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DIFFERENT FEED ZONES DETECTION IN A WELL THROUGH ITS PRODUCTION OUTPUT CURVES

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ABSTRACT

This paper describes how to detect the presence of more than one feed zone in wells by using production output curves. (It is presented as well) a new method to estimate the average value of the formation parameters, such as the permeability-thickness product, and the fluid stagnation pressure and temperature, among others, knowing the location of the feed zones.

Both analysis are based on the solutions of fluid mechanics equations under steady-state conditions. Results from a mexican well are given and it is shown that they agree reasonable well with those obtained from a pressure transient test carried out in the same well. The theory is rather simple and gives good results.

INTRODUCTION

This paper demonstrates that production output curves keep a lot of information not only on the capacity of wells to generate electricity but on the reservoir too.

Production output curves are usually referred to the graphs of steam or steam-water mixture mass flow rates versus wellhead pressures (pressure output curve) and steam or steam-water mixture mass flow rates versus wellhead specific enthalpies (specific enthalpy output curve), for a single well.

In general the shape of production output curves are strongly influenced by: the thermodynamic state of the fluids trapped into the reservoir (i.e., pressure, specific enthalpy, and chemical composition); rock characteristics (i.e., permeability distribution throughout the formation length exposed to production); form and size of the drainage volume; well design (number of different pipe diameters and their lengths); and number of different feed zones found in the drilled formation.

All those fact are precisely marked as featured signals in the shape of the production output curves, so that, when those curves are fitted by traditional methods (least squares or another equivalent technique), it is possible to lose all this information.

For the sake of simplicity the steam or steam-water mixture mass flow rates will be referred as total mass flow rates from here to the end of this work.

In general, it is expected for a well producing through a single feed zone, not to have significant changes in specific enthalpy at any total mass flow rate or wellhead pressure. On the other hand, if more than one feed zone are producing during the total discharging period of a well, it is expected to notice significant changes in specific enthalpy at different total mass flow rates or wellhead pressures.

For wells producing through a single feed zone, the change in fluid specific enthalpy between the bottom of the well and wellhead, basically depends on their separation distance at any wellhead pressure. This change is around 1% for two-phase producing wells and from 1 to 5 % for steam producing wells of that distance, so that, the thermodynamic process inside the well is almost isoenthalpic.

Fig.1 and Fig.2 separately present the shape of four different pressure and specific enthalpy output curves for a theoretical well 1800m depth. The design of this well is a blind 9 5/8" (I.D. 0.2205m) production pipe from 0 to 1000m depth, and a slotted liner 7" (I.D. 0.1571m) from 1000 to 1800m depth.

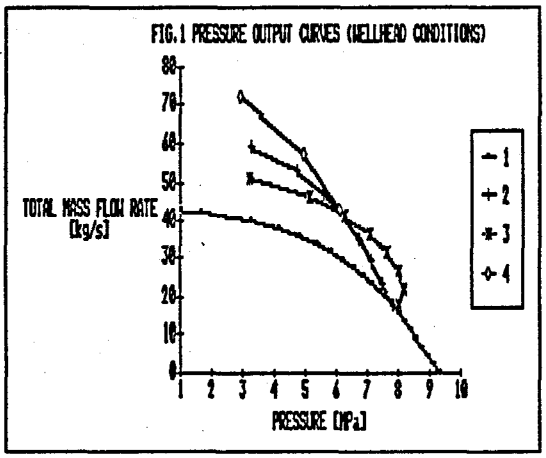


FIG.1 PRESSURE OUTPUT CURVES (WELLHEAD CONDITIONS)

