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EVIDENCE OF TWO EXTREME FLOW REGIMES OPERATING IN THE PRODUCTION ZONE OF DIFFERENT WELLS FROM LOS AZUFRES

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ABSTRACT.

A published method for calculating excess steam is modified in order to make it applicable to the case of a well producing fluid with a high non-condensable gas content. The method is applied to data from a number of wells from Los Azufres. The results show the expected linear relation between excess steam and the molar fraction of CO_2 in the total discharge. The modified method also provides an estimate for the molar fraction of CO_2 in the liquid phase of the reservoir. It is found that this concentration is relatively homogeneous in the southern section of the field, and seems to be slightly smaller in the deeper zones of the northern section. The calculated values of excess steam agree qualitatively, but not quantitatively, with values of steam quality in the undisturbed reservoir calculated by other authors. The calculation of excess steam tends to overestimate steam quality in cases where steam saturation in the reservoir is low, and has the opposite tendency when the steam quality in the reservoir is high. The first type of deviation is explained in terms of the effects of higher mobility of steam in the two-phase zone induced by pressure drawdown. The second type of deviation is explained as the result of boiling of liquid phase, and the consequent addition of (non-condensable) gas-poor steam to the flowing mass, also caused by the pressure drawdown. A necessary extension of the reasoning leading to these explanations, is the prediction that the non-condensable gas content in fluids produced from a reservoir with a high steam saturation, will either remain stable or decrease with time during exploitation.

INTRODUCTION.

The Los Azufres field, located atop a mountain range, covers an extension of about 30 Km2. The altitude of wellheads is in the range of 2800-3000 meters above sea level. The surraunding valleys lie about 500 meters below. The Los Azufres reservoir is a hydrologically complex system (Iglesias et al, 1985; Nieva et al, 1983) whose geometry, as it appears from a mapping of hydrothermal alteration minerals, could be described as a dome structure distorted by two zones of upward circulation (Cathelineau et al, 1985; 1983). These two zones give rise to the two areas of surface manifestations, Maritaró in the north and Tejamaniles in the south, where most of the wells have been drilled. One particular feature of Los Azufres field is the enormous variability in non-condensable gas concentration in total discharge from one well to another. This variability covers a range of almost two orders of magnitud. The largest differences are those found between deep wells of the northern section and the shallower wells of the southern section.

Giggenbach (1980) and D'Amore and Celati (1983) have devised similar methods to calculate the fractional molar contribution of equilibrium reservoir steam phase to the total discharge produced by a well. This parameter has come to be known as the "y value" (Giggenbach, 1980), steam fraction (D'Amore and Celati, 1983) or excess steam (Truesdell et al, 1984; Nieva et al, 1982), and has been interpreted by some authors as an estimate of the reservoir's in situ steam molar fraction, from which the steam quality could be readily obtained. Heretofore this parameter shall be referred to as excess steam, and expressed as a percentage rather than as fraction. In this contribution we will describe a modification to the procedure of Giggenbach (1980) that makes it applicable to the case of a well with a high content of non-condensable gases in its total discharge. The variability in total discharge compositions from Los Azufres will be interpreted in the light of the concept of excess steam, and the question of the relation between excess steam and <u>in situ</u> steam quality will be addressed.

THE CONCEPT OF EXCESS STEAM.

The excess steam or "y value" is calculated from the apparent distortion in the relative proportions of species participating in the Fischer-Tropsch reaction (or any reaction purported to be in equilibrium in the uperturbed reservoir), assuming that the total flow entering the wellbore is made up of a mixture of reservoir liquid and steam phases, each having kept the chemical composition it had at equilibrium (Giggenbach, 1980). To further clarify this concept, use will be made of Figure 1 where two hypothetical cases are presented. In the first case it is considered that a unit mass of reservoir liquid is transported to the wellhead. Even though a steam phase would develop because of decompression, as long as the chemical composition of the unit mass remains unchanged, one would calculate an excess steam value of zero. In the second case it is considered a unit mass composed of 10% (w/w) steam and 90% (w/w) liquid, each phase having the chemical composition corresponding to reservoir equilibrium conditions. Again, if this unit mass reached the wellhead without any change in its chemical composition (although with a change in the relative proportions of steam and liquid phases) one would calculate an excess steam value of ten percent. These examples might lead to the belief that the calculated excess steam is indeed a measure of steam saturation in the reservoir. However, as will be discussed later, it is probably incorrect in most cases to assume that a unit mass could be transported to the wellhead without any change in its chemical composition.

