PREDICTION OF HYDROSTATIC PRESSURE IN GEOTHERMAL WELLS

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SUMMARY - It was shown earlier that a simple empirical formula can be used as an equation of state (pressure-density-temperaturedependence) for water and brines. Precise laboratory test data were used for verification of the suggested formula. Using this formula as a base, we derived an equation for calculating the downhole hydrostatic fluid pressure. Calculations show that in many cases the effect of high temperatures and depth on waterhrine density should be taken into account at downhole fluid pressure predictions. An example of calculations is presented.

1. INTRODUCTION

In geothermal wells the densities of water and brines can be significantly different fiom those measured at surface conditions. Determining accurate density of water/brines under downhole conditions is therefore needed for calculating the actual hydrostatic pressure in a well. Also it is very important to estimate the effect of pressure and temperature on the density of the formation fluid. This will permit a more accurate prediction of differential pressure at the bottomhole and will help to reduce the fluid losses resulting from miscalculated pressure differentials. It is known that the lost fluid circulation is a particularly severe problem in geothermal drilling (Rowley, 1988). The determination of the hydrostatic pressure at the bottomhole is also needed for interpretation of pressure and flow tests data. To maintain pressure in geothermal reservoirs a significant amount of water is injected into the production zone. In this case the knowledge of the water formation volume factor B_w is needed in material balance calculations to predict the change in water volume that occurs between the surface and reservoir. An equation was suggested (Kutasov, 1989) which allow one to calculate the values of B_w for temperatures up to 200°C and pressures up to 1,800 bar. It was shown earlier that a simple empirical formula (Kutasov, 1989; Kutasov, 1991) can be used as an equation of state for water and brines. Using this formula as a base, we present below an equation for calculating the downhole hydrostatic fluid pressure. Calculations show that in many cases the effect of high temperatures and depth on waterhrine density should be taken into account at downhole fluid pressure predictions.

2. DENSITY OF WATER AND SODIUM CHLORIDEBRINES

Our analysis of laboratory density test data (Burnham, et., al. 1969; Potter. and Brown 1977) for water and sodium chloride brines has shown that their coefficient of thermal (volumetric) expansion can be expressed as a linear function of temperature and the coefficient of isothermal compressibility is practically a constant. It was found that the following empirical formula (Kutasov, 1989; Kutasov, 1991) can be used as an equation of state for water and $NaCl$ brines:

$$\rho = \rho_o \exp[\alpha p + \beta(T-T_s) + \gamma(T-T_s)^2] \qquad (1)$$

where p is pressure, T is temperature, T_s = 15 °C (International Standard Temperature), ρ is downhole water/brine density, ρ_o, α, β, and γ are coefficients. A multiple regression analysis computer program was used to process laboratory density-pressure-temperature data and to provide the coefficients of formula 1 (Tables land 2). The accuracy of the results was estimated fiom the sum of squared residuals and is shown in Table 1. For sodium chloride brines (Table 2) the value of $\Delta\rho/\rho$ x100% is less than 0.4. From Table 1 it follows that for temperatures up to 100 °C the equation (1) is very accurate because, for these temperatures, more precise laboratory test data were available. The coefficients presented in Table 2 were calculated for the temperature and pressure ranges of 2 1-250 °C and 0-2,000 bar.

3. THE NEW FORMULA

Field and analytical investigations (Ramey, 1962; Kuliev, et., al , 1968; Kutasov, et., al, 1988) have shown that the downhole circulating temperatures can be approximated by a linear function of depth

$$T = a_o + a_1 h \qquad (2)$$

where h is the current vertical depth, a_o and a_1 are coefficients. From this formula

Table 1. Coefficients in equation (1) for water

ρ_o kg/m^3	α 1/bar 10^{-5}	$-\beta$ 1/°F 10^{-4}	$-\gamma$ 1/°Fx°F 10^{-7}	$\Delta\rho/\rho$ x100 %
Pressure interval 100 - 1,100 bar		Temperature interval 20 - 100°C		
1001.2	3.9718	0.8530	2.3053	0.039
300 - 1,800		100 - 200		
1008.6	4.5547	1.5749	1.1589	0.175
300 - 1,800		20 - 200		
1002.0	4.4958	1.2300	1.5470	0.172

Table 2. Coefficients in equation (1) for *NaCl* brines. W = weight percent

W	ρ_o kg/m^3	α 1/bar 10^{-5}	$-\beta$ 1/°C 10^{-4}	$-\gamma$ 1/°Cx°C 10^{-7}
0	1003.2	4.7024	1.4353	1.25351
1	1001.3	6.3016	1.0039	1.51349
3	1015.4	5.9916	0.9516	1.44241
5	1029.4	5.7166	0.8893	1.39675
7	1044.0	5.4290	0.8576	1.32206
9	1058.7	5.2110	0.8392	1.25198
11	1073.9	5.0045	0.8567	1.14520
13	1088.9	4.8134	0.8614	1.05903
15	1104.2	4.7209	0.8712	0.99291
17	1120.0	4.5946	0.9354	0.87706
19	1135.7	4.5073	0.9843	0.78011
21	1153.2	4.4479	1.0543	0.67465
23	1168.4	4.4188	1.1355	0.56345
25	1184.7	4.4265	1.2204	0.45804

follows that the outlet ($h = 0$) fluid temperature is $T_o = a$, and the bottomhole (reservoir) water temperature is

$$T_b = T_o + a_1 H, \quad a_1 = \frac{T_b - T_o}{H} \qquad (3)$$

where H is total vertical depth.
It is known that

$$dp = \rho g dh \qquad (4)$$

where dp is the increment given to pressure, dh the increment given to vertical depth, and g acceleration constant due to gravity.

