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SUPERWELL - A SIMPLE WELL BORE FLOW SIMULATOR IN SPREADSHEET FORMAT

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ABSTRACT

Well testing is a key tool for the initial measurement and ongoing monitoring of well properties. When well testing is coupled with accurate well bore flow simulation, we can gain valuable information about well and reservoir properties. Furthermore, we can use this information to maintain the ‘health’ of our reservoirs and wells. We can also improve and optimize well and reservoir productivity, providing significant return on our geothermal investments. There is a need for a high quality, low cost, and reliable well bore flow simulator that is easy-to-use, simple, and tuned to geothermal wells. This report outlines the specification, development and testing of a simulator that solves geothermal problems.

INTRODUCTION

The drilling of geothermal wells is expensive, inconsistent, and risky. It is also essential to bringing reservoirs from exploration, through development, and into production. The monitoring, maintenance, and replacement of production wells are necessary to keep power station production at high levels. In addition to allocating an adequate drilling budget, it is highly desirable to allocate adequate resources to well testing and well test analysis. This report assumes that a successful drilling and well testing program is already in place, and its focus is on well bore flow simulation as a key well test analysis tool.

First, let us understand that well testing is a very broad topic. Generally, it comprises a variety of transient and steady state tests.

Typical well flow testing situations can be classified by the status of the well:

- Injection (low flow rate, steady state)
- Warm-up (zero flow rate, transient)
- Shut-in (zero flow rate, steady state)
- Bleed (very low flow rate, steady state)
- Production (high flow rate, steady state)

Well flow testing situations can also be classified by the type of fluid flow:

- Liquid (liquid-dominated reservoirs)
- Two-Phase (flashing liquid-dominated, natural two-phase, and condensing vapour-dominated reservoirs)
- Vapour (vapour-dominated reservoirs)

Due to time availability, the scope of this project was limited to steady state well testing, specifically flow testing. The greatest application for this project is in the production situation, where a new well is being brought into production for the first time or a periodic flow testing is being conducted on a mature well that is already in production. Other applications could include casing modification studies and assessment of scaling. This project focuses on these types of applications. Furthermore, the focus will be on the two-phase flow situations. They are the most complicated and the most common. In addition, vapour and liquid flows can later be treated as special, single-phase cases of the general, two-phase case.

When properly applied, two-phase, steady state, well bore flow simulation can provide the following benefits:

- Rapid calculation of well output curves
- Low cost, precise, well sizing studies
- Down hole pump benefit analysis
- Logging test robustness checking
- Flow test robustness checking
- Detection of well damage
- Decline curve analysis
- Scaling risk analysis
- Detection of scaling
- Well histograms

Other applications are possible. The key is to use simulation to analyze problems, evaluate options to fix them, and predict likely results. Then, the optimal mix of field services can be used strategically to reduce risk, improve consistency, lower expense, and boost output.

SURVEY

In a typical flow testing situation, measured values will generally be available to us at the well head for the following:

P_{WH}	Pressure, well head
T_{WH}	Temperature, well head
Q_{MWH}	Mass flow rate, well head
x_{WH}	Steam quality ratio, well head

Values at the casing shoe will be wanted for the following:

P_{CS}	Pressure, casing shoe
T_{CS}	Temperature, casing shoe
Q_{MCS}	Mass flow rate, casing shoe
x_{CS}	Steam quality ratio, casing shoe

Calculating these values is generally not difficult.

Values at the bottom hole (reservoir) will be wanted for the following:

P_{BH}	Pressure, bottom hole
T_{BH}	Temperature, bottom hole
$Q_{MBHInflow}$	Mass inflow rate, bottom hole
x_{BH}	Steam quality ratio, bottom hole

Estimating these values is not too difficult.

Values at depths within the slotted liner will be wanted for the following:

P	Pressure
T	Temperature
Q_M	Mass flow rate
x	Steam quality ratio
$Q_{MInflow}$	Mass inflow rate from reservoir

Accurately estimating these values can range from not easy to extremely difficult. This is especially true if the well has more than one feed zone, a large, distributed feed zone, or a combination of multiple, distributed feed zones. In addition, some of the feed zones can actually be 'loss zones', and some of them can be feed zones, loss zones or even internal flows, depending on other conditions during the operation of the well.

