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Two-Phase Geothermal Well Deliverability Output Curve Linearization Analysis

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ABSTRACT
Several attempts have been made in the past to transform the two phase Deliverability Output curve in a linear relationship by means of different types of graphics such as log-log and log-linear but there has been unsuccessfull. The present work plot Log (W) vs Log (MDP–P_{wh}) in order to give an answer at this issue. It has been proposed to use the Maximum Discharge Pressure (MDP) instead of Reservoir stabilized pressure (P_r) and the Wellhead pressure (P_{wh}) instead of flowing bottom reservoir (P_{wf}) to calculate the pressure drop; in the case of steady state flow has been achieved the stabilized flow condition, the plot should give a straight line at wellhead condition. Data from three geothermal wells is analyzed in order to show this procedure, coefficients obtained by means of least squares techniques will be used to determine the Deliverability Output curve equation.

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 W versus P_{wh}, limitation of this test is the long time required to reach stabilization in low permeability reservoirs. Sometime this task is hard if the wells do not have initial self-sustaining discharge or there are cold layer in the top, for that reason the production test spend long time just waiting for stabilized heat up condition of the wellbore. If all production test data are in the steady state condition, the plot Log (W) versus Log (MDP–P_{wh}) for two phase geothermal wells should give a straight line; coefficients determined by linear least squared fitting will be used to get the Deliverability Output curve equation.

2. DELIVERAVILITY OUTPUT CURVE LINEARIZATION ANALISYS

In the past Iglesias et al. (1983) plotted feed flowing pressure vs flow rate, transforming every measured data point of the characteristic curve (Deliverability Output curve) to the corresponding bottomhole conditions by means a wellbore simulator, in the case of steady state radial flow the plot of flow rate vs the corresponding sandface flowing pressure gave a straight line at reservoir condition. Wellbore and reservoir simulators has been used as tool for assess wellbore performance and reservoir respectively, some attempts has been made to link the two types of simulator Murray and Gunn (1993); considering that the accuracy of wellbore simulator is acceptable, the validity of the predicted output curve will be in dependent of the accuracy of the production parameters entered as input data, which is considered has achieved the steady state condition, the present work tries to improve these input data.

This contribution plot Log (W) vs Log (MDP-P_{wh}) to linearize the two phase geothermal wells Deliverability Output curve according with Recktenwald (2007). 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) is replaced by the Maximum discharge pressure (MDP) and the feeding point pressure (P_{wf}) is replaced by the well head pressure (P_{wh}), in order to calculate the pressure drop at wellhead conditions. When the measured data has reached the steady state condition the plot should be a straight line with equation given by:

$$Log\ (W) = a_0 + a_1 Log\ (MDP - P_{wh}) \tag{1}$$

Appling Exponential in both sides

$$W = Exp\left[a_0 + a_1 Log\ (MDP - P_{wh})\right]$$

$$W = 10^{a_0} (MDP - P_{wh})^{a_1} \tag{2}$$

C and n values are defined by

$$C = 10^{a_0} \tag{3}$$

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

Replacing values it yields the following equation

$$W = C(MDP - P_{wh})^{n} \quad (5)$$

This equation is a general form at one proposed by Kjaran and Eliasson (1983) for two phases geothermal well considering only turbulence flow regime and given by:

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

Maximum Discharge Pressure is obtained by James (1989).

$$\left(\frac{W}{W_{max}}\right)^2 + \left(\frac{P}{P_{max}}\right)^2 = 1 \quad (7)$$

MDP becomes equal to P_{max} value determined with this equation.

Figure 1 shows the typical slope diagram of linearized Deliverability Output curve by means of this proposed analysis.