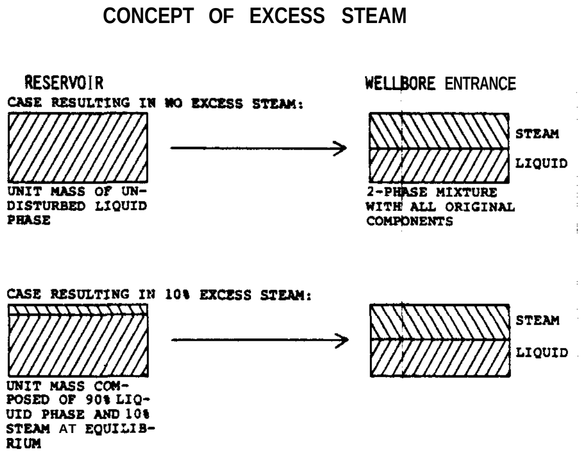

Figure 1. Idealized schematic transfer of unit mass from reservoir to wellhead.

PROCEDURE FOR CALCULATING EXCESS STEAM

It was found necessary to modify the procedure of Giggenbach (1980) in order to make it applicable to the case of wells with high excess steam. Specifically, two simplifying assumptions built implicity in the original procedure had to be eliminated. One is the assumption that the molar fraction of CO_2 is negligible compared to that of H_2O in the steam phase. The other is the assumption that the concentrationof CO_2 in the liquid phase of the reservoir is approximately the same as the concentration in the total discharge. Since it is unnecesary to repeat the derivation of the entire procedure, the modifications will be described by making direct reference to pertinent equations in the article of Giggenbach (1980). In order to eliminate the first assumption, it is necessary and sufficient to correct the expression for the molar fraction of species i in the steam phase, and to carry out all the consequent algebraic modifications in the derivation. The correct expression to be used instead of Equation 8 of the cited reference is:

$$X_{v,i} = \frac{B_i X_{1,i}}{1+B_{CO_2} X_{1,CO_2}} \qquad (1)$$

where $X_{v,i}$ and $X_{1,i}$ are the molar fractions of species i in the steam and liquid phases, respectively, and B_i is the partition coefficient between steam and liquid of species i, as defined in the cited reference.

After carrying through the necessary algebraic modifications, the following expression is obtained as a substitute of Equation 27 of the cited reference:

$$K_C = \frac{X_{d,CO_2} X^4_{d,H_2} B_{CO_2} B^4_{H_2} D^{\pm 1}_{CH_4} P^2_{H_2O}}{X_{d,CH_4} B_{CH_4} D^{\pm 1}_{CO_2} D^{\pm A}_{H_2}} \qquad (2)$$

where

$$D_i = 1 - y + \frac{y B_i}{F} \qquad (3)$$

and

$$F = 1 + X_{d,CO_2} B_{CO_2} \qquad (4)$$

In these equations, as in the cited reference, $X_{d,i}$ represents the molar fraction of species i in the total discharge K_C is the value of the equilibrium constant of the Fischer–Tropsch reaction in the gas phase and at the reservoir temperature, P_{H_2O} is the partial pressure of water at this temperature, and the parameter y is the excess steam expressed as the molar fraction. It should be mentioned that in our procedure the total pressure is calculated for the local reservoir temperature, and not for the temperature of the deeper part of the reservoir (ref: Equation 26 of cited reference).

Equation (2) could be rearranged so as to separate the y-dependent terms on one side, and then an iterative half-interval or Newton–Raphson procedure could be used to obtain the value of y. After obtaining the value of y, a mass balance for CO_2 could be made as follows:

$$X_{d,CO_2} = (1 - y) X_{1,CO_2} + y X_{v,CO_2} \qquad (5)$$

By combining Equations (1) and (5) one can obtain the value of X_{1,CO_2}, the molar fraction of CO_2 in the liquid phase of the reservoir. In general, this value will be quite different than the value of X_{d,CO_2}, which was used as a first approximation of X_{l,CO_2} to estimate the pressure in the reservoir. In order to obtain a self-consistent result (ie to eliminate the second assumption mentioned above), it is necessary to repeat the above procedure, but now using the calculated value of X_{l,CO_2} instead of X_{d,CO_2}. The procedure is repeated several times, each time using the last calculated value of X_{l,CO_2}, until a self consistent result is obtained, which usually occurs after three or four iterations.

LOS AZUFRES. OBSERVATIONS AND RESULTS.