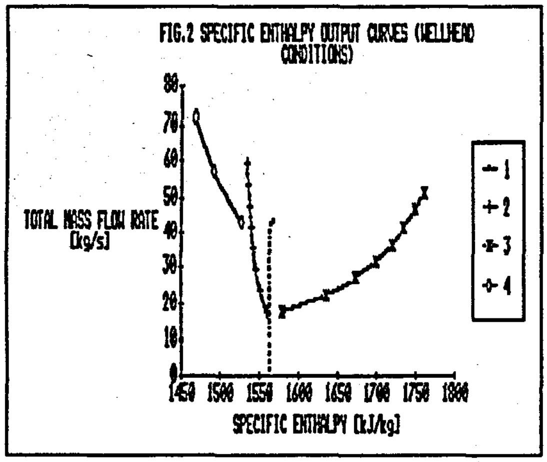


FIG.2 SPECIFIC ENTHALPY OUTPUT CURVES (WELLHEAD CONDITIONS)

Curves 1 in both figures represent the production output curves assuming a single feed zone located in a point at 1800m depth where the formation conductivity (kh_1) is 5 E-13m^3, and the thermodynamic state of the fluid under static conditions is defined by: P_{Y1} = 17.5 MPa; and h_{Y1} = 1580.3 kJ/kg, noticing that only pure-water is considered.

The intersection of Curve 1 and Curve 2 at a particular point describe the production output curves for two different feed zones. These behaviors were just obtained by superposing the effects of the additional feed zone onto the first one without taking into account internal flows or other effects. The second feed zone is located in a point 1600m depth where the formation conductivity (kh_2) is 1 E-12m^3 and the thermodynamic state of the fluid is defined by: P_{Y2} = 12.6 MPa; and h_{Y2} = 1515.5 kJ/kg. Considering the facts mentioned above, the second feed zone starts to produce when the pressure at 1600m is lower than 12.6 MPa.

Part of Curves 1 and Curves 3 also describes the production output curves for two different feed zones however, for this case the thermodynamic state of the fluid was defined as: P_{Y2} = 12.6 MPa; and h_{Y2} = 2093.5 kJ/kg.

In the same way than before, part of Curves 1 and 2 were jointed to Curve 4 in order to obtain the behavior of three different feed zones. This last zone is located in a point 1400m depth where the formation conductivity (kh_3) is 2 E-12m^3 and the thermodynamic state of the fluid is defined by: P_{Y3} = 10 MPa; and h_{Y3} = 1287 kJ/kg.

On the production output curves it is possible to notice featured trends which define the existence of different feed zones, however, there is an alternative way to confirm these existences, that is, if it is constructed a pressure output curve based on wellhead production data and referred to bottom hole conditions (in general to the location of the deepest feed zone), the obtained curves given in Fig.3 show notable change in straight line slopes , which justify the existence of the feed zones.

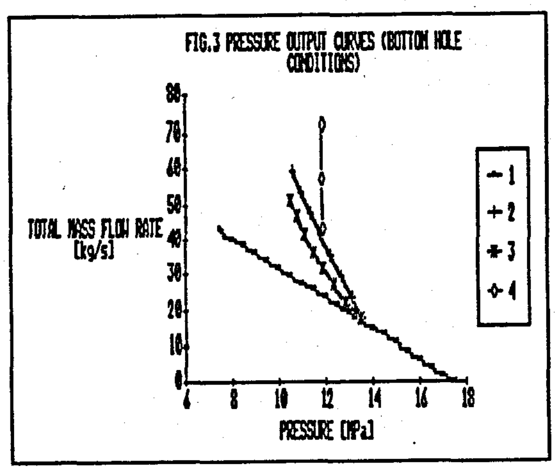


FIG.3 PRESSURE OUTPUT CURVES (BOTTOM HOLE CONDITIONS)

The models used for the reservoir and for the well are described in the following section.

MODELS

Two different flow models are presented in this work, namely: a reservoir model to describe the flow of fluids inside the reservoir; and a wellbore model to simulate the flow of fluids through production pipes.

Reservoir Model

The reservoir model presented here, is developed for the case of steady-state liquid pure-water flow inside the reservoir, it is based on the solution of the diffusivity equation of a radial, isotropic and isothermal reservoir where Darcian flow is considered.

