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RADIAL FLOW OF PRESSURED HOT WATER THROUGH NARROW CRACKS

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ABSTRACT

Geothermal wells discharging hundreds of tonnes/hour of steam-water mixtures may be supplied at depth from one very narrow crack of width 1 to 2 mm, or alternatively, from some hundreds of hairline cracks. In the former case, turbulent flow takes place out to tens of metres from the well while the sum of frictional and kinetic pressure-drop indicates the flashing distance to be of the order of 10 cm from the well wall for pressure-temperature equilibrium. However it is unlikely that equilibrium obtains because of the high water velocity (order of 100 m/s) near the well giving no time for bubble nucleation. Flashing and hence mineral deposition are therefore not at all likely in the crack but can occur within the well from the crack horizon upwards. In the case of a multitude of fine cracks giving the same total flow, streamline conditions prevail over the flow path with the flash front a metre or so from the well, hence deposition is a possibility.

INTRODUCTION

The flow of hot water to the feed level of geothermal wells may be considered as either through one crack or for the same flow through a large number of much finer cracks. The latter condition is analogous to flow through granulated beds but has the advantage of avoiding concepts of permeability expressed by units such as the darcy.

The radial flow of pressurised hot water has been studied, James, (1975a) using test results from a well with a maximum discharge of 77 kg s^{-1} (277 t h^{-1}) with a crack width calculated at about 1.5 mm. Pressure fell rapidly within the crack when close to the well to below the value at which it would boil under stable equilibrium conditions. However, it was determined that the time interval for bubble nucleation was too short and hence that the fluid remained as a single-phase until it burst into the well, at which point exposive generation of steam takes place followed by a continuous generation as the mixture ascends to the wellhead. This result is of some importance as if flashing commonly occurs within cracks, there would be a strong likelihood of deposition of minerals taking place which would be impossible - or extremely difficult - to remove, whereas deposition within the well casing is a tractable condition even if not an attractive one.

However, if the flow was distributed over a number of fine cracks, streamline (viscous) conditions would prevail over the flow-path requiring a different calculation and in this case, the fluid velocity would be severely restricted and the radius at which pressure falls to the boiling point would be increased. Both these effects lead to steam generation within the crack and hence a potential for mineral deposition would now exist. Because geothermal wells commonly have sharply defined horizons of good inflow within the depth of interest with the remainder giving little, if any, feed over hundreds of metres of uncased hole, it appears that flow from a large number of minute cracks is rare compared with the case of one (or a few) large cracks.

It would be useful to study a well with a comparatively poor output (as a commercial proposition) and see which of these two conditions best apply. Fortunately such a well has been described recently by Menzies and others (1982) with a few values of flow and feed-horizon pressures reproduced below as Table 1.

TABLE 1: Flow Characteristics of Well 403, Tongonan, Philippines.

w Flow, kg s^{-1}	P_b Feed horizon pressure, bar
0	120
9	113.3
22.8	72
28.8	37.3
30.2	not available

RADIAL FLOW CALCULATIONS

Taking the largest flow with its associated pressure from the table; 28.8 kg s^{-1} and 37.3 bar, we can calculate the crack width, t, from the equation of James (ibid) making the assumption that turbulent flow conditions operate from the well outwards to a distance of at least a hundred well radii. This will be checked after provisionally determining the crack width. The fluid is considered as hot water using the published enthalpy of 1270 J g^{-1} for this well giving an associated water temperature of 286.5°C, specific volume 1.3535 l g^{-1} and viscosity of 0.088 centipoise. Notation is given later. Using the metric form, the pressure-drop along the radial flow-path is:

$$P_o - P_b = 515.32 \left(\frac{w}{t\ d}\right)^2 V_f + \frac{w^{1.85} V_f\ \mu_f^{0.15}}{t^3\ d^{0.85}} \qquad (1)$$

For a well bore diameter of 220 mm and feed horizon pressure in the reservoir of 120 bar, we have:

$$120 - 37.3 = 515.32 \left(\frac{28.8}{t\ 220}\right)^2 1.3535 + 3.034 \frac{(28.8)^{1.85}\ 1.3535\ (0.088)^{0.15}}{t^3\ \ 220^{0.85}}$$

Solving, $\underline{t = 0.64615}$ mm

The changeover from viscous to turbulent flow is generally regarded as taking place at a Reynolds Number, N_r = 2000, Perry (1963).