Table I presents gas composition data for separated steam from a number of wells from Los Azufres field. Also presented are the steam separation temperature, the mass fraction of steam and the estimated reservoir temperature.

The Table contains enough information to calculate the concentration of each gaseous species in the total discharge, with the use of the appropriate partition coefficients at the separation temperature.

The application of the procedure described above yields the values of excess steam presented in Table 2. Also shown are the molar fractions of CO_2 in the total discharge and in the liquid phase of the reservoir. At the reservoir temperatures shown in Table 1, CO_2 partitions very favorably into the steam phase, and therefore it could be considered to be a marker or tracer of this phase. One would then expect a linear correlation to exist between excess steam and the molar fraction of CO_2 in the total discharge. Figure 2 demonstrates that this is indeed the case. In this Figure the quadrangles enclose the area of uncertainty in the location of the data point, considering uncertainties of ± 5 °C in the estimated reservoir temperatures, and ± 5% in the analyzed non-condensable gas concentration in the total discharge.

Figure 3 shows a plot of the calculated molar fraction of CO_2 in the liquid phase of the reservoir versus the calculated excess steam. There seems to be no correlation between these two parameters, and the results show that the concentration of CO_2 in the liquid phase is relatively homogeneous. The only clear deviations toward lower values are those of wells A-28, A-19 and A-9. These wells are found in the northern section of the field, whereas the rest are in the southern section (see map in Nieva et al, 1983, or Cathelineau et al, 1985). This observation, although based on only those three cases, would tend to indicate that the gas concentration in the liquid phase is larger in the southern section than in the northern section. The horizontal line in Figure 3 marks the average value of 2×10^{-3} for the molar fraction of CO_2 in the liquid phase.

If the molar fraction of CO_2 in the liquid phase is known, than, by considering a simple mixing model, one could calculate the relative proportions of reservoir liquid and steam phases which make up the total discharge. This can be done by using Equations (1) and (5), and obtaining the value of y (ie the excess steam). These calculations were carried out, using for every well the value of 2×10^{-3} for the molar fraction of CO_2

TABLE 1

COMPOSITION OF SEPARATED STEAM
FROM LOS AZUFRES WELLS

WELL	T_s °C	f_s	X_g	MOLAR FRACTION X 1000 H_2O-FREE BASIS CO_2	H_2S	H_2	CH_4	N_2	NH_3	T_{res} °C
A-16AD	172.0	0.900	12.04	980.6	9.78	3.838	0.136	4.191	1.474	260
A-17	172.0	1.000	21.51	982.5	11.61	3.208	0.282	1.760	0.635	260
A-18	150.0	0.497	32.26	990.3	5.89	0.952	0.093	1.960	0.783	270
A-22	190.0	0.432	4.74	963.3	24.50	8.519	0.144	2.009	1.535	300
A-33	206.0	0.842	27.57	986.6	7.64	1.956	0.610	2.424	0.815	263
A-34	194.0	1.000	45.28	988.6	5.56	2.443	0.882	2.166	0.361	260
A-35	192.0	0.826	14.89	975.2	12.52	6.707	0.579	4.110	0.886	274
A-36	150.0	0.742	14.39	980.6	11.30	4.176	0.097	2.900	0.876	292
A-38	205.0	1.000	24.41	984.9	7.54	3.093	0.462	3.654	0.312	270
A-9	148.0	0.483	2.10	920.1	62.30	7.412	0.385	1.083	8.685	310
A-17	176.0	1.000	14.37	982.4	12.38	1.631	0.111	0.966	2.539	260
A-19	145.0	0.437	1.14	865.6	95.75	18.269	0.236	4.081	16.064	290
A-22	197.0	0.422	8.16	978.6	15.25	3.660	0.031	0.551	1.950	300
A-28	169.0	0.364	0.92	872.9	83.45	24.993	0.396	2.708	15.584	300
A-36	148.0	0.667	17.31	984.2	9.67	2.164	0.231	2.328	1.391	292

SYMBOLS: T_s = Steam separation temperature; f_s = Steam weight fraction in total discharge; X_g = Milimoles of non-condensable gas per mol of H_2O in steam; T_{res} = Reservoir temperature.