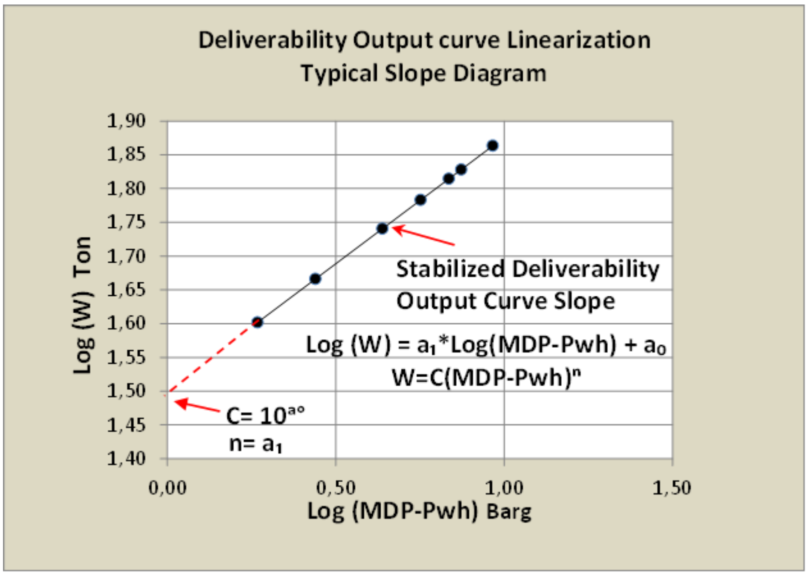


Figure 1: Deliverability output curve linearization typical slope diagram.

3. STUDIES CASE

Data obtained from Production test performed on MT-17 and MT-26 at Momotombo Geothermal field, Nicaragua Dal Spa (1988, 1988 a) and MW-1 from Menengai Geothermal Field, Kenya Suwai (2011), have been analyzed using the graph *Log (W)* versus *Log (MDP -* P_{wf}*)*, in order to get the linearized Deliverability Output curve and to determine Deliverability Output curve equation for each well in study.

3.1 Momotombo geothermal field, Nicaragua.

Momotombo geothermal field Geothermex (2002), is located approximately 50 km North West of Managua capital city of Nicaragua at an altitude of 40 m above sea level on Maribios volcanic chain on the South West slope of Momotombo Volcano with a concession exploitation area of 9 km^2 (Figure 2); In 1983 was commissioned the First Unit of 35 MW, later in 1988 was commissioned the Second Unit of 35 MW. In July 1999, Ormat started to manage the Momotombo geothermal field Porras (2008) as a result of an international bid signed a 15 years concession and power purchase agreement. At date 2015 a private company Momotombo Geothermal Power (MPC) has an exploitation concession by 15 years.

Wells deliverability in Momotombo geothermal field usually has been determined by Back Pressure Test spending 30-40 days, initial results were satisfactory with the production field at the beginning of Exploitation stage.

3.1.1 MT-17

MT-17 is a shallow well 328 meters depth at Momotombo geothermal field, it was tested from Dec 16, 1987 to January 19, 1988; total flow rate was measured by means Russell James method. Temperature and pressure profile were carried out before the test, maximum temperature recorded was 206.37°C, and MDP value of 13.24 Barg was determined using equation (7). Production test results are shown in Table No. 1, the discharge time by stage is not uniform and calculation worksheet with the proposal analysis is shown in Table No 2, brown squares data are not been considered in the analysis.

Figure 2: Location Map of Momotombo Geothermal field, Nicaragua.

Momotombo Geothermal Field MT-17
Production test results Dec 1987 - January 1988

Table No. 1

Date	Discharge T	Time	WHP	Water	Steam	W	H
	Hours		Barg	Ton/h	Ton/h	Ton/h	kj/kg
16/12/1987		11:10					
22/12/1987	144,50	10:50	3,8	8,593	65,605	74,198	2414,5
29/12/1987	167,00	10:00	5,6	10,898	61,994	72,892	2337,9
04/01/1988	149,25	15:15	6,2	10,305	60,131	70,436	2345,4
08/01/1988	94,25	13:35	7,4	8,045	55,108	63,153	2387,7
12/01/1988	95,50	14:00	8,7	5,017	50,557	55,574	2472,7
14/01/1988	45,25	11:10	10,3	1,792	44,577	46,369	2516,7
19/01/1988	122,50	13:30	11,2	0,887	40,440	41,327	2627,2
19/01/1988		14:10	12,8				

Fig No. 3 shows the Plot *Log (W)* versus *Log (MDP - P_{wh})*, values a_0 and a_1 are been determined and Deliverability curve equation is yield by substitution $W = 10^{1.4896} (MDP - P_{wh})^{0.3933}$ that is shown in Fig No. 4; black knots are the production test results data and the red squares are the calculated data with the proposed analysis, the correlation respect to original data is between 98-102 %.

