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Application of Wellbore Simulators to Management Problems for a Geothermal Field — Case Studies

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ABSTRACT

The performance and design of geothermal wells can be influenced by a range of factors, some of which are dictated by reservoir conditions, others by geometric design or by operational requirements. Recently a number of dynamic models of the flow in a geothermal well have been produced. In this paper we take two of these models and demonstrate their use by applying them to management problems associated with the Rotorua and Wairakei geothermal fields. The need for a reliable model which can account for changes in thermodynamic properties of the fluid due to gas and solids in suspension are emphasised as well as being able to account for wells with multiple feed points.

INTRODUCTION

The calculation of flowing pressures and output of a geothermal fluid from a well bore has received attention in the literature recently. The early work of Gould (1974) and Upadhyay et al (1977) consisted of using Hagedorn & Brown type correlations for vertical flows to determine pressure and temperature profiles in geothermal wells. Since that time more work has resulted in further correlating and an extension of the results from profiles to predicting well output characteristics Miller and Harrison (1985), Gudmundsson (1984).

Such simulators have a wide application in the development of geothermal resources. Some examples of their use are 1) to show the effect of well bore diameter on the flowrate including the effects of wellbore scaling. 2) Given wellhead conditions, downhole pressures can be calculated or alternatively, if the reservoir conditions are known, the simulator can be used to determine the wellhead pressure as a function of flowrate, that is, the output curve. 3) A simulator may also be used to predict an output curve from a single output measurement, a technique which is useful if discharge of a well is restricted on environmental grounds, i.e. noise or waste water disposal, or if the economics of testing over the full range of output are not justified at the field investigation stage.

In all cases the accuracy of the simulation has to be justified by continually matching output with experimental data. In all the simulators that are available, correlations are used for void fraction, slip factor, etc, to close the one dimensional equations of motion. In addition to these fundamental equations, correlations of steam tables are required and have been developed with suitable provision for modifications of the fluid transport properties due to deviations from pure water, such as the addition of salts and carbon dioxide. However many of the simulators have had little exposure to a variety of actual well test data, consequently it has been found by the authors that whereas a simulator will give an adequate output for one well, its use in another well, even in the same reservoir, may not produce a satisfactory result. Efforts are being made to rectify this situation and this paper presents case studies of two wells in two different reservoirs which have completely different fluid temperature and well geometry characteristics using two different simulators.

The first is from the Rotorua geothermal field with over 400 production wells which provide low enthalpy fluid for residential, commercial and light industrial use, mainly in the form of domestic hot water, heating and bathing. The wells are characterised by downhole temperatures in the range 120 - 200°C, drilled to shallow depths of less than 200 m and lined with 102 mm (4 in) casing. A few of the wells are termed high pressure, that is, they produce an artesian flow which is easily controlled. However the majority are low pressure which have to be stimulated to start the flow. They operate at low wellhead pressures (0.5 - 3.0 bar) and enthalpies (500 - 700 kJ/kg). Operation of such wells at low flow rates results in flow instability and final collapse. "Calciting", that is the deposition of calcite (Calcium carbonate), in these wells causes the output to decline with time. The wells have to be reamed to remove this buildup. Calcite forms in the well bore due to the flashing of the water as it rises to the surface.

The geothermal field at Rotorua is currently under stress and the efficient use of the resource is essential to prolong the life of the field and preserve the naural features which are of historical interest and an attraction for the tourist. A study is reported of one low pressure well (715) from which output and downhole data were available and the effects of controlling discharge by changes in geometry were investigated using a simulator.

The second case study was centred on the Wairakei geothermal field, a resource which has been used for thirty years to produce a generation output of over 1000 GWhrs/annum. Here wells are typically around 600 m deep completed with 8 5/8" casing and producing enthalpies of about 1000 kJ/kg from hot water temperatures of 250 - 260°C. Wairakei well WK 107 was experiencing production problems because of a casing failure and it was proposed to reduce the diameter of the production casing from 8 5/8" to 6 5/8". An estimate of the well output was required in order to make an economic decision as to whether such a modification to the well was justified.

WELL BORE FLOW SIMULATORS

For this paper two case studies are analysed using two different simulators. A study of the published simulators shows that although they are all generated from the same basic equations of motion and generally use a stepwise integration technique up and down the well depending upon whether wellhead or downhole conditions are specified, there is a wide variation in the correlations used for the two phase parameters void fraction, slip velocity etc, and the transport properties of the mixture. In addition some simulators include the effects of well bore heatflow whilst others have allowances for changes in friction factor due to roughness. Some use corrections for non-dissolved solids whilst others also include correlations for dissolved gases.