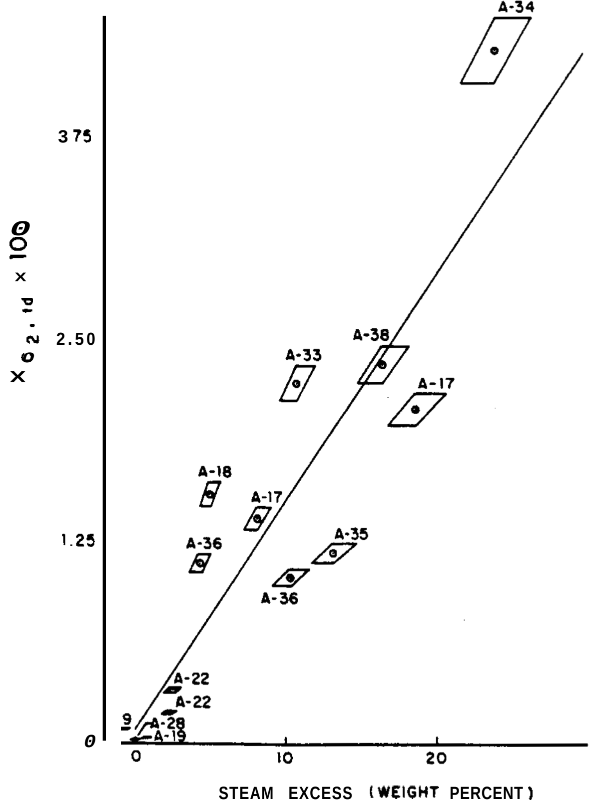

Figure 2. Molar fraction of CO_2 in total discharge vs calculated steam excess.

TABLE 2 Molar fraction of CO_2 in total discharge, and calculated excess steam and CO_2 molar fraction in liquid phase.

	X_{1,CO_2} x 10^3	X_{d,CO_2} x 10^2	excess steam %
A-16AD	0.96	1.05	13
A-17	1.4	2.07	19
A-18	4.4	1.54	5.0
A-22	1.2	0.197	2.2
A-33	2.7	2.33	11
A-34	2.5	4.29	24
A-35	3.6	1.18	13
A-36	2.3	1.03	10
A-38	2.3	2.35	16
A-9	1.1	0.093	- 0.9
A-17	2.1	1.39	8.1
A-19	0.33	0.043	0.8
A-22	2.0	0.335	2.5
A-28	0.29	0.029	0.0
A-36	4.8	1.12	4.3

in the liquid phase. The resulting values of excess steam are shown in Figure 4, plotted versus the values obtained by the more involved procedure based on apparent Fischer-Tropsch disequilibrium. The solid trace shown rep-

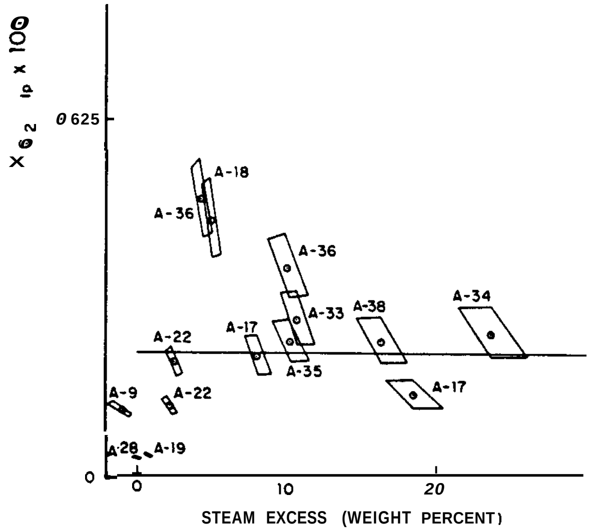

Figure 3. Calculated molar fraction of CO_2 in the liquid phase of the reservoir vs calculated steam excess.

resents the equality line. As is apparent from this plot, there is a remarkable agreement between the values obtained by the two procedures, except for the predictable deviations of wells A-9, A-19 and A-28.

DISCUSSION.

The linear correlation between CO_2 concentration and excess steam (Figure 2), the relative homogeneity in the calculated CO_2 concentrations in the reservoir liquid phase of the southern section of the field (Figure 3), and the excellent agreement betweenexcess steam values calculated by the two methods described (Figure 4), present a picture of remarkable internal consistency. It is thus clear that the large differences in non-condensable gas concentrationsin fluids from different wells from Los Azufres, is due to the variable contributions of excess steam.

