ESTIMATING MAXIMUM DISCHARGE OF GEOTHERMAL WELLS

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ABSTRACT

We cannot tell how 'good' a well is unless we can estimate the maximum flow possible under such ideal conditions as complete permeability at the production horizon and boiling point throughout the depth of the reservoir. Calculated Lip pressures for vertical wide-open discharge under these conditions are surprisingly independent of the kind of fluid tapped by the well, whether dry saturated steam or saturated hot water.

The status of an actual well can be established by comparing the measured Lip pressure with the calculated theoretical maximum.

Discharges are simply determined from the values of Lip pressure and supply fluid enthalpy.

INTRODUCTION

Some years ago, I was working on a Wairakei well which tapped a supply of saturated hot water (water at the boiling point for its pressure). During a period of about a month, the fluid changed to dry saturated steam at the same temperature and pressure, but no change was observed in the Lip pressure attached to the vertically discharging well when blown wide-open. Of course, the actual flow-rate would have decreased considerably as this is related to Lip pressure and fluid enthalpy in the following equation, James (1962).

$$G = \frac{1839\ P_c^{0.96}}{h_o^{1.102}} \qquad (1)$$

G Flow, t/m^2s

P_c Lip pressure, bars

h_o Fluid enthalpy, kj/kg

Obviously the driving force and controlling factor was the presence of the compressible vapour phase, with the water being merely dragged along as a passenger; at least that was the superficial hypothesis advanced at the time. It would, of course, be extremely difficult to experimentally verify this phenomenon over a range of well depths and fluid temperatures and types. Hence, the approach undertaken here is to calculate Lip pressures over a range of well depths and bore diameters for (a) dry saturated steam, and (b) saturated hot water. This is accomplished specifically for the condition shown in Figure 1 where the well is discharged wide-open vertically and where supply horizon permeability is considered as perfect with no restriction on flow into the well at depth.

As an unmanageable mix of well depths and bottom hole conditions is possible to envisage, it was decided to simplify matters by imposing a relationship between these factors. Fortunately, such a relationship exists in practice as it appears that geothermal reservoirs either are, or tend towards Boiling Point with Depth (BPD), so that both pressure and temperature increase progressively with depth from the ground surface, often down to a so-called Base temperature. Over the depth at which BPD obtains, boiling water and steam co-exist, and depending on the permeability-porosity of the rocks, the well may draw either of these fluids from the supply horizon or even a mixture of both. When supplied with saturated hot water, steam generation (flashing) starts immediately and continues as the fluid ascends to the wellhead. Supplementary steam from the rock matrix may increase the fluid enthalpy above that expected from the horizon water temperature but we shall only consider the extreme conditions here, of all-water or all-steam entering the well.

For the case where water is boiling at the ground surface at 100°C and at greater temperatures at depth due to the increasing hydrostatic head imposed by boiling water, we have the following equation derived by James (1970) and in the metric form:

$$C = 69.56\ H^{0.2085} \qquad \text{for} \quad 30 < H < 3\,000 \qquad (2)$$

C Reservoir temperature, ° Celsius
H Depth in metres

So for any particular depth of well, under conditions of BPD, we may take the supply fluid temperature from the above equation and hence obtain from published Steam Tables, the associated pressure, specific volumes of steam and water as well as enthalpies and other data.

DRY SATURATED STEAM CALCULATION

Lapple (1943) theoretically estimated the flow of compressible fluid through long pipes to the atmosphere and this was later experimentally confirmed by James (1964) specifically for dry saturated steam. The method of calculation is given in detail by James (1970) where charts are presented of flow, viscosity and specific volume together with formulas to estimate Reynold Numbers of flows and friction factors in commercial steel pipes.

The approach is to select a temperature, say 250°C and, from Steam Tables, obtain the steam pressure of 39.73 bars, and from equation (2) the depth of 462 m. The steam flow to atmosphere is now calculated and converted to Lip pressure employing equation (1) in which the steam enthalpy h_o = 2801.5 kJ/kg at 250°. A trial method is required after initial guessing of the friction factor, and assumption of a well bore diameter. Results are charted on Table 1 against $\frac{p_c}{d_c^{0.602}}$ which gave a reasonable straight line on log-log paper when plotted against supply fluid as shown on Figure 2.

