation.

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Table 2. Linearization analysis considering selected data

WHP	W	MDP-WHP	Log(1)	Log(W)		W (T/h)		Comparison
Bar	T/h	(1)		●	●	(C,n)	Elliptical Eq.	%
7,434		27,4676	1,4388			1425,54	1214,23	17,40
10,700		24,2016	1,3838			1347,61	1205,69	11,77
13,450		21,4516	1,3315			1277,32	1184,99	7,79
15,000		19,9016	1,2989			1235,48	1167,64	5,81
17,500		17,4016	1,2406			1163,98	1130,44	2,97
20,600	1140	14,3016	1,1554		3,0569	1066,86	1066,86	0,00
21,100	1060	13,8016	1,1399	3,0253		1050,13	1054,58	-0,42
21,400	1040	13,5016	1,1304	3,0170		1039,93	1046,93	-0,67
23,000		11,9016	1,0756			983,28	1002,16	-1,88
25,000		9,9016	0,9957			906,13	935,75	-3,16
26,700	925	8,2016	0,9139		2,9661	833,42	868,28	-4,02
27,700	770	7,2016	0,8574	2,8865		786,66	822,81	-4,39
29,200		5,7016	0,7560			709,15	744,49	-4,75
30,500	640	4,4016	0,6436	2,8062		632,16	663,79	-4,77
31,500		3,4016	0,5317			563,79	590,39	-4,50
32,570		2,3316	0,3677			476,73	495,45	-3,78
33,000		1,9016	0,2791			435,47	450,18	-3,27
33,500		1,4016	0,1466			380,29	389,66	-2,40
34,000		0,9016	-0,0450			312,62	315,89	-1,03
34,500		0,4016	-0,3962			218,30	215,05	1,51
34,700		0,2016	-0,6955			160,74	155,50	3,37
34,852		0,0500				86,54	82,49	4,91
34,892		0,0100				42,34	42,34	0,00
MDP	34,9016				a_o	2,515		
P_o	7,4340				a_1	0,4441		
Wmax	1214,23				n	0,4441		
W_o	9,849				C	327,3407		

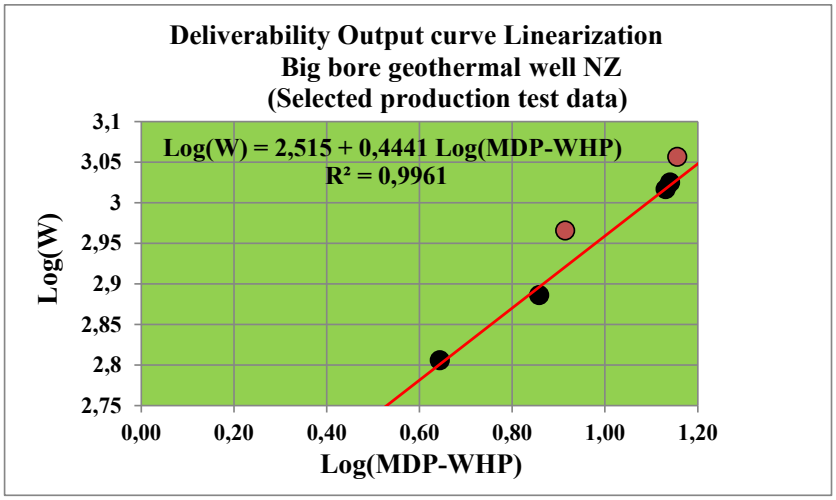

Figure 6. Deliverability Output curve linearization analysis considering selected data.

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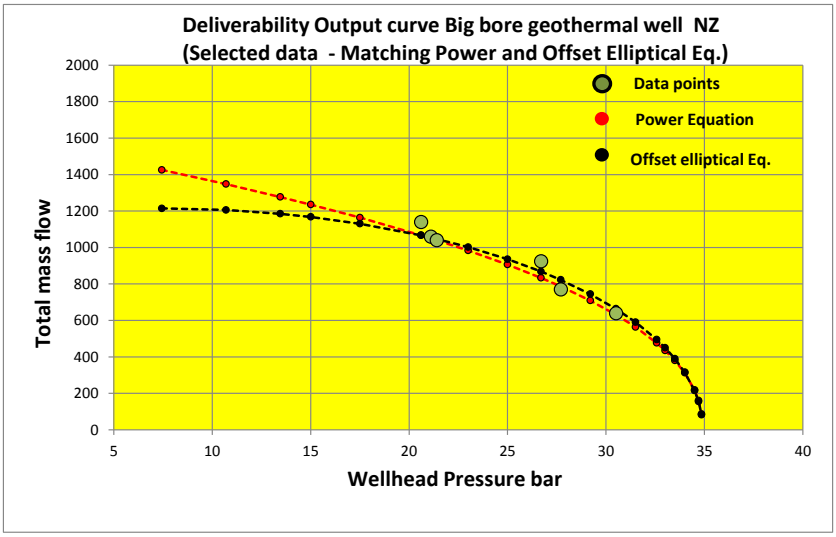

Figure 7. Deliverability Output curve (Selected data - Matching power and Offset elliptical equation).

4.2 Analysis results comparison

Power equation results at 20.6 and 34.892 bars have been considered as references in order to determine offset elliptical equation parameters by trial and error (W_{max} and W_0). In general the calculated values from both equations in the selected data analysis to high wellhead pressure are in agreement between 0.0 and -4.77%; for all data analysis the agreement is between 0.0 and -5.90%; power equation values in both cases are conservative.

Flow rate determined by Power equation at low wellhead pressure give overestimated values with respect to offset elliptical equation results, in the analysis considering all data the overestimation is 18.28 % in the comparison with the offset elliptical curve; in the selected data analysis the overestimation is 17.40 %.

5. CONCLUSION

Deliverability Output Linearization analysis has been used to determine the Deliverability power equation.

Flow rate equation has been defined by means an Offset elliptical equation.

The power and offset elliptical equation has been matched between MDP and the minimal wellhead discharge during the production test in order to determine offset elliptical equation parameters.

Flow rate values at low wellhead pressure determined by Power equation are overestimated instead is recommend to use the offset Elliptical equation for extrapolation.

The selected data analysis gave a conservative result that the analysis considering all the production test data.

Others potential applicability of linearization analysis are to determine Deliverability Output curve using the Isochronal or Modified isochronal test in sites where there are environmental or logistic restrictions that avoid realizing a long term production test and the extrapolation of the Deliverability curve gotten by means of Two Phase Tracer Test.

Attempt must be do for using the proposal analysis presented in other wells and fields in order to validate results.

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NOMENCLATURE

C : Linearized performance coefficient
MDP: Maximum discharge pressure (bar)
P_o : Pressure offset value (bar)
P_r : Stable reservoir pressure (bar)
P_{wf} : Bottomhole flowing pressure (bar)
W : Total flow rate (t/h)
WHP: Wellhead pressure (bar)
W_{max} : Maximum flow rate (t/h)
W_0 : Flow rate offset value (t/h)

a_0 : Independent term of trend line
a_1 : Slope of trend line
n : Deliverability exponent

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