STEAM DELIVERABILITY OF VAPOR DOMINATED RESERVOIR

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ABSTRACT

There are five in the world of unique and complex vapor dominated system, mainly one in the Geyser (U.S.A.), Lardarllelo (Italy), Matsukawa (Japan) and two Kamojang and Derajat in Indonesia.

History or future performance of steam production from vapor dominated geothermal system can be predicted using one-dimensional (i.e., lumped - parameter) or complex three-dimensional reservoir model.

The objective of this study is to simulate the response of the system using a lumped - parameter model. The lumped - parameter is a simple model of reservoir simulation which consist of single reservoir block feed by a recharge flow proportional to pressure drop.

The lumped - parameter model is an ideal for vapor dominated reservoirs that have produced the steam at least one third to one half of field lifetime.

*This study have been done to predict the reservoir performance such as pressure depletion, steam rate or deliverability of steam in vapor dominated reservoirs where the material balance for the gas was adopted. The basic principle of the lumped - parameter model assumes that a reservoir has some average properties of fluid and rock****)*

1. INTRODUCTION

The lumped parameter model developed base on study case in "BS" geothermal field, which has the total capacity installed of 22 Mwe in 1966.

The model indicates the reservoir pressure tend to depleted by 0.7 kg/cm^{2}g.annum. This significant reservoir pressure decrease indicated by a decrease of water level of 1.8 m per year at X exploration well.

2. DATA PREPARATION.

The pressure decline process in vapor dominated reservoir can be approached by using (P/Z) simple method or lumped parameter model. This technique adopt a method which has been developed by Brigham and Neri for Gabbro zone, Lardallelo, 1979, 1980[1)], Dee and Brigham, 1985[3)].

2.1. Basic Concept

The model based on a vapor dominated hydrothermal system developed by White, e.t, al, 1971. The following assumptions are:

- Steam is the pressure - controlling phase
- The vertical pressure gradient should be greater than vapourstatic
- Saturated steam and water coexist
- Steam/water counter flow exists in the vapor dominated zone, where pore space is mostly filled with steam which ascend from boiling zone at depth and condensed at the to of the zone and the condensate moves downward.
- There are large pressure difference between the vapor dominated zone and the surrounding aquifer, so the reservoir must be shielded from surrounding aquifer by low permeability barriers at least at the top and side of reservoir.

2.2. Reservoir Production and Pressure Data

The performance of steam flow shown in ***Figure-1***. The production flow rate data for ten years starting from 1980 through 1990 which has an average flow rate 240 ton/hr in total.

Consider the field performance, indicates that steam production rate slightly decrease with time, although in certain well shows the fluctuated steam flow rate.

The reservoir temperature is assuming equal to 240^{O}C or saturated pressure, Ps = 33.48 kg/cm2, and using of water level data, the reservoir pressure is constructed and expressed as follows,

$$Pr = Pi - \rho gh \quad (1)$$

Based on the water level data and eq. (1), a relationship between reservoir pressure and time could be formulated:

$$Pr = -0.3395t + 711.41 \quad (2)$$

the result are depicted in **Tabel-1** and **Figure-2**.

2.3. Steam Compressibility Factor (Z)

Term of steam compressibility factor is adopted from the gas formula and defined as measure to express a degree of deviation from perfect behavior of ideal gas[2)]. This property obtained by using steam table and formulated into

$$Z = \frac{P\upsilon}{RT} \quad (3)$$

Using the Eq.3 and pressure data (***Table-1***) and value at 240^{O}C, the result presented in **Table-2**.

3. RESERVOIR MODELING

In a deep boiling water zone, (P/Z) plotted against cumulative production of steam will present a linear relationship. The linearity of curve obtained during the period from one-third to a half of field development phase, and using this result, the correlation of (P/Z) and cumulative steam production is expressed as follows[1].

$$\left(\frac{P}{Z}\right)_{deep} = A - B * G_p \qquad (4)$$

To obtain a value of constants A and B. a least square method applied. For this case, the constant of ***A = 57.084*** and ***B = 0.0096***, respectively.