To speed up calculations after equation (9) we prepared a computer (FORTRAN) program "WATPRES" (available on a request). To apply the program "WATPRES" for sodium chloride

Combining equations (1, 4) we obtain,

$$\int_0^p \exp(-\alpha p)dp =$$

$$\rho_o g \int_0^h \exp[\beta(T - T_s) + \gamma(T - T_s)^2]dh$$

(5)

The product αp for geothermal wells ($H <$ 3 km) is very small and we can assume that

$$\int_0^p \exp(-\alpha p)dp =$$

$$-\frac{1}{\alpha}[\exp(-\alpha p) - 1] \approx p - \frac{\alpha p^2}{2} \qquad (6)$$

From equations (2, 5, 6) we obtain

$$p - \frac{\alpha p^2}{2} \cong$$

$$\rho_o g \exp(b_1) \int_0^h \exp(b_2 h + b_3 h^2)dh \qquad (7)$$

$$b_1 = \beta(a_o - T_s) + \gamma(a_o - T_s)^2$$

$$b_2 = \beta a_1 + 2\gamma a_1(a_o - T_s), \quad b_3 = \gamma a_1^2$$

It is not difficult to calculate the last integral (Abramowitz and Stegun, 1972) and from equations (1-7) we obtain,

$$p - \frac{\alpha p^2}{2} = F(h), \quad (8)$$

$$F(h) = \rho_o g \sqrt{\pi b} \exp(ba^2 + b_1) \cdot$$

$$\left[\Phi\left(a\sqrt{b} + \frac{h}{2\sqrt{b}}\right) - \Phi(a\sqrt{b})\right]$$

$$a = -b_2, \quad b = -\frac{1}{4b_3}$$

where Φ is the error function. Solution of equation (8) is:

$$p = \frac{1}{\alpha} - \sqrt{\frac{1}{\alpha^2} - \frac{2F}{\alpha}} \qquad (9)$$

brines, the data fkom Table 2 should be used in the input file. The fluid density increases with pressure and reduces with the increase of the temperature. Many engineers consider this compensating effect as **a** basis for the using the surface fluid density for the calculation of the hydrostatic pressure p^*. For water density at standard conditions (p =1.013 bar, T_s = 15 "C)

$$p^* = \rho_o g h$$

The program "WATPRES" also calculates the depth dependent variation of p^*- p.

4. EXAMPLE OF CALCULATION

After completion of drilling operations a 2000-m water producing well was shut-in for a long period of time. The wellbore temperatures were practically identical to undisturbed temperatures of the surrounding formations. The surface temperature is 10 °C and the geothermal gradient is **0.045** °C /m. The aquifer is located in the vicinity of the bottomhole. The production of hot water (100 °C) started at a low flow rate and the flow rate was gradually increased. Due to heat losses to the surrounding wellbore formations the outlet temperature varied between 50 and 95 °C. What was the downhole hydrostatic pressure profile prior to water production? It is also required to estimate the bottomhole pressure variation during the production period. The results of calculations after the Equation 9 are presented in Table 3 and Figure 1,

5. CONCLUSION

A simple method of calculating the downhole hydrostatic fluid pressure is suggested. The proposed formula allows one to estimate the effect of high temperatures and depth on downhole fluid pressure predictions.

Table 3. The effect of water density-depth variation on hydrostatic pressure predictions

h m	P bar	P-P* bar	ρ kg/m³	T °C
200	20.66	0.009	1001	19
400	40.27	-0.020	999	28
600	59.83	-0.095	996	37
800	79.34	-0.222	993	46
1000	98.79	-0.409	990	55
1200	118.17	-0.663	987	64
1400	137.48	-0.992	983	73
1600	156.71	-1.403	978	82
1800	175.84	-1.903	974	91
2000	194.88	-2.499	968	100

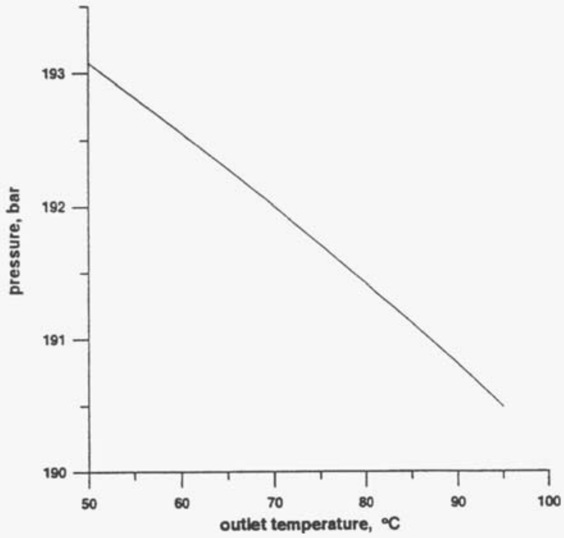

Fig. 1. Bottomhole pressure versus outlet water temperature.

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