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SIMPLIFIED ANALYSIS OF POWER POTENTIAL IN A GEOTHERMAL DEVELOPMENT

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SUMMARY – Equations governing the flow of geothermal fluids through the reservoir, up the wellbore and through the production pipeline can be simplified. The simplifying assumptions are based on conditions commonly encountered in New Zealand geothermal fields. The characteristic pressure profile of fluids throughout the production system can be calculated by the use of a spreadsheet.

1. INTRODUCTION

The time between initial exploration of a geothermal resource and the final decision to develop it for electricity generation may be more than 5 years. During this period the annual expenditure needed to collect the information by which the final decision can be made increases significantly. The developer takes the risk that this expenditure is worthwhile, because the final economic analysis cannot be completed without the information gathered. It would be preferable to have some way of estimating every year, or at each stage during the exploration period that capital is released, the economic benefit to be gained from the final development. This would allow the project to be shelved until economic predictions looked better.

There would be two stages to such an estimation process, the cost and financial stage and the performance stage. This paper deals with the latter, the prediction of performance. The cost and financial information will change over the exploration period, for example interest rates, selling price of electricity, plant and construction costs, etc.. These will have to be estimated separately.

The aim of the work reported here is to allow a performance prediction to be made for reservoir producing 2-phase geothermal fluid and driving a steam turbine power station using a spreadsheet. This would allow an exploration team of essentially earth scientists to estimate performance without the need for more time consuming techniques such as reservoir and wellbore simulation.

2. PERFORMANCE CALCULATION DEVELOPMENT

The objective is to produce a simplified representation of the performance of each of the principal components of the geothermal system. The components that dictate the rate of electricity generated (the revenue) are the reservoir, wellbore, two-phase pipeline, separator, steam line and turbine. The performance of the reinjection system has an indirect effect on the rest of the system in that it dictates some of the design parameters of the steam system (see for example Watson, Lory and Brodie, 1997), but this is ignored here. The reinjection system is a cost to be considered separately in the "other part" of the whole estimation process. The equations used in the simplified process identify variables affecting performance. Any associated economic analysis to optimise the production configuration is facilitated by the explicit relationship between the variables and turbine inlet pressure.

2.1 Reservoir flow

Fluid flow in a porous medium is described by the "diffusivity" equation based on conservation of mass, an equation of state and Darcy's Law:

$$\frac{\partial^2 P}{\partial r^2} + \frac{1}{r}\frac{\partial r}{\partial r} = \frac{\phi \mu c}{k}\frac{\partial P}{\partial t} \qquad (1)$$

where P = pressure (Pa)
ϕ = porosity
μ = dynamic viscosity (Pa.s)
c = system compressibility
k = permeability (m^2)
r = radial distance (m)
t = time (s)

Important assumptions in the development of the diffisivity equation are horizontal radial flow, negligible gravity effects, homogeneous isotropic porous medium, fluid of small and constant compressibility, Darcy flow in the formation, and properties k, ϕ, μ that are independent of pressure. These assumptions are rarely met with satisfaction in a geothermal reservoir, however there is no simple alternative to this approach and the solution of the above equation in the simplified Theis form is used :-

$$P_i - P_{wf} = \frac{-m u}{4\pi\rho kh}\left[\ln \frac{kt}{\phi\mu c(r_w)^2} + 0.809071\right] \quad (2)$$

where P_i is the undisturbed reservoir pressure and P_{wf} the pressure in the well at the production zone.

In many cases the permeability near the wellbore is reduced as a result of drilling and completion practices - the "skin" effect. This effect of can be taken into account as an additional pressure drop (AP) proportional to the rate of mass production (m). For the typical case where the skin factor is negative the pressure drop can be shown to be simplified to

$$P_i - P_{wf} = \frac{m\mu}{4\pi\rho kh}\left[\ln \frac{kt}{\phi\mu c(r_w)^2}\right] \quad (3)$$

Where the fluid is 2 phase in the formation and for typical values of porosity of 0.15, and specific volumetric formation heat capacity of 2.5 x 10^6 J/m^{3}K then total compressibility (c_t) can be derived from Grant et al. (1982) as:

$$c_t = 70[P_{sat}^{-1.66}] \times 10^{-6} \text{ /Pa} \quad (4)$$

where P_{sat} is saturation pressure (MPa).