Combining the concept of reservoir depletion in deep boiling water zone with the concept of linear flow from that zone to the production zone, Dee and Brigham[3], Brigham and Neri[1], have expressed the reservoir depletion relationship as

$$\left(\frac{P}{Z}\right)_{top} = \left(\frac{P}{Z}\right)_{deep} - \Delta\left(\frac{P}{Z}\right)_{flow} \qquad (5)$$

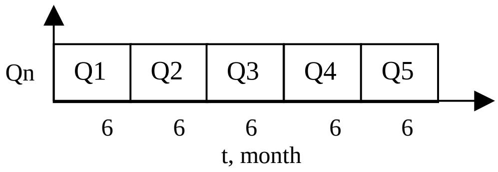
The reservoir pressure decline in deep boiling zone already expressed in Eg.4. Now, to derive an equation for pressure decline from deep boiling zone through fractured to the production zone, that geometry of flow into this zone is assumed approximately linear. This implies that the flow in the production zone is transient flow. The pressure decline will depend on the term in the P_D function for linear flow, and the timing of pressure transient will depend on the term in t_D function[1]. Explanation of such problem in detail found in Nabor and Barham[9]. The solutions summarized in **Figure-3.**

There are three curves, which represent the effects of pressure of a boundary on flow conditions. Curve $F_1(t_D)$ represent for a system with a closed outer boundary, curve $F_{1/2}(t_D)$ for a system without outer boundary and curve $F_o(t_D)$ for a system with constant pressure outer boundary. To solve the problem $F_o(t_D)$ will be used. A curve for constant flow in **Figure-3** also presumed for production zone, and for actual variable flow rate, a superposition calculation method is necessary. Explanation of the method of superposition in detail seen in Brigham and Neri[1].

From the $F_o(t_D)$, it assumed that P_D is proportional to square root of t_D until t_D is equal to 0.785 and it's constant being equal to 1 after t_D = 0.785. The parameters t_D in the real system are unknown, so it has to be assumed a real time which is equivalent to t_D = 0.785. This real time is called ***lag time,*** defined as time required for fluid flow to reach effective steady-state[3]. By assuming this time and combined with the method of superposition, the steady-state equivalent flow rate, Q_{eq} could be defined as a function of lag time. For example the time incremental to be used of, 6, 6, 6 and 6 months and the lag time of 30 months, so the equivalent steady state flow rate would be

$$Q_{eq} = Q_1 + \frac{1}{\sqrt{30}}\left[(Q_2 - Q_1)\sqrt{18} + (Q_3 - Q_2)\sqrt{12} + (Q_4 - Q_3)\sqrt{6}\right] \qquad (6)$$

Explanation of obtaining the Qeq in detail shows in the following schematic diagram



In this case, the equivalent steady state flow rate for lag times 30 months shown in **Tabel-3.**

For the steam flow rate Eq. 6 corrected by using [1].

$$Q_{eq} = D'\int_{P_1}^{P_2} \frac{2p\partial p}{\mu z} = D'\Delta m(p) \qquad (7)$$

Where

$m(p) = \int_{P_1}^{P_2} \frac{2p\partial p}{\mu z}$, and D' is inversely proportional to fracture permeability.

For the vapor dominated reservoir m(p) is proportional to (P^2)[8]. Equation 7 simplified as follows

$$Q_{eq} = D'\Delta\left(p^2\right) \qquad (8)$$

There is an empirical correlation between Eq.7 and Eq.8, so that pressure decline of deep boiling zone through fracture zone to the production zone can be written as

$$\Delta\left(\frac{P}{Z}\right)_{flow} = \frac{D'\left[\Delta\left(p^2\right)\right]^n}{\left(\frac{P}{Z}\right)_{top}^m} = \frac{\left(Q_{eq}\right)^n}{\left(\frac{P}{Z}\right)_{top}^m} \qquad (9)$$

Combine the Eq.4, Eq.5 and Eq.9 and use the least square method to obtain the ***m*** and ***n*** constants. In case of this field, ***m = 0.017*** and ***n = 0.985***, respectively. Thus, the general formula for reservoir pressure depletion defined as:

$$\left(\frac{P}{Z}\right)_{top} = 57.084 - 0.0096 * G_p - 16.976\frac{\left(Q_{eq}\right)^{0.985}}{\left(\frac{P}{Z}\right)_{top}^{0.017}} \qquad (10)$$

4. DISCUSSION

In order to obtain a representative model of reservoir pressure decline and predict the future performance of reservoir pressure, a pressure history performed.