where

$$N_r = \frac{G\ t}{\mu_f}$$

and

$$G = \frac{w}{2\ \pi\ R \left(\frac{t}{1000}\right)}\ \text{kg m}^{-2}\ \text{s}^{-1}$$

Hence,

$$2000 = \frac{w}{2\ \pi\ R \left(\frac{t}{1000}\right)} \quad \frac{t}{\mu_f}$$

and

$$R = \frac{w}{4\ \pi\ \mu_f}\ \text{metres} \qquad (2)$$

For a flow of 28.8 kg s^{-1} and viscosity of 0.088 c'poise, the radius at the viscous-turbulent interface is 26.04 mtres. Equation (2) is surprisingly independent of crack width and gives a radius to the viscous condition which is roughly equivalent numerically to the flow-rate, and at a distance of 237 well bore radii.

We may take it therefore that Equation (1) is applicable and hence we can estimate the feed horizon pressure P_b for various flows through the crack width above, as follows:

$$120 - P_b = 515.32 \left(\frac{w}{0.646\ (220)}\right)^2 1.3535 + 3.034 \frac{w^{1.85}\ 1.3535\ (0.6945)}{(0.646)^3\ \ 220^{0.85}}$$

Hence

$$P_b = 120 - \left(\frac{w^2}{28.972} + \frac{w^{1.85}}{9.2664}\right) \qquad (3)$$

Equation (3) is used to evaluate values of P_b for various values of w and these are plotted on Fig. 1 together with test results from Table 1 and it is seen that good agreement is obtained. No sign of choking is indicated, as suggested by Menzies, et al. (ibid) and it appears that flow progressively increases with lowering of feed horizon pressure.

PRESSURE PROFILE TOWARDS WELL

To determine the fluid pressure as it flows radially towards the well, we employ Equation (1) with d replaced by radius R in metres where

$$R = \frac{d}{2\ (1000)}$$

Flow is taken as w = 28.8 kg s^{-1} and t = 0.646 mm with other factors as before.

$$120 - P_b = 515.32 \left(\frac{28.8}{t\ 2000\ R}\right) 1.3535 + 3.034 \frac{(28.8)^{1.85}\ 1.3535\ (0.6945)}{t^3\ \ (2000\ R)^{0.85}}$$

$$P_b = 120 - \left(\frac{0.3464}{R^2} + \frac{8.2822}{R^{0.85}}\right) \qquad (4)$$

Equation (4) enables the pressure profile to be determined from values of radius R and results are plotted on Fig. 2, where it is seen that pressure only starts to fall significantly when within a radius of about 1 m from the well centre-line. As the boiling pressure for water at 286.5°C is 70.14 bar, the associated radius is 0.1684 - 0.11 = 0.058 m. To evaluate the time taken in passing from this radius to the well, we require the water velocity

$$u_f = \frac{\left(\frac{w}{1000}\right) V_f}{2\pi R \left(\frac{t}{1000}\right)} = \frac{w V_f}{2 \pi R t}$$

For $w = 28.8$, $V_f = 1.3535$, $t = 0.646$ and assuming provisionally that there is no flashing (steam generation),

$$u_f = \frac{28.8\ (1.3535)}{2 \pi R\ 0.646} = \frac{9.601}{R}\ \text{m s}^{-1}$$

Time in seconds =

$$\int_{r_w = 0.11}^{R = 0.1684} \frac{\delta R}{u_f} = \int_{r_w = 0.11}^{R = 0.1684} \frac{R.\ \delta R}{9.601}$$

$$= 0.000847 \text{ seconds}$$

It is submitted that this is much too short a time to permit bubble nucleation, hence the water remains steam-free before it enters the well even though the pressure declines significantly below the boiling (saturated) value.

WHAT CRACK SIZE FOR COMPLETE VISCOUS FLOW?