The simulators chosen for the study are due to Bilicki et al (1981) of Brown University, USA, which we label the Brown simulator and the other one is labelled the Stanford simulator and is due to Ortiz-Ramirez (1983).

Brown Simulator

The model calculates flow parameters in a well based on conditions at bottomhole. A stepwise integration technique is used up the well bore. The model assumes a steady one dimensional flow of geofluid up the well. It also assumes a single feed point and single phase fluid (liquid) at the bottom of the well. As the fluid ascends to the surface it flashes to two phase water-steam as the saturation pressure is reached. Above the flashing level a sequence of flow regimes can occur depending on the criteria for their appearance. Four flow regimes are identified. In order of appearance these are bubbly, slug, froth and annular mist. The limits which delineate the four flow patterns from each other follow from definite criteria, a detailed statement of which is given in Bilicki Z and Kestin J (1980). For transitions from the bubble to slug and slug to froth regimes Prandtls mixing length theory is followed. The criteria for transition from froth to annular was taken from the work of Pushkin and Sorokin (1962).

The one dimensional equations are then closed using Petrick's (1958) correlation for wall stress together with empirical correlations which determine the void fraction for each topological flow structure, Mendelson (1967) Dukler (1978). The thermophysical properties of water and steam of pressure and/or temperature are taken from analytic formulations based on the 1967 International Formulating Committee (IFC). The effect of the presence of dissolved solids on the thermodynamic properties is also accounted for in the model. The solids are represented by an equivalent NaCl content which is considered to be the major constituent and its effect on the density, viscosity, enthalpy and saturation temperature at a given pressure is accounted for by suitable correlations developed from the literature, Bilicki et al (1981).

This model does not include the effects of non-condensible gases or heat transfer to the surrounding formations however both these effects and the reasons for not considering them are discussed in the original paper, Bilicki et al (1981). One further assumption used is that the pressure drawdown (reservoir pressure - well pressure) at the feed point is a linear function of well mass flow. This infers single phase Darcy-type flow and is applicable for low mass flow wells. At higher flow rates when a steam/water enters the well bore the relationship between mass flow rate and drawdown pressure will become non-linear. Gudmundsson and Marcou (1986).

In order to accommodate variations in well bore roughness the authors modified the friction factor in Petricks equation from the smooth wall Blaisus expression to the analytic expression of Churchill (1977) so that production casing, slotted liners and open hole friction factors could be used where appropriate. The roughness values proposed by Gould (1974) namely 3.05×10^{-4} m for open hole and 4.5×10^{-5} m for production casing where used for the case studies.

Stanford Simulator

This simulator uses the conventional one dimensional equations and identifies flow regimes from the Duns and Ros flow regime map. The procedure used thereafter is that described by Orkiszewski (1967). The flow regimes identified are termed Bubble, Slug, Transition and Mist, all very similar in description to those of the Brown model. The transition criteria between the flow regimes as described by Orkiszewski (1967) have been used and the friction factors are based on the Moody diagram.

When geothermal fluid flows to the surface a temperature difference may exist between the formation and the well bore which results in unsteady radial heat transfer. An approximate solution, which permits estimation of fluid and casing temperature as a function of time, due to Ramey (1962) is used in this simulator.

Other features which are different from the Brown simulator described above are that the computer code allows pressure calculations to be made from bottomhole to wellhead as from wellhead to bottomhole, a feature which is useful, particularly where it is suspected that a well may have multi-feed points. Thermodynamic properties are calculated from steam tables using Lagrange interpolation but no corrections for non-condensible gases or salt content are included.

CASE STUDIES

Study 1 - Rotorua

Well 715 located on the eastern side of the field was selected. It is drilled to a total depth of 122 m, lined with a 4 in casing (BS 1387 heavy grade pipe) to 100 m and completed to the bottom with an open hole. It has a permeable zone near the bottom with a feed temperature of around 167°C. At present it is coupled to 9 domestic users with a nominal summer output of 0.4 kg/s. It is classed a typical low pressure well with a maximum wellhead pressure (WHP) of 4.5 bar abs. Maximum output mass flow was measured at 4.3 kg/s at an enthalpy of 720 kJ/kg and a WHP of 4 bar abs. Normal production flowrate varies between 0.4 and 1 kg/s depending upon the load.