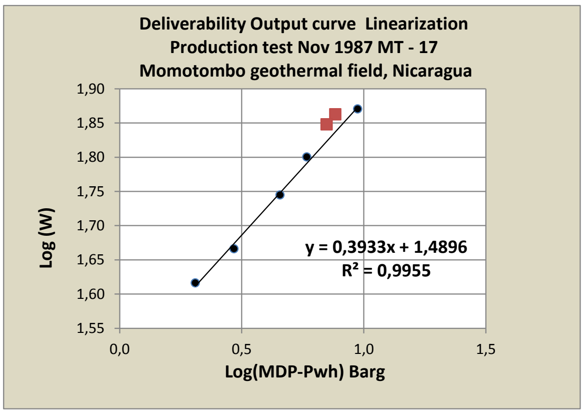


Figure 3: Linearization MT-17 data.

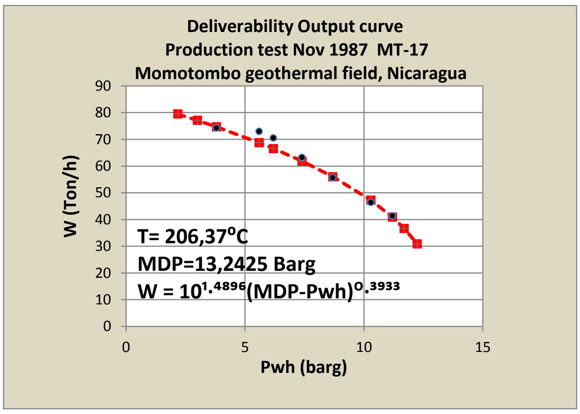


Figure 4: Deliverability Output curve MT-17.

Momotombo Geothermal Field MT-17
Deliverability Output curve Linearization analysis
Production Test Dec 1987 - January 1988

Table No. 2

WHP	W	MDP-Pwh (1)	Log (1)	Log W		W (C,n)	Comparison
Barg	T/h	Barg	Barg	●	■	Ton/h	%
3,8	74,198	9,44	0,9751	1,8704		74,66	100,6
5,6	72,892	7,64	0,8832		1,8627	68,70	94,3
6,2	70,436	7,04	0,8477		1,8478	66,53	94,5
7,4	63,153	5,84	0,7666	1,8004		61,82	97,9
8,7	55,574	4,54	0,6573	1,7449		55,99	100,7
10,3	46,369	2,94	0,4687	1,6662		47,20	101,8
11,2	41,327	2,04	0,3102	1,6162		40,89	98,9
11,7		1,54	0,1882			36,61	
12,2425		1,00	0,0000			30,87	
				a0		1,4896	
	MDP (Barg)	13,2425		a1		0,3933	
	Temperature	206,37		n		0,3933	
				C		30,8745	

3.1.2 MT-26

Well MT-26 is a shallow well with 620 m depth it was tested from Oct 23 until Nov 11, 1987. Temperature and pressure profile were carried out before the test, maximum temperature recorder was 237.25°C, MDP value was 17.081 barg gotten excellent matching. Production test results are shown in Table No. 3 and calculation worksheet is shown in Table No 4 with the proposal analysis, the brown square data is not considered in the analysis.