From Equation (2) and taking R as equivalent to the well radius of 0.11 m we obtain;

$$0.11 = \frac{w}{4 \pi\ (0.088)}$$

hence $w = 0.1216$ kg s^{-1} and for this flow, viscous conditions apply over the whole flow-path. To determine the crack width, we employ the basic equation of James (1975b) in the metric form and for Reynolds Numbers less than 2000.

$$P_o - P_b = \frac{\mu_f\ w\ V_f\ \ln \left(\frac{50}{r_w}\right)}{39.37\ t^3} \qquad (5)$$

To obtain the identical flow as before, we require

$$\frac{28.8}{0.1216} = 237 \text{ cracks each with}$$

the same pressure drop from 120 to 37.3 bar. We take a value of the peripheral radius of 50 m approximating to half the distance between wells.

$$120 - 37.3 = \frac{0.088\ (0.1216)\ 1.3535\ \ln \frac{50}{0.11}}{39.37\ t^3}$$

$$t = 0.030 \text{ mm}$$

To obtain the pressure profile with radial flow towards the well, we have:

$$120 - P_b = \frac{0.088\ (0.1216)\ 1.3535\ \ln \left(\frac{50}{R}\right)}{39.37\ (0.030)^3}$$

$$P_b = 120 - 13.51 \ln \left(\frac{50}{R}\right) \qquad (6)$$

Equation (6) is used to plot the pressure profile for viscous flow on Fig. 2 and can be compared with the case of turbulent flow. Identical flows are assumed with one crack of width 0.646 mm passing a turbulent flow of 28.8 kg s^{-1} while for viscous flow 237 cracks are required each of 0.03 mm width and passing 0.1216 kg s^{-1}. For cracks narrower than 0.03 mm a larger number is required to sustain the same flow, but the pressure profile remains the same. For all such viscous curves of Fig. 2, the pressure falls to the boiling value of 70.14 bar at a radius of 1.25 m from the well centre-line and from there to the well wall takes about 0.9 seconds for the 0.03 mm crack and much longer for narrow cracks. Hence flashing of steam is certain and the potential for mineral deposition exists, creating a 'skin' effect close to the well with increasing resistance and hence diminishing flow with time.

For viscous conditions and sufficient cracks to give equivalent flows, a straight line relationship is obtained on Fig. 1 which can be compared with the curve derived for the same flows through one crack. Downhole measurements of flowing wells should permit differentiation between these flow types as suggested in James (1975a).

CONCLUSIONS

Probably the feed to geothermal wells is from solo fissures of a size greater than 1 mm for reasonable commercial discharges. For minute cracks of total equivalent flow, a very large number is required approaching thousands, and is analogous to flow through granulated beds, which appears to be relatively rare, otherwise mineral scaling in the neighbourhood of wells, would be common in regions where the deep water has a high chemical content. Even wells which scale right down to the feed zone are rejuvenated after reaming, indicating that solids are not deposited within the rock fractures. If the opposite were true, geothermal science would be faced with potentially serious problems of descaling the matrix.

REFERENCES

Menzies, A.J., Gudmundsson, J.S. and Horne, R.N. 1982: Flashing Flow in Fractured Geothermal Reservoirs. Proc. 8th Workshop, Geothermal Reservoir Engineering, Stanford University, California, U.S.A.

James, R. 1975a: Drawdown Test Results Differentiate between Crack Flow and Porous Bed Permeability. 2nd U.N. Symp. Development and Use of Geothermal Resources. San Francisco California, U.S.A.

James, R. 1975b: Optimum Well Spacing for Geothermal Power. 2nd U.N. Symp. Development and Use of Geothermal Resources. San Francisco, California, U.S.A.

Perry, J.H. 1963: Chemical Engineers' Handbook. McGraw-Hill, U.S.A.

NOTATION

d	Diameter, mm.
G	Mass-velocity, kg m^{-2} s^{-1}.
N_r	Reynold's Number (non-dimensional).
P_O	Reservoir pressure (no-flow) at feed horizon, bar.
P_b	Pressure at feed horizon, bar.
r_w	Radius of well, mm.
R	Radius, m.
t	Crack width, mm.
u_f	Velocity of hot water, m s^{-1}.
V_f	Specific volume of hot water, kg m^{-3}.
w	Flow-rate, kg s^{-1}.
μ_f	Viscosity of hot water, centipoise.