Two phase flow density (ρ_t) can be calculated from the specific volume requirement that:

$$v_t = 1/\rho_t = xv_g + (1-x)v_f \quad (5)$$

where x = dryness fraction of steam by weight

Given relative permeabilities of Grant (1977) of $k_{rf} + k_{rg} = 1$. Then the total kinematic viscosity, υ_t , is:

$$\upsilon_t = x\,\upsilon_g + (1-x)\,\upsilon_f \quad (6)$$

The dynamic viscosity is found from $\mu = \rho\upsilon$.

$$\mu_t = x\,\mu_g + (1-x)\,\mu_f \quad (7)$$

2.2 Wellbore flow

The pressure drop, due to vertical flow in pipes, consists of three components, gravity, friction and acceleration. The acceleration component is usually negligible, leaving the other two to be represented as:-

$$\Delta P = \rho g\Delta z + \frac{8fm^2}{\pi\rho D^5} \quad (8)$$

where f = friction factor
z = elevation (m)
v = velocity (m/s)
D = well diameter (m)

The application of this formula to geothermal wells does require caution. Flow from geothermal wells is usually 2 phase and 2 component. The second component arises from gas entrained in reservoir fluids. The application of equation 8 will result in the correct form of output curve but will usually over-estimate well productivity for a given wellbore pressure. Assumptions inherent in the application of equation 8 are that actual flow can be modelled using a single friction factor which incorporates the effects of mineral deposition and turbulence incurred around the casing joints and liner slots. As flow in the well bore is in most instances turbulent the friction factor can be described as (Leaver & Freeston, 1981).

$$f = 0.094(e/D)^{0.91} \quad (9)$$

where e = pipewall roughness (m)

Changes in casing diameter can be modelled from Leaver & Freeston (1981)

$$D_e = L_T\,[(L_1/D_1^5) + (L_1/D_1^5) + \ldots\ldots + (L_n/D_n^5)] \quad (10)$$

where

L_T = total length = $L_1 + L_2 + \ldots\ldots + L_r$

2.3 Two-phase pipeline flow

The Harrison-Freeston correlation for prediction of pressure drop in two phase lines is given as:

$$dP/dz = 4\tau_w/D(1-A_c) \quad (11)$$

where: $A_c = m^2x^2v_g/(P_{av}A^2\alpha)$

$1/\alpha = 1 + [(1-x)/x)^{0.8}\,(v_f/v_g)^{0.52}]$

$\tau_w = \lambda/4\,(V_f^2/2v_f),\ V_f = m(1-x)v_f/((1-\alpha)A)$

where m = mass flow (kg/s)
V = velocity (m/s)
τ_w = wall shear stress (Pa)

An alternative correlation (equation 12) has been developed to better illustrate the relationship between two phase pressure drop and primary dependent variables. The correlation coefficient with the Harrison-Freeston correlation is $R^2 = 0.987$ for the ranges $m = 50 - 200$ kg/s, $P_{av} = 5 - 30$ bars, $x = 0 - 1$, $D = 0.3 - 0.46$ m. For the pressure drop for pure steam equation 12 showed an average of 5% deviation, with a maximum of 12%.

$$\frac{dP}{dL} \approx \frac{(19.35x^2 + 1)}{1.353 \times 10^8} m^2 P_{av}^{-0.9} D^{-5} \text{ bar/m} \qquad (12)$$

2.4 Flow in the separator and steam pipeline

The pressure drop in the separator is best assumed to be negligible, for the precision of the approach being adopted, or if considered necessary, represented as a fixed pressure drop.

2.5 Turbine output

Electrical load as a function of turbine inlet pressure can be calculated from a combination of the Wilans line relating steam demand to electrical load and the turbine swallowing capacity. The characteristics of large condensing steam turbines are essentially linear so for a given condenser pressure and turbine speed, the inlet pressure controls the mass flow rate through the turbine and the power generated. For a particular 50 MW(e) machine the relationship relating pressure to power output is:

$$E = 9.7P_{inlet} - 11.8 \qquad (13)$$

where E = electrical output (MW)
P_{inlet} = turbine inlet pressure (barsa)

3. THEORETICAL CASE STUDY

Consider a geothermal development proposed with the following characteristics.

Initial reservoir pressure = 80 barsa, reservoir thickness = 1000 m, $k = 100$ md, $D = 300$ mm, $h = 1317$ kJ/kg, porosity = 15%, well depth 2000 m, $d_{well} = 7$ in.