Momotombo Geothermal Field MT-26
Production test results Oct - Nov 1987

Table 3

Date	Discharge T	WHP	Water	Steam	Wt	H
	hours	Barg	T/h	T/h	T/h	Kj/Kg
29/10/1987	141,00	6	154,8	70,5	225,3	1125,8
02/11/1987	94,25	8	144,8	61,8	206,6	1094,4
04/11/1987	47,25	9,7	131,0	57,6	188,5	1108,2
06/11/1987	48,25	11,8	117,6	53,3	170,9	1122,5
09/11/1987	75,25	13,8	93,6	45,9	139,6	1160,2
11/11/1987	47,00	15,3	69,4	37,5	106,9	1211,2
13/11/1987	46	15,7	48,6	33,9	82,5	1346,5

Fig No. 5 shows Plot *Log (W)* versus *Log (MDP - P_{wh})*, values a_o and a_1 are been determined, Deliverability curve equation is yield by substitution $W = 10^{1.9338} (MDP - P_{wh})^{0.4009}$ that is shown in Fig No. 6, black knots are the production test results data and the red squares are the calculated data with the proposed analysis, the correlation respect to original data is between 98-102 %.

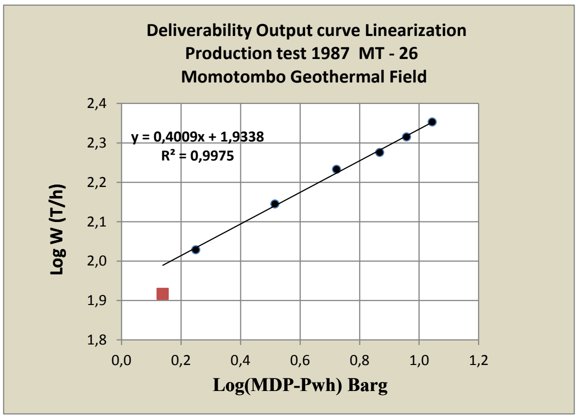


Figure 5: Linearization MT-26 data.

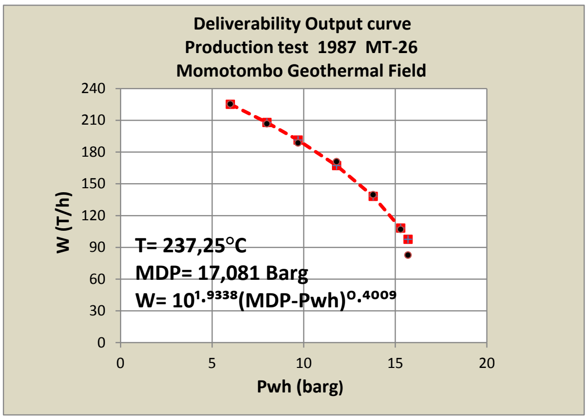


Figure 6: Deliverability Output curve MT-26.

Momotombo Geothermal Field MT-26
Deliverability Output curve Linearization analysis
Production test results Oct - Nov 1987

Table 4

WHP	Qt	MDP-Pwh	Log (1)	Log W		W(C,n)	Comparison
	T/h	(1)		●	■	T/h	%
6	225,292	11,08	1,0444	2,3527		225,2	99,9
8	206,618	9,08	0,9579	2,3152		207,9	100,6
9,7	188,542	7,38	0,8678	2,2754		191,3	101,5
11,8	170,868	5,28	0,7223	2,2327		167,2	97,9
13,8	139,559	3,28	0,5153	2,1448		138,2	99,0
15,3	106,850	1,78	0,2494	2,0288		108,1	101,2
15,7	82,501	1,38	0,1385		1,9165	97,6	118,3
				a0		1,9338	
MDP=	17,08			a1		0,4009	
				n		0,4009	
				C		85,8618	

3.2 Menengai geothermal field, Kenya

Menengai geothermal field encompasses the Menengai volcano, the Ol-Rongai volcanoes, Ol-Banita plains and parts of the Solai graven to the northeast. Regional exploration for geothermal resources in Kenya indicates that the Quaternary volcanic complexes within the Kenya rift valley provide the most promising prospects for geothermal exploration.