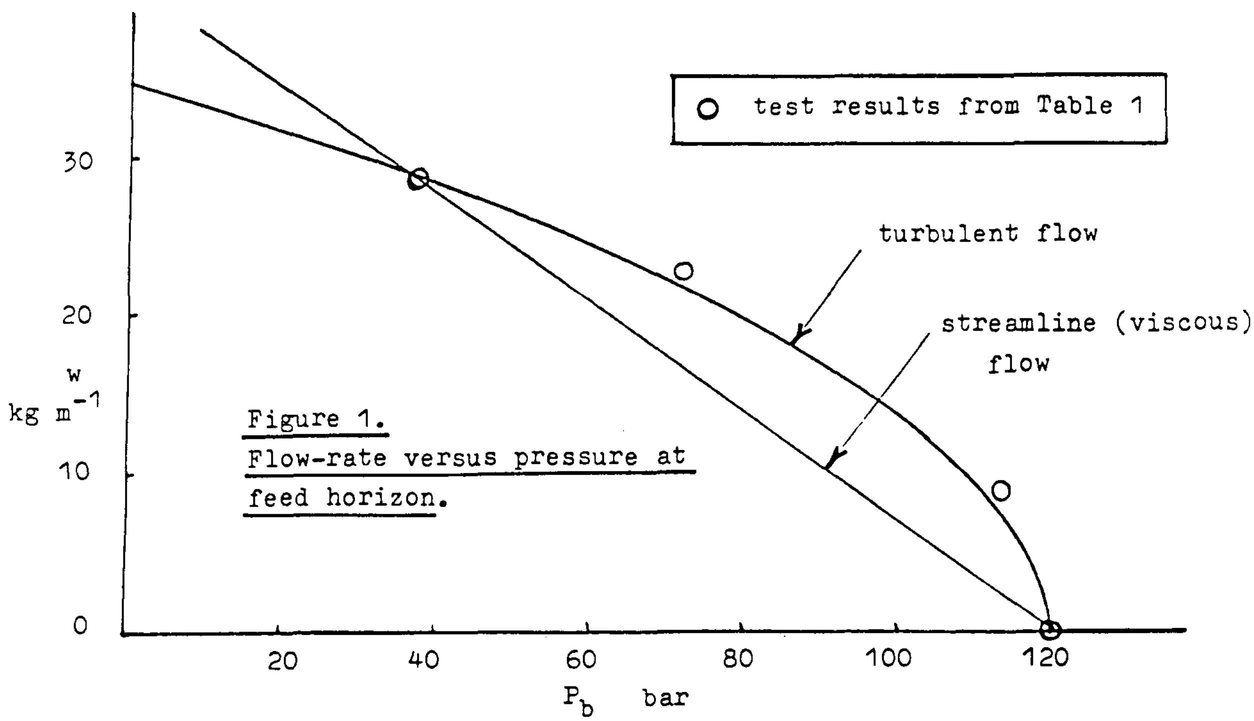

Figure 1.
Flow-rate versus pressure at feed horizon.

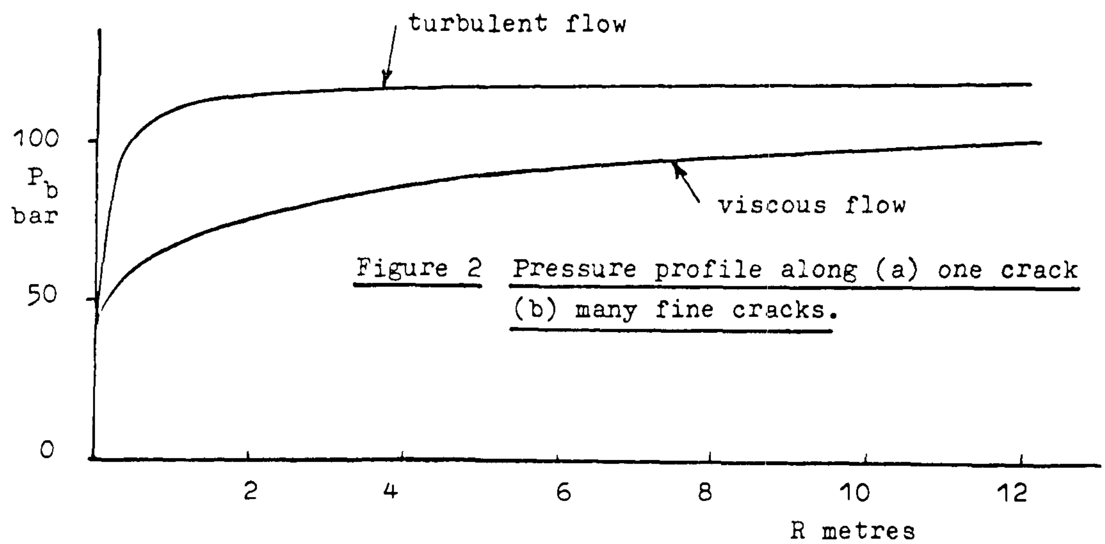

Figure 2 Pressure profile along (a) one crack (b) many fine cracks.