The measured output for this well is shown at Figure 1. The maximum discharge pressure (MDP) was 4.5 bar abs at a flow rate of 3.2 kg/s. Maximum output to a 80 mm pipe was 4.3 kg/s at an enthalpy of 720 kJ/kg. The Brown program was used to calculate the well performance and a final match was achieved with data input as in Table 1. Note that the drawdown factor (K) was fixed at zero and the weight of dissolved solids at 0.07%. K = 0 is justified from the discussion below. Rotorua wells produce alkaline chloride water with chloride concentrations in the range 250 - 1000 ppm. A value of 0.07% total dissolved solids is therefore not unreasonable. The output is not too sensitive in this range to solids content for the higher pressure wells, however the chloride contents are greater.

Having achieved a reasonable match the sensitivity of the output to small changes in some of the variables was investigated. Bottomhole temperature has the major effect on the output curve. Figure 2 shows the effect of changes in temperature and hence on the required accuracy of measured temperature as input to the program, whilst the effect of drawdown factor is illustrated in Figure 3. Increase in drawdown factor K reduces the dynamic bottomhole pressure which results in a lowering of the flash point. For the small flows taken from this well large pressure is not expected, particularly since the reservoir is known to be highly permeable, so choosing K = 0 for the matching profile is justified.

Work by the Geothermal Task Force in Rotorua (1985) established that the mean draw-off for a domestic home on a low pressure bore was about 0.12 kg/s. Although well 715 serves 9 homes the demand shows that it has to be able to operate at low flow rates - however control of such wells is difficult. When operated at low output the wells operate in the slug flow regime with vigorous cycling of well head pressure which eventually leads, as flow rate is reduced, to well collapse, Figure 4. The normal operating range is illustrated in this figure. To avoid such problems users would tend to adopt usage at higher flow rates which leads to a wastage of energy. It is desirable therefore to be able to operate at higher flow rates above the mass flow given by MDP, i.e. the upper part of the output curve.

The Brown program was used to study the influence of reduced casing diameters on output. Production casings of 0.076 m (3 in) and 0.063 m (2 1/2 in) were used as input keeping the other parameters as used in the matching exercise constant. For flow rates less than 1.4 kg/s, the 0.076 m diameter casing gives a higher WHP for the same mass flow, Figure 5. It follows that a smaller diameter is more suitable for these lower flow rates since it allows the well to be operated on the stable part of the output characteristic whilst giving the desired mass flow.

Wairakei Well 107

This well was drilled in 1964 to a total depth of 643 m. Initial measurements indicated a maximum temperature in the well of 247°C with a flowing enthalpy of 1328 kJ/kg at a mass flow rate of 20.5 kg/s and a WHP of 5.8 bar. Since the field has been exploited, conditions in the field have changed. Recently a casing failure has led to the well being taken off production. However by Wairakei standards this well is a good producer and it was necessary to find out whether by lining the well it was economic to be able to put it on stream again. The Stanford program was used to provide these answers.

The initial data is given in Table 2 and a sketch of the well geometry is at Figure 6. Simulation was first done from wellhead to bottom to test the model against recorded downhole data. Well bore heat loss and solids content were assumed to be zero. A calculated bottomhole pressure of 27.6 bar abs and temperature of 229°C were obtained (cfd 29 bar abs, 229°C). This was considered to be satisfactory. With the drawdown factor at zero and using the calculated bottomhole data a production curve was constructed, Figure 7.

It was proposed to modify the well as follows. Removal of the 6 5/8" slotted liner and cementing a 6 5/8" casing to 450 m leaving an open hole to the bottom from 450 m. The program was then used to obtain the output curve with the modified geometry using the derived wellbottom data.

The production curves are compared at Figure 7 and show a reduction, as might be expected, in output for the modified well. For a WHP of 7.5 bar abs, a typical Wairakei operating pressure, the mass flow is reduced by about 20%. It was not expected that the maximum discharge pressure (MDP) would change so much. For a given feed temperature, diameter changes usually cause only small changes in MDP. However the modification involved changes in casing setting depth which made a relatively large reduction in the length of open hole, causing smaller bore friction losses due to reduction in roughness effects.