A detailed exploration of the geothermal resources in the Menengai area was conducted in 2004 and later with infill work in 2010. Geoscientific investigations comprising geology, geophysics, geochemistry and heat loss measurements were utilized in searching for indicators for the existence of geothermal resources in the area within the Menengai caldera, Ol-Rongai and Ol-Banita calderas to the northwest of the Menengai caldera. The existence is evidenced by active strong surface manifestations and young lavas, signifying an active heat source. Geophysical analysis indicates a hot magmatic body underlying the caldera structure. Reservoir temperatures deduced from gas geothermometry were estimated to be more than 280°C. Efforts to harness the untapped geothermal energy led to the siting of exploratory wells MW-1, MW-2, and MW-3.

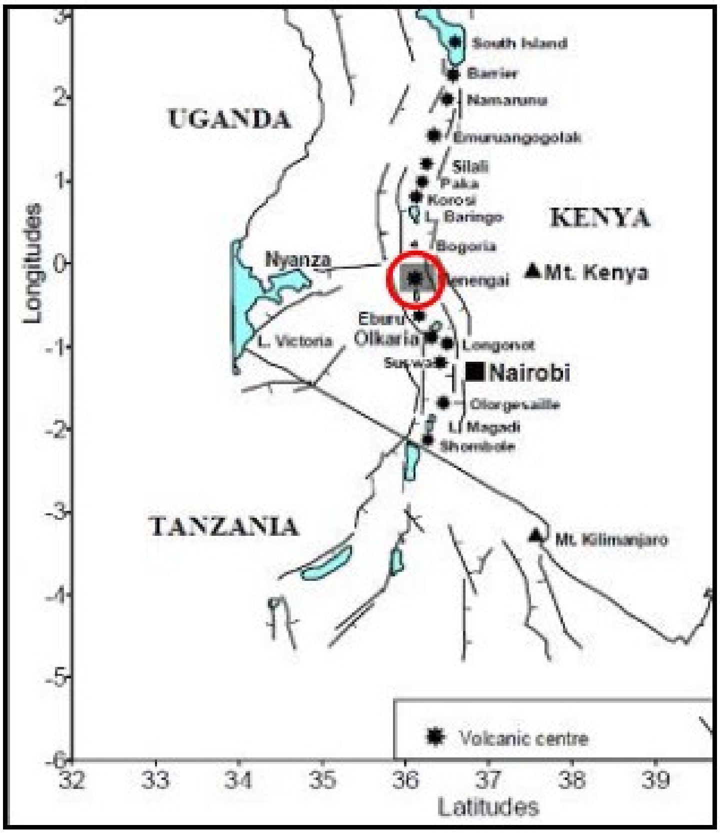


Figure 7: Map showing Menengai geothermal area location (Wameyo, 2005)

Dávila.

3.2.1 MW-1

Well MW-1 was spudded on 12th February, 2011 and completed on 1st of May, 2011. Drilling commenced with a 26" hole down to 80 m where the 20" surface casing was installed to 79.6 m. Next, a 17½" hole was drilled down to 400.5 m where a 13⅜" intermediate (anchor) casing was installed to 398.7 m. Then a 12¼" hole was drilled down to 843 m, and then the well was cased to 842 m using a 9⅝" casing. After the casing depth, an 8½" hole was drilled and progressed well down to 2206 m, a 7" slotted liner was installed from 802 down to 2172 m, with a 23.5 m 7" blank liner at the top (inside the production casing).

Well MW-1 was drilled with mud initially and later with water, aerated water and foam to its final depth. Partial circulation losses were encountered at 1247-1342 and 1739-1802 m, while partial to total circulation losses were encountered at 1077, 1988-2007, 2031-2059 and 2124 m.

Sometime determine the Deliverability output curve is hard if the wells do not have initial self-sustaining discharge or there are cold layer in the top, for that reason the production test spend long time just waiting for stabilized heat up condition of the wellbore. It is a common practice for Kenyan reservoir engineers to carry out the production test by means of a series of discharge period using different pipe discharge diameters in order to get the deliverability curve of the well in study. MW-1 production test data was carried out by means of three discharge periods expending 125 days, the first two discharge periods were carried out reducing the diameter discharge and the last one increasing the diameter discharge.

Production test data is summarized in Table 5 Suwai (2011) and shown in Figure 8.