So far, pure water has been considered; its thermodynamic properties are very well known. In most geothermal settings, two-phase flow of water is prevalent, with liquid flashing into vapour and/or vapour condensing into liquid. These complicate our calculations.

Most geothermal fluids also contain at least some dissolved gases and solids; these further complicate our calculations. Commonly, CO_2 is used as a proxy for all gas species and NaCl for all solid species, as these are usually the two dominant dissolved species.

A variety of correlations exist for steady state flowing conditions, and these correlations can be classified by the types of fluids that are modelled:

H_2O	Mandatory and obvious
CO_2	Optional and desirable
NaCl	Optional and desirable

Many well bore flow simulators already exist, and surveys of them have previously been done. For example, Hadgu (1989) studied 5 well bore flow simulators:

BROWN
STANFORD
WELF
GEOTEMP2
BARELLI

As a result of his survey, he developed 3 more well bore flow simulators:

WFSA
WFSB
STFLOW

Also, Karaalioglu (1998) made a detailed comparison of 2 simulators: WELLSIM and WELL. WELLSIM is much more complex than WELL. It is based on 5 different correlations. WELL is based on ESDU (1971).

SuperWell is also based on ESDU, implementing the ESDU methodology in a spreadsheet approach.

DESCRIPTION OF PROCEDURES

Stepping Down

The procedure for starting with well head conditions and then stepping down through the production casing, casing shoe, and slotted liner to the bottom hole is summarized below.

Beginning with known well geometry and well head conditions and starting at $z = 0$, we calculate initial properties. Then, we calculate the total pressure gradient as we step down:

$$P(z+dz) = P(z) + \left[\left(\frac{dP_g}{dz}\right) + \left(\frac{dP_f}{dz}\right) + \left(\frac{dP_a}{dz}\right)\right] \cdot dz$$

We must first calculate the pressure gradient components due to gravity, friction, and acceleration. A variety of correlations are available for calculation of these components, and they are described in great detail in the ESDU documents. The correct calculation of these three component pressure gradients allows us to step down from known well head conditions to bottom hole conditions.

Also of note is the Haaland equation (1983), which is an explicit equation (compatible with spreadsheets) that provides excellent results for the calculation of Darcy-Weisbach friction factors (as can be found in Moody charts) for laminar, transition, and turbulent flows over a wide range of Reynolds numbers from 10^3 to 10^8 and (ε/D) ratios ranging from 0 (smooth pipes) to 0.01. Recalling that the Fanning friction factor is equal to exactly ¼ of the Darcy-Weisbach friction factor, the Haaland equation can be used to correctly calculate Fanning friction factors, and it is expressed as follows:

$$f = \frac{1}{12.96 \cdot \left\{ Log\left[\left(\frac{\varepsilon/D}{3.7} \right)^{1.11} + \left(\frac{6.9}{\mathrm{Re}} \right) \right] \right\}^2}$$

Stepping Up

The procedure for starting with known bottom hole conditions and then stepping up through the slotted liner, casing shoe, and production casing to the well head is summarized below.

Beginning with known well geometry and bottom hole conditions and starting at $z = z_{BH}$, we calculate initial properties. Then, we calculate the total pressure gradient as we step up:

$$P(z-dz) = P(z) - \left[\left(\frac{dP_g}{dz} \right) + \left(\frac{dP_f}{dz} \right) + \left(\frac{dP_a}{dz} \right) \right] \cdot dz$$

The pressure gradient components due to gravity, friction, and acceleration are calculated as they were in stepping down.

Practical Applications

In the ideal situation, a well is modelled from known well head conditions, stepping down to solve for well bore conditions as a function of depth, through the production casing, casing shoe, and slotted liner to the bottom hole. The key variables to be matched are the effective roughness heights for the production casing and the slotted liner.