FINAL COMMENTS

The two studies have illustrated one aspect of how well bore simulators can be used to aid management decisions in the operation of geothermal fields. However there is still a need to have a more reliable model which has been validated in a wide range of operational geothermal fields. A detailed knowledge of the effects of gas and solid chemistry on the thermodynamic properties of the geofluid is necessary as well as methods of accounting for multiple feed points in the wells have to be solved before a general simulator can be used with confidence.

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Table 1: Rotorua Well 715

Bottom Hole Pressure	12.0 bar abs
Bottom Hole Temperature	167°C
Openhole Diameter	0.152 m (6")
Roughness	3.05×10^{-4} m
Casing inside diameter	0.1032 m (4.06")
Roughness	4.57×10^{-5} m
Depth to change of diameter	100 m
Weight % dissolved solids	0.07
Drawdown factor	0
Calculation step	2 m

Table 2: Wairakei WK 107

Depth of feed zone	600 m
Depth to top of liner	270 m
Inside diameter of liner	0.152 m (6 5/8" OD)
Roughness	1.07×10^{-4} m
Inside dia of prod casing	0.2 m (8 5/8" OD)
Roughness	4.57×10^{-5} m
Mass flow	44.5 kg/s
WHP	7.5 bar abs
Bottom hole pressure	29 bar abs
Bottom hole temperature	228°C
Enthalpy	1023 kJ/kg

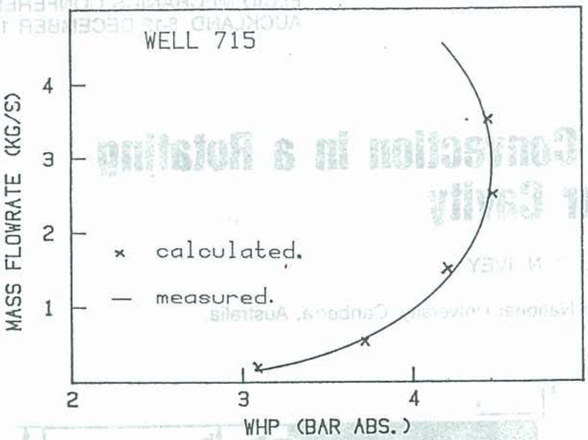


FIG. 1 MATCHING OF OUTPUT CURVE

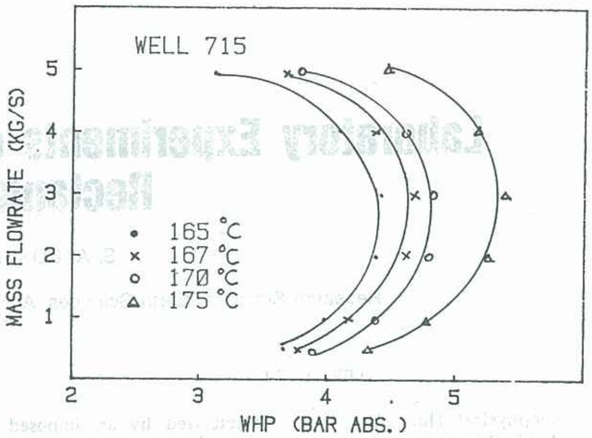


FIG. 2 EFFECT OF BOTTOM HOLE TEMPERATURE

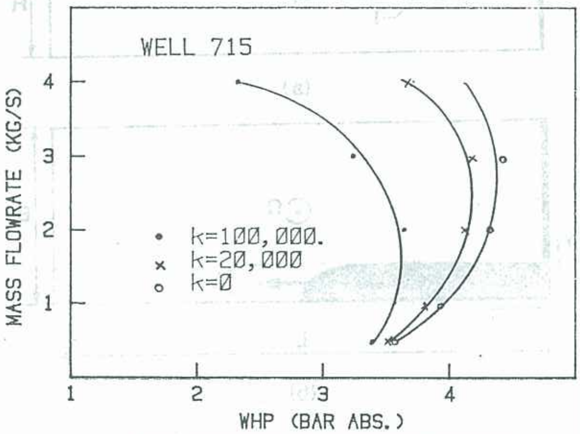
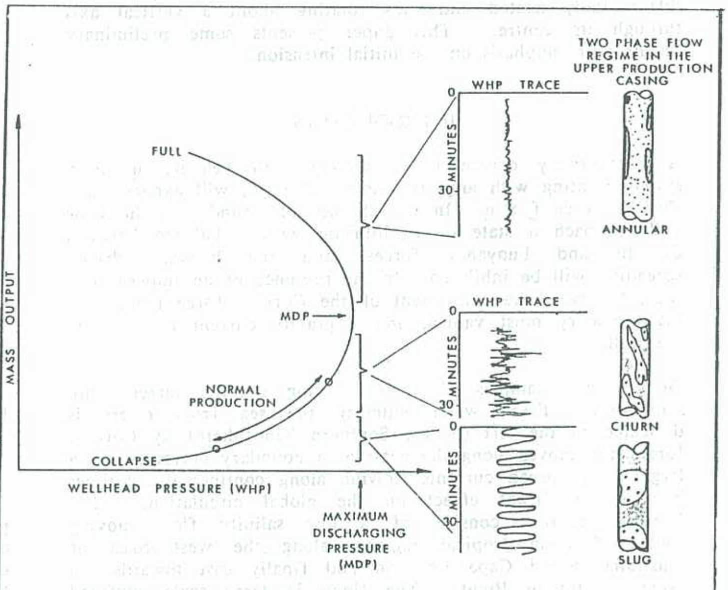