Table 1 Plot relating supply steam temperature to Lip pressure and well bore diameter

C	$\frac{P_c}{d_c^{0.602}}$
175	7.46
200	9.60
225	12.13
250	15.08
275	18.56
300	22.75
320	26.88
340	32.25

SATURATED HOT WATER CALCULATION

As for dry saturated steam, detailed calculations are presented by James (1970) together with charts of viscosity and specific volume for homogeneous mixtures of steam-water substance, at various pressures and enthalpies. The acceptance of no-slip between the steam and water is assumed valid for the case of maximum unrestricted vertical flow to the atmosphere as it agrees with measured values on powerful wells.

As in the case for dry saturated steam, a downhole temperature is selected which permits the depth to be calculated from equation (2) and thermodynamic data derived from Steam Tables, but here we have all-water entering the well and increasing in steam fraction as it rises to be discharged to the atmosphere. This discharge takes place at the speed of sound at the Lip pressure located on the rim of the pipe outlet. A trial method is necessary in which both Lip pressure and pipe friction factor have to be initially guessed. Overall pressure-drop is the sum of hydrostatic pressure-drop, frictional pressure-drop and pressure-drop due to the increase in kinetic energy within the pipe from bottom entry to top exit.

Results are charted on Table 2 similar to that for dry saturated steam, and then plotted on Figure 2.

Table 2 Plot relating supply water temperature to Lip pressure and well bore diameter

C	$\frac{P_c}{d_c^{0.602}}$
200	9.35
250	15.60
300	22.71
330	27.75
350	31.00
360	33.70

CONCLUSIONS

It should be pointed out that the extraordinary agreement shown on Figure 2 for both steam flow and flashing hot water would most probably not have been investigated if unobserved on a geothermal well at Wairakei, where hot water at the bottom changed over to steam at the same temperature and pressure.

As both bottom hole and exit pressures are identical, one might assume that the pressure curve over the well depth is also the same and hence it may be possible to estimate the steam-water pressure-drop at any location by calculating that for the steam curve, but this would need verification by experiment.

If the match is so good for vertical flow, would we expect a similar match for horizontal flow? Provisional calculations indicate what one would suspect, namely an increasing divergence with depth as the weight of the water fraction in the steam-water mixture exerts its dominance. Presumably vertical flow has some compensating factors which bring close agreement with the homogeneous model, at least over the temperature range common to geothermal reservoirs suitable for power exploitation (175^{o} to $350^{o}C$).

The straight line on Figure 2 passes through all the plotted points with good agreement and has the following equation:-

$$\frac{P_c}{d_c^{0.602}} = \left(\frac{C}{72.2}\right)^{2.195} \qquad (3)$$

ILLUSTRATIVE EXAMPLE

If a 0.2 m diameter geothermal well is drilled 800 m into a reservoir which is at boiling point throughout its depth, what is the maximum flow possible?

Maximum flow occurs at wide-open vertical discharge as shown in Figure 1, and for perfect permeability at the downhole supply horizon, which is here assumed.

The temperature at a depth of 800 m is calculated from equation (2)

$$C = 69.56\ (800)^{0.2085} = 280.32^{\circ}\ C$$

From Figure 2, the equation of the line is now used:-

$$\frac{P_c}{d_c^{0.602}} = \frac{P_c}{(0.2)^{0.602}} = \left(\frac{280.32}{72.2}\right)^{2.195} \qquad \underline{P_c = 7.45 \text{ bars}}$$

If the fluid entering the well is saturated hot water at 280.32° the enthalpy from Steam Tables is 1238 kj/kg. Then from equation (1),

$$G = \frac{1839\ (7.45)^{0.96}}{(1238)^{1.102}} = 4.87\ t/m^2s$$

$$\text{Fluid flow in tonnes/hour} = 4.87\ (3600)\ \frac{\pi}{4}\ (0.2)^2$$

$$= \underline{550.31}\ t/h$$

If fluid entering the well is dry saturated steam, the enthalpy from Steam Tables is 2779 kj/kg.
Then from equation (1),

$$G = \frac{1839\ (7.45)^{0.96}}{(2779)^{1.102}} = 2.01\ t/m^2s$$

$$\text{Steam flow in tonnes/hour} = 2.01\ (3600)\ \frac{\pi}{4}\ (0.2)^2$$

$$= \underline{226.91}\ t/h$$

These are the maximum flow-rates possible; actual wells have reduced discharges due principally to relative impermeability of reservoir rocks retarding inflow at the supply horizon (granulated bed, fissure or fractures).

REFERENCES

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Figure 1.
Maximum discharge of a well.
Vertical flow with valve wide-open.