4.1. Pressure History Matching

The value of constant in the Eq.10 is 57.084, 0.0096, and 16.976. These values related to the initial reservoir pressure, liquid volume in deep boiling zone and pressure drop in deep boiling zone through fracture zone to the production horizon, respectively, where the lag time of 30 months is used.

The reservoir pressure calculated by Eq.2, shows a significantly match with observed pressure **(Figure-4)**, so that model could be applied in this field and future behavior of reservoir pressure depletion could be predicted.

4.2. Future Production Rate and Reservoir Pressure Depletion

To predict the future production rate and reservoir pressure decline the universal deliverability equation formulated by Forchheimer[8)] can be applied

$$P_{avg}^2 - P_{tf}^2 = aq - bq^2 \quad (11)$$

In several cases, the second term in the equation above, represent the effect of Non-Darcy flow can be omitted, so

$$P_{avg}^2 - P_{tf}^2 = aq \quad (12)$$

The inlet turbine pressure into the plant is of 3.5 kg/cm^2G and Eq.2 used to obtain P_{avg}. To fit the Eq.12 with Eq.10 and to obtain ***a*** constant regression, trail and error methods are applied. The constant ***a*** in this case is equal to **139.34** ton/month/well **Table-4** summarize a result of the future production and reservoir pressure decline, while **Figure-5** represents a relationship between steam cumulative production and reservoir pressure decline.

4.3. Steam Recovery Factor

The unit recovery also called the initial unit reserve, which is generally lower than the initial unit in place. The remaining reserve at any stage of depletion is different between the initial reserve and the unit production at that stage of depletion[1)]. The recovery factor expressed in percentage of the initial reserve in place or,

$$RF = \frac{G - Ga}{G} X 100\% \quad (13)$$

Extrapolating the curve to reservoir pressure equal to zero **(Figure-6)**, gives the initial steam in place to be 5.6 x 10^9 ton. Assuming the abandon reservoir pressure is 10 kg/cm^2G or equal to 180^OC and draw a straight line parallel to steam cumulative production. By extrapolating the line at 10kg/cm^2G, give a recoverable reserve of steam to be 4.2x10^9 ton.
By performing Eg.13 the recovery of field calculated to be 25%.

5. CONCLUSION

This paper present the lumped parameter model that used for predict the future reservoir pressure depletion in vapor dominated reservoir and the result is summarized:

1. The reservoir pressure in this field tends to decrease at a rate of 0.7kg/cm^2G per year. This significant reservoir pressure indicated by a decrease of water level of 1.8 m/year at X exploration well.
2. A good match obtained between observed and simulated pressure for the period 1980 - 1990. This model applied to estimate future behavior of reservoir pressure.
3. For an abandonment reservoir pressure of 10kg/cm^2G or 180^OC the life time of field will end at a year of 2031 and ultimate steam recoverable reserve would be 4.2 x 10^9 ton.
4. The initial steam in this field is estimated to be 5.6 x 10^9 ton and has a recovery factor of 25%.
5. By the year of 2000, the reservoir pressure (P/Z) predicted to be 26.36kg/cm^2G.

6. REFERENCES

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NOTATION

a = constant
b = constant
A = initial (P/Z) of the deep reservoir system, ksc.
B = constant which defines the depletion tare of the reservoir;a larger B signifies a smaller reservoir.
D = unknown constant, which inversely pro-portional to reservoir fracture permeabe-lity.
g = gravity acceleration, m/sec^2.
G = initial steam in place, ton

Ga = cumulative steam production at abandon pressure, ton.
Gp = cumulative steam production, ton
h = high of water level drop, m
m = constant
n = constant
P = steam pressure, kscG
Pavg = average pressure in production zone, kscG
Pi = initial reservoir pressure, kscG
Pr = reservoir pressure, kscG
Ptf = turbine inlet pressure, kscG
(P/Z)deep = value of P/Z at deep boiling zone, kscG
(P/Z)flow = drop in P/Z due to steam flow from deep zone to the upper production interval, kscG.
(P/Z)top = value of P/Z seen at the producing zone; it is less than the value of P/Z within the deep boiling interval due to linear flow from the deep zone to producing zone, kscG.
q = steam flow rate, ton/month
Q1, Q2.. = the steam flow rate of certain period, ton/month.
Qeq = equivalent steady state flow rate, ton per month.
= density of steam, kg/m^3
R = universal of gas constant, kJ/kg ^{O}K.
T = temperature, ^{O}C.
T = time, year.
ν = specific volume of steam, m^3/kg
Z = the steam compressibility factor.