Menengai Geothermal Field, Kenia

Tabla 5. Summary of Output conditions during discharge MW-1

Pipe diameter (mm)	WHP (bar-a)	Total mass flow (kg/s)	Water flow (kg/s)	Enthalpy (kj/kg)	Steam Flow at WHP (kg/s)
Set 1 (29/5/2011 - 11/7/2011)					
202	7,9	59,4	40	1155,3	14,5
155	8,3	54,6	37	1150,7	13,1
130	9,4	54,2	34,6	1234,5	15,3
104	11,9	48	31,7	1210,7	13
Set 2 (13/7/2011 - 24/8/2011)					
202	6,9	51,8	34	1195.6	13
155	7,4	46,7	32,5	1115,3	10,6
130	8,4	47,9	31,2	1198,8	12,6
104	10,7	44,9	29	1217,3	12,3
80	14,5	40,3	25,6	1241,6	11,5
Set 3 (25/8/2011 - 21/9/2011)					
202	6,3	45	29,1	1213,5	12,2
155	7,3	44,5	29	1208,8	12
130	8,5	45,2	29	1231,2	12,7
104	10,3	42,8	27,6	1213,9	11,6

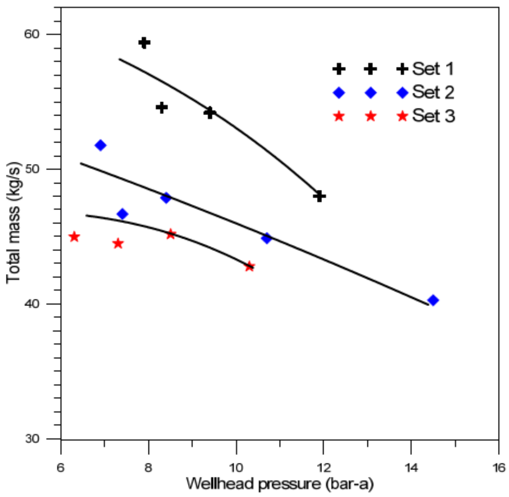


Figure 8: Output curves for MW-1 from three sets of discharge data (Suwai J. J., 2011).

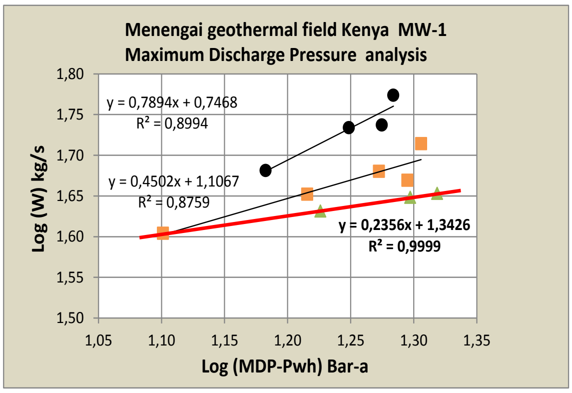
In this analysis has been assumed that the third discharge time has gotten the stabilized condition. In that way it has been calculated the Maximum discharge pressure using the production test data at 6.3 and 10.3 Bara by means equation (7) given a value of 27.13 Bara, worksheet analysis is shown in Table 6.

The three discharge Production test data has been plotted in Figure 7, using *Log (W)* versus *Log (MDP-Pwh)*, the black circles, orange squared and green triangles represent set 1, set 2 and set 3 respectively, in order to get a better correlation in set 3 has not been considered the data at 8.5 bar-a; It can see that the discharges slope line decrease in the way that the well is heating up.