The diffusivity equation which describes this flow is

$$d^2P/dr^2 + 1/r\ dP/dr = 0 \quad (1)$$

the solution of this equation which takes into account the inner and outer boundary conditions is

$$P_{WF} = P_E - mv\mu/2\pi kh\ \ Ln\ (r_E/r_W) \quad (2)$$

considering practical reasons the following assumption is made:

$$Ln(r_E/r_W) = 2\ \pi \quad (3)$$

this fact implies that $r_e = 535.49\ r_w$ which for normal wellbore radius means that r_e = 60m, so that

$$m = kh(P_E-P_{WF})/v\mu \quad (4)$$

The final equation which considers any thermodynamic state for pure-water is

$$m = A + BP_{WF} \quad (5)$$

where:

$$A= khP_E\ (x(v\mu)_F\ + (1-x)(v\mu)_G)/((v\mu)_F(v\mu)_G) \quad (6)$$

$$B = A/P_E \quad (7)$$

Well Model

The well model presented here considers an adiabatic process throughout the well, that is, there is no heat transfer anywhere between the well and the formation, this is valid when the discharge period is long enough for an specific total mass flow rate.

In general, it is considered a steady-state regime inside the well. For single phase flow either steam or liquid flow, the Nikuradse-Moody friction factor is calculated by using the Colebrook-White correlation. The specific case of two phase flow is treated as an homogeneous flow with a constant friction factor of 0.025 anywhere.

The thermodynamic properties of the fluids are obtained by using the steam tables and correlations.

The resulting wellbore simulator called SIMU89V.2 (S.Upton (1989)) is based on the following principles

Mass Conservation

$$d(\rho AV)= 0 \quad (1)$$

Momentum Conservation

$$dP + (f\rho V^2+2D_H\rho g\cos\theta)\ dx/\ 2D_H + \rho VdV = 0 \quad (2)$$

Energy Conservation

$$dh + VdV + g\cos\theta dx = 0 \quad (3)$$

THEORETICAL EXAMPLE

This theoretical example is taken from the three feed zones data reported in the introduction part of this work. These data are presented in Table 1.

Table 1. Theoretical Discharge Conditions.

Wellhead Pressure [MPa]	Total Mass Flow Rate [kg/s]	Wellhead Specific Enthalpy [kJ/kg]
8.95	4.24	1562.6
8.77	6.36	1562.6
8.59	8.47	1562.6
8.41	10.59	1562.6
8.24	12.71	1562.6
8.06	14.83	1562.6
7.83	17.70	1559.9
7.48	23.47	1550.8
7.12	29.30	1545.2
6.72	35.22	1541.4
6.23	43.08	1526.7
4.96	57.13	1490.7
2.91	71.90	1467.7

The first step to detect how many different feed zones are acting throughout the total discharge period is as follows

1. Calculate the fluid properties of the fluid at 1800m depth by using a calibrated simulator (Table 2)

Table 2. Thermodynamic State of the fluid at 1800m depth

Total Mass Flow Rate [kg/s]	Pressure [MPa]	Temperature [C]	Specific Enthalpy [kJ/kg]
4.24	16.50	339.2	1580.3
6.36	16.00	338.9	1580.3
8.47	15.50	338.6	1580.3
10.59	15.00	339.4	1580.3
12.71	14.50	340.1	1580.3
14.83	14.00	336.7	1580.3
17.70	13.52	334.0	1577.6
23.47	13.08	331.4	1568.5
29.30	12.62	328.6	1562.9
35.22	12.18	325.9	1559.1
43.08	11.84	323.7	1544.4
57.13	11.80	323.5	1508.5
71.90	11.83	323.7	1486.2

2. Build the pressure output curve at bottom hole conditions (Fig. 3), the number of straight lines developed give the number of feed zones acting, in this example three feed zones appear as mentioned above.