APPENDIX

Table-1
RESERVOIR PRESSURE @ 240OC OF
VAPOR DOMINATED FIELD

YEAR	W.LEV. m	WL m	m3/kg	P kscG	Pr kscG
1979	1.810				
1980	2.155	0.345	0.001	0.275	33.205
1981	4.483	2.328	0.001	1.858	31.622
1982	5.776	1.293	0.001	1.032	32.448
1983	8.276	2.500	0.001	1.995	31.485
1984	11.121	2.845	0.001	2.270	31.210
1985	12.500	1.379	0.001	1.100	32.380
1986	20.303	7.803	0.001	6.226	27.254
1987	17.359	-2.944	0.001	-2.349	35.829
1988	15.022	-2.337	0.001	-1.865	35.345
1989	17.706	2.684	0.001	2.142	31.338
1990	21.255	3.896	0.001	3.109	30.371
1991	25.435	10.413	0.001	8.309	25.171

Table-2
THE STEAM COMPRESSIBELITY FACOR @ 240^{O}F
"BS" GEOTHERMAL FIELD

YEAR	Pr kscG	m^3/kg	Z Factor	Pr kscG
1979				
1980	33.205	0.06020	0.84390	39.34
1981	31.622	0.06330	0.84510	37.42
1982	32.448	0.06160	0.84390	38.45
1983	31.485	0.06350	0.84410	37.03
1984	31.21	0.06410	0.84460	36.95
1985	32.38	0.06170	0.84350	38.39
1986	27.254	0.07350	0.84570	32.23
1987	35.829	0.05570	0.84260	42.52
1988	35.345	0.05640	0.84160	42.00
1989	31.338	0.06390	0.84550	37.07
1990	30.371	0.06530	0.84500	36.27
1991	25.171	0.08100	0.83080	29.24

Table-3
STEADY STATE EQUIVALENT FLOW RATE IN
10E6ton/6month OF VAPOR DOMINATED,
"BS" GEOTHERMAL FIELD

YEAR	FLOW RATE	LAG TIME			
		12 mo.	24 mo.	30 mo.	36 mo.
	0.975				
1980	0.969	0.971	0.972	0.973	0.973
	0.912				
1981	1.007	0.978	0.977	0.977	0.977
	0.943				
1982	0.896	0.929	0.924	0.923	0.922
	0.876				
1983	0.882	0.872	0.890	0.895	0.898
	1.058				
1984	0.948	0.982	0.951	0.943	0.937
	0.919				
1985	0.895	0.877	0.930	0.944	0.954
	0.865				
1986	1.034	0.979	0.962	0.957	0.954
	1.111				
1987	1.025	1.088	1.023	1.006	0.994
	0.999				
1988	1.024	0.997	1.031	1.039	1.045
	1.074				
1989	0.994	1.023	1.016	1.014	1.013
	0.970				
1990	0.993	0.968	0.999	1.007	1.013

Table-4
OBSERVED, CALCULATED AND PREDICTED OF THE
RESEVOIR PRESSURE DEPLETION OF THE "BS" FIELD

YEAR	GP 10^6ton	(P/Z)obs. ksc.G	Qeq. 10^6ton	(P/Z)flow ksc.G	(P/Z)calc. Kg/cm^2.G
1980	59.15	39.2	0.973	15.348	41.14
1981	117.58	38.86	0.977	15.419	40.49
1982	173.26	38.52	0.923	14.563	40.78
1983	226.76	38.18	0.895	14.125	40.69
1984	287.92	37.84	0.943	14.889	39.31
1985	343.09	37.5	0.944	14.904	38.74
1986	400.93	37.16	0.957	15.116	37.95
1987	465.86	36.82	1.006	15.897	36.52
1988	527.66	36.48	1.039	16.42	35.38