FIG. 3 EFFECT OF DRAWDOWN FACTOR



AN OUTPUT CURVE FOR A ROTORUA BORE (FEED 165°) SHOWING THE ASSOCIATED WHP AND FLOW REGIMES

FIG. 4 (FROM GEOTHERMAL TASK FORCE REPORT)

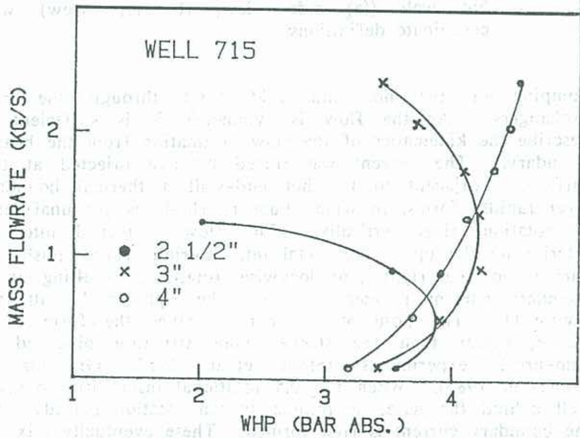


FIG. 5 EFFECTS OF DIFFERENT DIAMETER

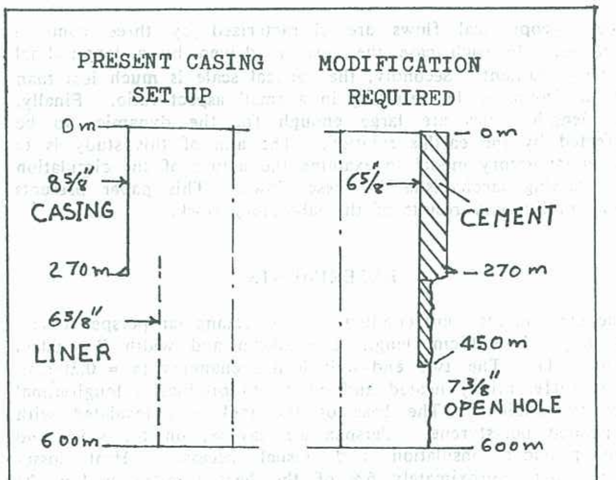


FIG. 6 SCHEMATIC DIAGRAM OF WELL GEOMETRY

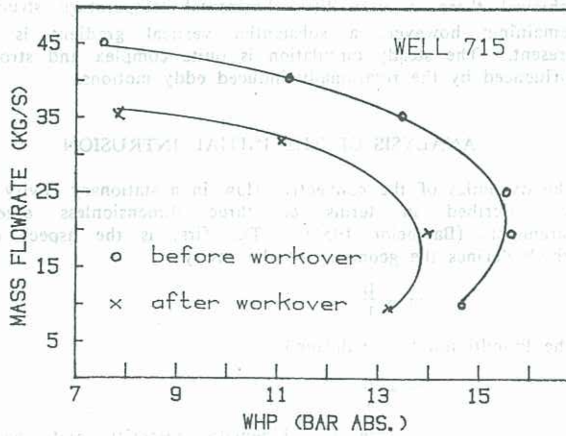


FIG. 7 SIMULATION OF OUTPUT OF WK-107