The second step is to calculate the formation and fluid parameters as follows

Stratum (1)

1. The data of the straight line 1 which corresponds to the highest values of pressure have to be fitted by using least squares technique and obtain the coefficients A and B

A=74.124 B=4.235 R=-1.0

2. Using Equation (7) obtain the average stagnation pressure (P_{Y1}) of Stratum 1

$$P_{Y1}= 74.124/4.235= 17.5 \text{ MPa}$$

3. Noting that the specific enthalpy of the fluid at bottom hole conditions is invariant (1580.3 kJ/kg) and using the steam tables (Keenan et al. (1978)) and a viscosity correlation (Nagashima et al. (1974)) one has

T_{Y1}=340 C v_{Y1}= 1.5961 E-03 m^3/kg
μ_{Y1}= 7.3939 E-11 MPa-s

4. Now from Equation (6) which is reduced for liquid phase to

$$A=(kh)_{Y1}P_{Y1}/(v\mu)_{Y1}$$

it is obtained

$$(kh)_{Y1} = (74.124)(1.5961X10^{-03})(7.3939X10^{-11}) / 17.5 = 5X10^{-13}m^3$$

it is noted that A has the units of kg/s.

Stratum (2)

1. It is necessary to refer straight line (2) to a depth of 1600m, and extrapolate straight line (1) up to a pressure around 10.7 MPa, after that, it is also necessary to refer the extrapolated data to a depth of 1600m.

Table 3. *Thermodynamic State of the fluid at 1600m depth (straight line 1')*

Total Mass Flow Rate [kg/s]	Pressure [MPa]	Temperature [C]	Specific Enthalpy [kJ/kg]
17.70	12.51	328.0	1575.6
23.47	12.08	325.3	1566.5
29.30	11.65	322.5	1560.9
35.22	11.22	319.7	1557.1

Table 4. *Thermodynamic State of the fluid at 1600m depth (straight line 2')*

Total Mass Flow Rate [kg/s]	Pressure [MPa]	Temperature [C]	Specific Enthalpy [kJ/kg]
16.94	12.51	327.9	1578.3
19.07	12.08	325.3	1578.3
21.18	11.64	322.5	1578.3
23.30	11.19	319.5	1578.3

2. By substraction from straight line (1') and straight line (2') obtain the total mass flow rates given by the second feed zone.

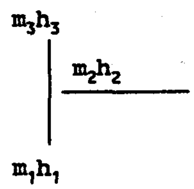
3. Using least squares technique obtain the newer values of A and B

A=108.704 B= 8.631 R=-1.0

4. Using Equation (7) obtain the average stagnation pressure P_{Y2} of Stratum 2

$$P_{Y2}= 108.704/8.631= 12.6 \text{ MPa}$$

5. Calculate the specific enthalpy of the fluid as follows



$$h_2=(m_3h_3-m_1h_1)/m_2$$

$$h_2=(17.7X1575.6-16.94X1578.3)/(17.7-16.94)= 1515.5 \text{ kJ/kg}$$

6. Now with the calculated pressure and enthalpy one gets from the steam tables the following

T_{Y2}= 328.51 C v_{Y2}= 1.5506 E-03 m^3/kg
μ_{Y2}= 7.6263 E-11 MPa-s

7. From Equation (6) one obtains

$$(kh)_{Y2} = 108.704X1.5506X10^{-03} X7.6263X10^{-11}/12.6= 1X10^{-12}m^3$$

Stratum (3)

1. It is necessary to refer straight line (3) to a depth of 1400m, and extrapolate straight line (2') up to a pressure around 9.5 MPa, after that, it is also necessary to refer the extrapolated data to a depth of 1400m.

Table 5. Thermodynamic State of the fluid at 1400m depth (straight line 3')

Total Mass Flow Rate [kg/s]	Pressure [MPa]	Temperature [C]	Specific Enthalpy [kJ/kg]
43.08	9.91	310.4	1540.5
57.13	9.44	308.9	1504.6
71.90	9.00	303.4	1482.2

Table 6. Thermodynamic State of the fluid at 1400m depth (straight line 2'')

Total Mass Flow Rate [kg/s]	Pressure [MPa]	Temperature [C]	Specific Enthalpy [kJ/kg]
41.15	9.90	310.3	1552.4
47.16	9.42	306.7	1550.4
53.25	8.90	302.6	1548.9

2. By substraction from straight line (3') and straight line (2'') obtain the total mass flow rates given by the third feed zone.