Table-4
(continued)
OBSERVED, CALCULATED AND PREDICTED OF THE RESEVOIR PRESSURE DEPLETION OF THE "BS" FIELD

YEAR	GP 10^6ton	(P/Z)obs. ksc.G	Qeq. 10^6ton	(P/Z)flow ksc.G	(P/Z)calc. Kg/cm^2.G
1989	588.44	36.14	1.014	16.029	35.17
1990	648.20	35.8	1.007	15.92	34.68
P R E D I C T E D					
1991	776.65	35.47	0.964	15.239	34.07
1992	902.62	35.13	0.942	14.889	33.16
1993	1026.15	34.79	0.922	14.584	32.23
1994	1147.26	34.45	0.898	14.206	31.40
1995	1265.97	34.11	0.878	13.897	30.52
1996	1382.30	33.77	0.859	13.602	29.66
1997	1496.27	33.43	0.840	13.303	28.81
1998	1607.92	33.09	0.823	13.023	27.98
1999	1717.27	32.75	0.805	12.75	27.16
2000	1824.33	32.41	0.788	12.481	26.36
2001	1929.13	32.07	0.771	12.219	25.57
2002	2031.70	31.73	0.755	11.962	24.80
2003	2132.06	31.39	0.739	11.709	24.05
2004	2230.24	31.05	0.723	11.46	23.32
2005	2326.25	30.71	0.707	11.214	22.60
2006	2420.12	30.37	0.692	10.972	21.91
2007	2511.88	30.03	0.677	10.733	21.23
2008	2601.55	29.69	0.662	10.497	20.57
2009	2689.15	29.35	0.647	10.264	19.92
2010	2774.70	29.01	0.632	10.033	19.30
2011	2858.24	28.68	0.618	9.805	18.69
2012	2939.78	28.34	0.603	9.58	18.10
2013	3019.35	28.00	0.589	9.358	17.53
2014	3096.97	27.66	0.575	9.138	16.97
2015	3172.66	27.32	0.561	8.921	16.43
2016	3246.45	26.98	0.548	8.707	15.91
2017	3318.37	26.64	0.534	8.495	15.40
2018	3388.43	26.30	0.521	8.285	14.91
2019	3456.67	25.96	0.508	8.079	14.43
2020	3523.09	25.62	0.495	7.874	13.97
2021	3587.74	25.28	0.482	7.673	13.53
2022	3650.63	24.94	0.469	7.474	13.10
2023	3711.78	24.60	0.457	7.277	12.69
2024	3771.22	24.26	0.445	7.083	12.28
2025	3828.98	23.92	0.432	6.892	11.90
2026	3885.07	23.58	0.421	6.703	11.53
2027	3939.52	23.24	0.409	6.516	11.17
2028	3992.36	22.90	0.397	6.333	10.82
2029	4043.60	22.56	0.386	6.151	10.49
2030	4093.28	22.22	0.374	5.973	10.17
2031	4141.41	21.89	0.363	5.797	9.87
2032	4188.02	21.55	0.352	5.623	9.58
2033	4233.13	21.21	0.341	5.452	9.30
2034	4276.78	20.87	0.331	5.284	9.03
2035	4318.97	20.53	0.320	5.118	8.77
2036	4359.73	20.19	0.310	4.954	8.53
2037	4399.10	19.85	0.300	4.794	8.30
2038	4437.09	19.51	0.290	4.635	8.07
2039	4473.72	19.17	0.280	4.48	7.86
2040	4509.02	18.83	0.270	4.327	7.66
2041	4543.02	18.49	0.261	4.176	7.47
2042	4575.73	18.15	0.251	4.028	7.29
2043	4607.18	17.81	0.242	3.883	7.13
2044	4637.40	17.47	0.233	3.74	6.97
2045	4666.41	17.13	0.224	3.599	6.82
2046	4694.23	16.79	0.216	3.462	6.68
2047	4720.88	16.45	0.207	3.327	6.54
2048	4746.40	16.11	0.199	3.194	6.42
2049	4770.79	15.77	0.191	3.064	6.31
2050	4794.10	15.43	0.183	2.937	6.20