Iglesias et al (1985) have estimated the steam quality in sections of the Los Azufres reservoir reached by a number of wells. A comparison of their results with those presented in this contribution makes it possible to probe the relation between excess steam (or "y value") and the steam quality in the reservoir. Within a reasonable error margin, the calculated excess steam is zero for wells A-9 and A-28, thus agreeing with the finding of single-phase (liquid) conditions in those sections of the reservoir. However, for wells A-18, A-19 and A-22 the same conditionis also found (Iglesias, personal communication), but nontheless a finite steam excess is calculated. On the other hand, for the sections of the reservoir reached by the relatively shallow wells A-34, A-35, A-36 and A-38, the values of excess steam are much smaller than the estimated steam quality, although the relative ordering of the two sets of numbers

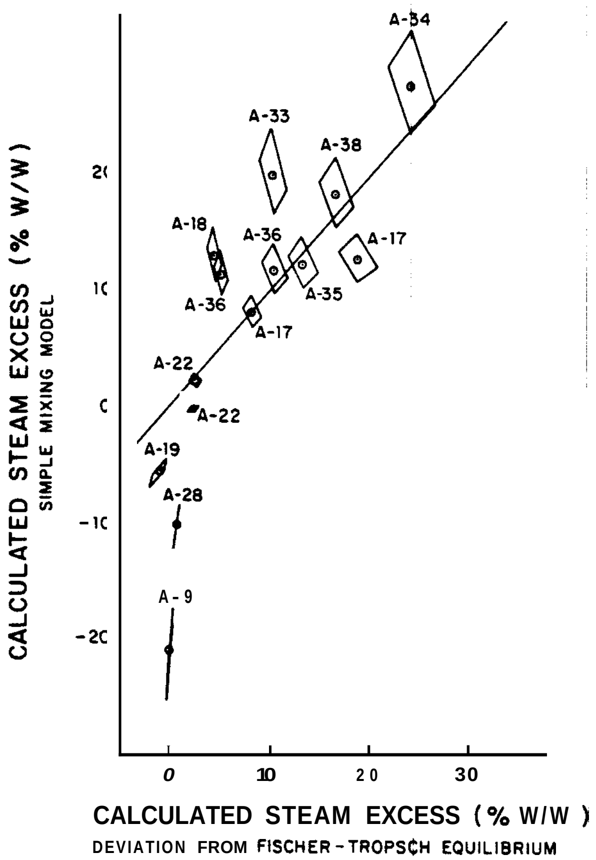

Figure 4. Steam excess calculated with the simple mixing model vs steam excess calculated from Fischer-Tropsch deviation from equilibrium.

is the same. This tendency of the excess steam calculation to overestimate steam quality in sections close to single phase liquid conditions, and to underestimate it in cases of high steam quality, could be understood qualitatively through the following reasoning. Consider the case of a well reaching a zone of single phase liquid at the boiling point. When flow through the well is small enough **so** that no appreciable local pressure drawdown is caused, the well will receive no excess steam. However, as the flow and the resulting drawdown are increased, a local two-phase zone will develop and, because of the different mobilitites of the two phases, the mixture reaching the well will have an excess of steam (Bodvarsson et **al,** 1980; Nieva et al, 1982; Sorey et **al,** 1980). This process is responsible for the familiar trend of increasing flowing enthalpy and non-condensable gas concentration with increasing flow (Grant and Glover, 1984). On the other hand, consider a well reaching a section of the reservoir with a high (but smaller than unity) steam quality. Under these circumstances, steam will very much dominate the flow through the fractures and, at low production rates, the well will receive a mixture containing a high non-condensable gas concentration. As the flow and the resulting pressure drawdown are increased, even though the steam flowing from some distance to the wellbore still will have a high non-condensable gas content, there will be a tendency of the liquid in the vicinity of the wellbore to boil, thus incorporating its mass but a relatively low gas content to the flowing steam phase. Thus, in this case it is expected that the non-condensable gas concentration in the total discharge will tend to decrease with increasing flow. These predicted tendencies agree with the results of simulation studies (O'Sullivan et **al,** 1983), which showed that stabilized flowing conditions depend upon the initial (ie undisturbed) steam saturation. Indeed, those studies predictedthat for low initial steam saturation, the flowing CO_2 concentration will increasewith flowrate, whereas this trend would be the reverse for high initial steam saturations, although no physical explanation was given.

A necessary and important extension of the arguments presented above, is the prediction that the fluids produced from a section of a reservoir with high steam quality conditions (such as the shallow sections in the southern part of Los Azufres), will have a non-condensable gas concentration that will either remain relatively constant or decrease with time during long-term exploitation.

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