The calculation of enthalpy and specific volume is facilitated with the correlations shown below which are accurate to better than 1.7% in the range 1-150 barsa.

$$h_f = 353.275 + 216.02\log P + 61.189P^{0.5} + 1.0995 \times 10^{-5}P^3 \qquad (14)$$

$$h_{fg} = 2317.11 - 101.44\log P - 57.211P^{0.5} - 1.9433P - 3.0737 \times 10^{-5}P^3 \qquad (15)$$

$$v_f = 0.991853 + 0.049269(1/P)^{0.5} + 0.095166\log P + 0.0024859P + 1.63286 \times 10^{-4}P^4 \qquad (16)$$

$$v_g = 396.535(1/P)^{0.5} + 1412.53/P + 41.7855\log P - 8.96751 \times 10^{-4}P^2 + 3.5036 \times 10^{-6}P^3 - 113.945 \qquad (17)$$

From equation 3 the pressure drop at the sand face is 1.03 bars.

Wellbore and pipeline pressure profiles are then calculated by starting at the sand face and calculating the pressure drop over an incremental length downstream over which fluid properties are assumed constant.

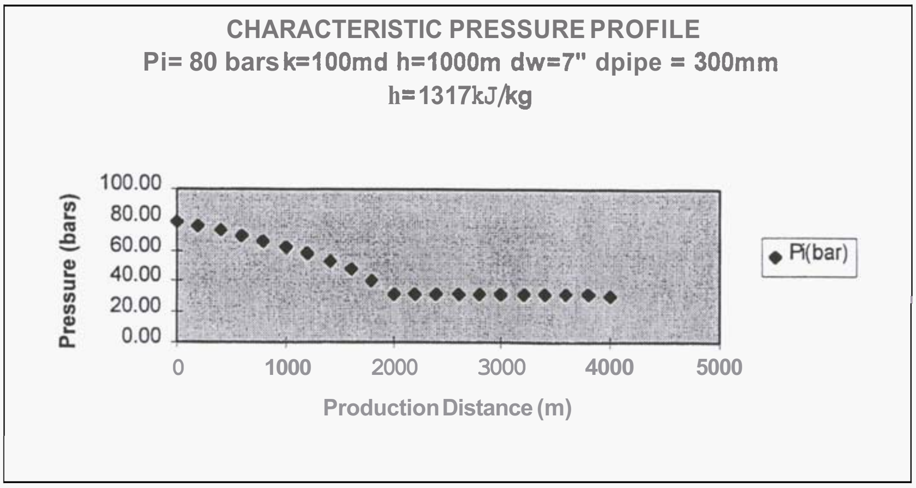

Figure 1: Characteristic pressure profile

The profile obtained from a spreadsheet analysis is shown in Figure 1. Note that production distance includes the wellbore.

The turbine inlet pressure is available fiom Figure 1. The power potential can estimated using equation 13.

4. DISCUSSION

It is important to minimise pressure drop in the production system to maximise power output from the steam turbine and also maximise the thermal efficiency of the geothermal resource.

The simplified method of assessing power potential presented enables some of the variables to be explicitly identified. Optimising these variables will assist in minimising the number of wells drilled.

A comprehensive analysis would ensure that factors such as fluid gas content and deposition in the wellbore are also considered.

4.1 Reservoir

Fluid flow in the reservoir is influenced by permeability, porosity, fluid enthalpy, fluid saturations, gas and mineral content.

For radial flow in a homogeneous isotropic medium pressure drop can be minimised by ensuring that the "skin" is as negative as possible and that for near vertical wells the wellbore radius is as large as practicable as $\Delta P \propto 1/\ln(r_w)^2$.

4.2 Wellbore and Pipeline

Pressure drop is minimised by maximising well and pipeline diameter as $\Delta P \propto D^5$. In addition pressure drop is increased as specific volume increases as this also is a function of pressure drop.

4.3 Economic considerations

To assist in determining optimum pipeline and well diameters along with the preferred turbine inlet pressure simple optimisation techniques can be used which balance the cost of well completion and pipeline commissioning as a function of diameter against the variation in power output with turbine inlet pressure and well productivity. The effect of the reinjection system could also be included if desired.

5. CONCLUSIONS

Simplified analysis of a geothermal production system can be performed by spreadsheet. The simplifications used assist in identifying the effects that individual variables have on system performance and assist with calculating the effects of hardware changes on system power output.

Simplified analysis can be used to give useful approximations of the electrical output at the early stages of a geothermal development. This allows low cost and convenient assessment of power potential without needing investment in specialist software.

6. ACKNOWLEDGEMENTS

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