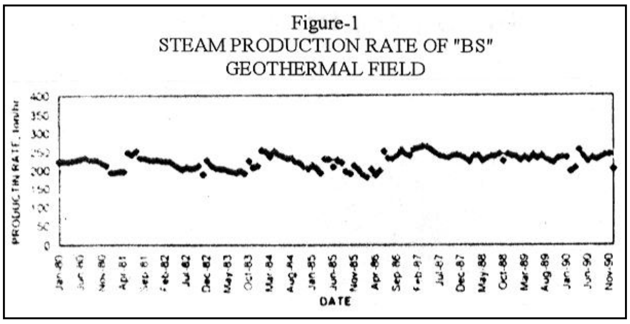

Figure-1
STEAM PRODUCTION RATE OF "BS" GEOTHERMAL FIELD

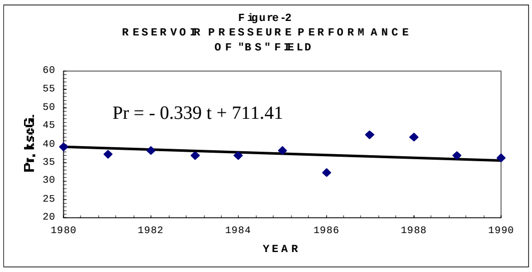

Figure-2
RESERVOAR PRESSURE PERFORMANCE OF "BS" FIELD

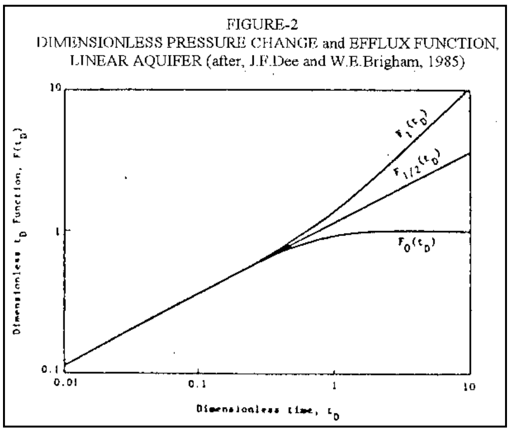

Figure-3
DIMENSIONLESS PRESSURE CHANGE and EFFLUX FUNCTION, LINEAR AQUIFER
(after, J.F.Dee and W.E.Brigham, 1985)

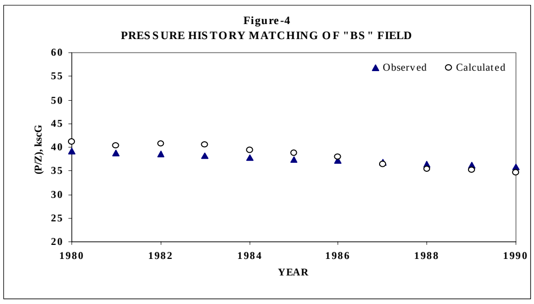

Figure-4
PRESUURE HISTORY MATCHING OF "BS" FIELD

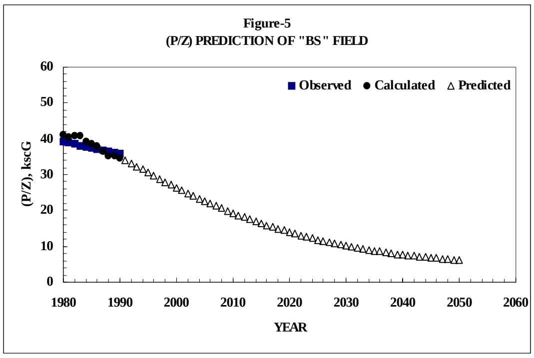

Figure-5
(P/Z) PREDICTION OF "BS" FIELD

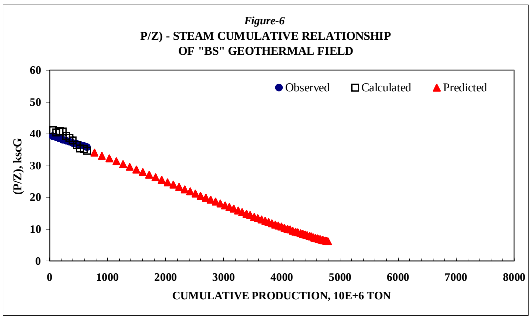

Figure-6
(P/Z) STEAM CUMULATIVE RELATIONSHIP OF "BS" GEOTHERMAL FIELD