Menengai Geothermal field Kenya
Deliverability output curve linearization analysis
Production test data MW-1, 2011

Table 6

WHP	Total mass	MDP-Pwh	Log (1)	Log W (Total mass)			W (C,n)	Comparison
Bar-a	kg/s	Bar-a		Set 1	Set 2	Set 3	kg/s	
		(1)		●	■	▲	●	%
7,9	59,4	19,23	1,017	1,7738				
8,3	54,6	18,83	1,000	1,7372				
9,4	54,2	17,73	0,950	1,7340				
11,9	48	15,23	0,807	1,6812				
6,9	51,8	20,23	1,160		1,7143			
7,4	46,7	19,73	1,145		1,6693			
8,4	47,9	18,73	1,113		1,6803			
10,7	44,9	16,43	1,028		1,6522			
14,5	40,2	12,63	0,837		1,6042			
6,3	45	20,83	1,319			1,6532	45,0	100,01
7,3	44,5	19,83	1,297			1,6484	44,5	99,97
8,5	45,2	18,63				1,6551	43,8	96,98
10,3	42,8	16,83	1,226			1,6314	42,8	100,00
14,5		12,63					40,0	
18		9,13					37,1	
20		7,13					35,0	
22		5,13					32,3	
24		3,13					28,8	
25		2,13					26,3	
26,13		1,00					22,0	
MDP=	27,13	Bar-a	a0			1,3426	1,3426	
			a1			0,2356	0,2356	
			n			0,2356	0,2356	
			C			22,0090	22,0090	



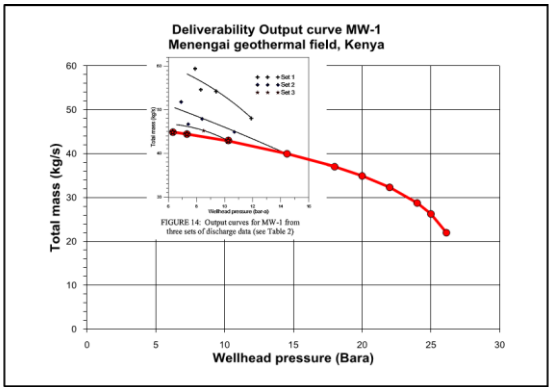


Figure 9: Linearization analysis MW-1

Figure 10: Deliverability Output curve MW-1

Set 3 coefficients from the linear correlation shown in the Fig 9, have been used to determine the Deliverability Output curve equation given by:

$$W = 22.009 * (MDP-P_{wh})^{0.2356}$$

Total mass flow has been calculated using this equation and shown on Table 6 in column W(C, n), the values obtained are in agreement with the third discharge production test, except the value at 8.5 Bar-a that is least than the value from production test, should be than this point had not gotten the stabilized steady state condition, calculated results shown that production test data at 14.5 Bara of set 2 is in agreement, in the Figure 9 this point is plotted on the linear correlation of set 3; results data is shown in Figure 10 together with the original deliverability Output curves, red circles represent the calculated results using the Deliverability

Output curve equation determined before. Dashed red line is the Deliverability Output curve showing an extrapolation at higher wellhead pressure, the accurate is important at the future for designing the appropriated piping layout.

4 CONCLUSIONS

The Maximum Discharge Pressure (MDP) value for a geothermal well with single or multiple feed zones is determined by equation (7) using two stabilized stages values from the production test data.

When the different production stage tests have achieved the stabilized time, Plot *Log (W)* versus $Log\ (MDP–P_{wh})$ shows a linearization. It is possible to detect production test data that has not gotten the stabilized discharge condition.

In multiple discharge production test period it can see that the trend line slope decreases according with the stabilized condition is achieved.

Coefficients determined by linear least squared fitting have been used to get the Deliverability Output curve equation.

Due to that the pressure drops in two phases geothermal well is affected mainly by turbulence flow the Deliverability exponent value (n) must be less than 0.5.

The proposal procedure give results in agreement between 98-102% with respect to production test data.

It is not necessary to know the well geometry and location of feed zones because the data used is at wellhead condition.

A potential applicability of linearization is to determine Deliverability Output curve using the Isochronal or Modified isochronal test in sites where there are environmental or logistic restrictions that avoid carry out a long term production 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_g)
P_r : Stable reservoir pressure (Bar_g)
P_{wh} : Wellhead pressure (Bar_g)
W : Total flow (t/h)
a_0 : Independent term of trend line
a_1 : Slope of trend line
n : Deliverability exponent

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