3. Using least squares technique obtain the newest values of A and B

A= 158.407 B= 15.834 R= -1.0

4. Using Equation (7) obtain the average stagnation pressure (P_{Y3}) of Stratum (3)

P_{Y3}= 158.407/15.834= 10 MPa

5. Calculate the specific enthalpy of the fluid as follows

m_2h_2

m_3h_3 $h_3=(m_2h_2-m_1h_1)/m_3$

m_1h_1

h_3= (43.08X1540.5- 41.15X1522.4)/(43.08- 41.15)= 1287 kJ/kg

6. Now with the calculated pressure and enthalpy one gets from the steam tables the following values:

T_{Y3}= 290 C v_{Y3}= 1.3564 E-03 m^3/kg
μ_{Y3}= 9.1732 E-11 MPa

7. From Equation (6) one obtain

$(kh)_{Y3}$= 158.407X1.3564X10^{-03}X9.1732 X10^{-11}/10= 2X10^{-12}

FIELD EXAMPLE

The data of this example is taken from the works realized by Horne and S.Upton (1989) and S.Upton and Horne (1989), in which they treat the interpretation of a pressure buildup test carried out in well A-17 from the Los Azufres Geothermal Field and they present some principles used in this work.

The production test data reproduced in Table 7 show that this well produces only steam with around 5 °C of superheated at any wellhead pressure.

Table 7. Production Test Data

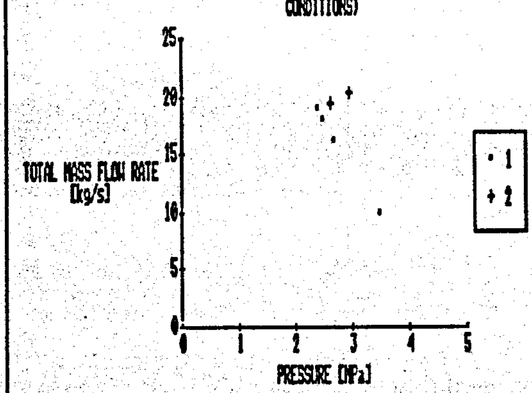
Wellhead Pressure [MPa]	Total Mass Flow Rate [kg/s]	Wellhead Specific Enthalpy [kJ/kg]
0.57	20.39	2767.4
0.67	19.44	2778.5
0.97	19.14	2793.7
1.33	18.19	2809.7
1.86	16.33	2818.9
3.18	9.81	2828.2

The design of this well is a blind 9 5/8" (I.D. 0.2224m) pipe from 0 to 560m depth and a liner (I.D. 0.1571m) from 450 to 622m depth. The slotted liner goes from 561 to 622m depth.

The circulation loses were presented between 613 and 627m depth, according with the drilling report, so that, it is considered the existence of a single feed zone throughout the wellbore.

It is presented in Fig.4 the conditions of the fluid at 610m depth

FIG.4 PRESSURE OUTPUT CURVE (BOTTOM HOLE CONDITIONS)



It is possible to observe from this figure that four points can be aligned to a straight line, meanwhile two points are quite separated of this line. This last implies the necessity of accounting on data of enough accuracy in order to determine correctly the reservoir parameters.

Taking into account that the wellhead specific enthalpy of the fluid can not change as strongly as it is noticed in these data, the two points mentioned will not be considered.

In this way, the calculated coefficients A and B are the following

$$A = 39.201 \quad B = -8.516 \quad R = -0.999$$

so that,

$$P_Y = 4.6 \text{ MPa}$$

and assuming that the fluid specific enthalpy at static reservoir conditions is 2834.2 kJ/kg, one has

$$T_Y = 268 \text{ C} \quad v_Y = 44.84 \text{ E-03 } m^3/kg$$
$$\mu_Y = 1.8349 \text{ E-11 MPa-s}$$

and then

$$kh = 7 \text{ E-12 } m^3$$

COMPARISON OF RESULTS

It is presented in Table 8 the results obtained by: Horne (1989), using a computerized method; S.Upton (1989), using a manual type curve match method; and using the new presented method.

Table 8. Comparison of Results

	Horne (1989)	S.Upton (1989)	New Method
kh [m^3]	4 to 5E-12	2.4E-12	7E-12
$(k_F w_F)_D$	5.8 π	2 to 5 π	-----
X_F [m]	33	53	-----
Temp. [C]	--------	263	268
Pres. [MPa]	--------	4.35 to 4.66	4.6

CONCLUSIONS

The conclusion can be ordered as follows

1. Any result obtained by using this method depends on the quality and quantity of the available information.

2. It is possible to detect different feed zones in wells and estimate their fluid and formation parameters by using this new method. The last can done if the location of the feed zones are known.

3. This method can be employed as a basis to repair wells with problems such as corrosion and scaling due to the production from several zones with different types of fluids.

4. This method can be used in new wells to avoid the production of some particular strata.

5. It seems to be possible to obtain more information on the reservoir than this presented here, by implementing other principles such as boundaries or others.

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REFERENCES

Hadgu, T.: Personal Communication

Horne, R.N., and S.Upton, P.:"The Use of Computers in Well Test Analysis",Proceedings: Symposium in the Field of Geothermal Energy, Agreement Between U.S. Department of Energy and Comisión Federal de Electricidad de México, San Diego, California, April 4-5, 1989, pp 135-142.

Iglesias, E., Arellano, V., Garfias, A., Miranda, C., Hernández, J., and González, J.: "A Method to Recover Useful Geothermal-Reservoir Parameters from Production Characteristic Curves. (1) Steam Reservoirs",Proceedings Ninth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, December 13-15, 1983, pp 285-290.

Iglesias, E., Arellano, V., and Molinar, R.: "A Method to Recover Useful Geothermal-Reservoir Parameters from Production Characteristic Curves. (2) Hot Water Reservoirs",Proceedings Ninth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, December 13-15, 1983, pp 291-297.

James, R.: "One Curve Fits All", Preprints Fourteenth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 24-26, 1989.

Keenan, J.H., Keyes, F.G., Hill, P.G., and Moore, J.G.: Steam Tables (S.I. Units), Wiley-Interscience, 1978.

Leaver, J.D.: "Steam Tables Correlation (0-16 MPa)", Ministry of Works and Development, New Zealand, Unpublished Report, 1984.

Meyer, C.A., McClintock, R.B., Silvestri, G.J., and Spencer, R.C.: "1967 ASME Steam Tables, ASME, 2nd ed., New York, (1968) 328.

Nagashima, A., Ikeda, M., and Tanishita, I.: "Correlation of Viscosity for Water and Steam", Paper to be presented at the 8th International Conference on the Properties of Steam, Giens, France, 1974.

S.Upton, P., and Gudmundsson, J.S.: "Pressure Buildup Testing of Well A-18 in Los Azufres Geothermal Field, Mexico, Proceedings Twelfth Workshop Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 20-22, 1987, pp 189-194.

S.Upton, P.: "Ajuste de Curvas Utilizando Curfit.Exe", Reporte No. 1388-018, Subgerencia de Estudios Geotérmicos, C.F.E., Septiembre de 1988.

S.Upton, P.: "The Well Simulator SIMU89V.2", non edited, June 1989.

S.Upton, P., and Horne, R.N.: Análisis de Pruebas en Pozos: " Interpretación de una Prueba de Incremento de Presión Efectuada en el Pozo A-17 del Campo Geotérmico de Los Azufres, Mich., México", Proceedings: Symposium in the Field of Geothermal Energy, Agreement Between U.S. Department of Energy and Comisión Federal de Electricidad de México, San Diego, California, April 4-5, 1989, pp 143-148.