After this model is successfully matched to the flow and logging tests, the well is simulated from the now known bottom hole conditions, stepping up to the well head conditions. This provides a robustness check.

By varying only the mass flow rate and calculating the pressure at the well head, an accurate output curve can be rapidly constructed, showing mass flow rate as a function of well head pressure for the now fixed well geometry and reservoir conditions.

Another way to check for errors in implementation is to check these results against a previously developed simulator using the same set of well data. This was done for a hypothetical geothermal well stepping down and then stepping up using both SuperWell and WELL, as shown in Figures 1 and 2.

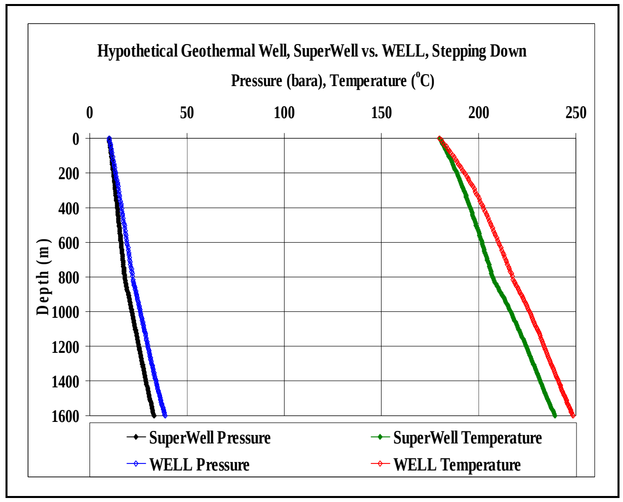

Figure 1. Hypothetical Geothermal Well SuperWell vs. WELL, Stepping Down

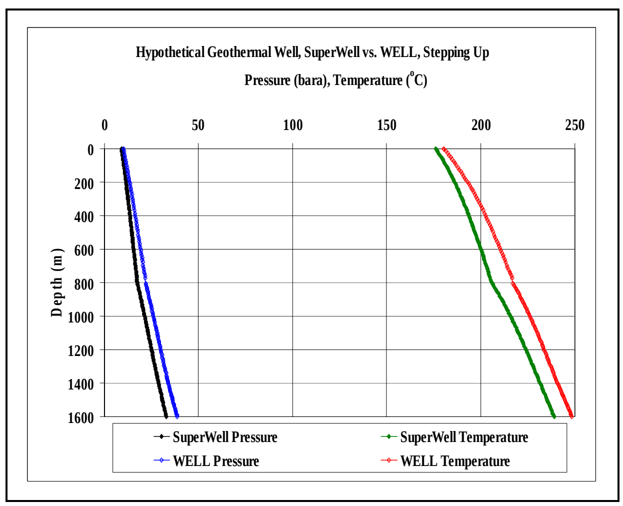

Figure 2. Hypothetical Geothermal Well SuperWell vs. WELL, Stepping Up

There are some differences. For the same well head conditions of our hypothetical geothermal well, the WELL program calculated significantly higher bottom hole pressure and temperature and lower steam quality. When stepping up using these hotter bottom hole conditions, WELL correctly reproduces the original initial conditions that were used prior to stepping down. This means that WELL produces cooler well head conditions for the same bottom hole conditions, as compared to SuperWell. Brennand and Watson (p. 66, 1987) mention in their article that WELL has a tendency to predict excessive pressure drop in high flow rate situations, so this occurrence was not too disturbing. Real wells would provide the true test.

R831

Rotorua well R831 was selected as an initial test well, as its data had been publicly released (Rotorua Geothermal Task Force, 1985). First, a model of the well's geometry was entered into the spreadsheet. Then, the known well head conditions were used to initialize the spreadsheet at depth $z = 0m$. Stepping down produced temperature and pressure profiles and calculated bottom hole conditions. In general, these match the well logging test measured data, but the fit is not perfect, predicting lower bottom hole temperature than the measured data, as shown in Figure 3.

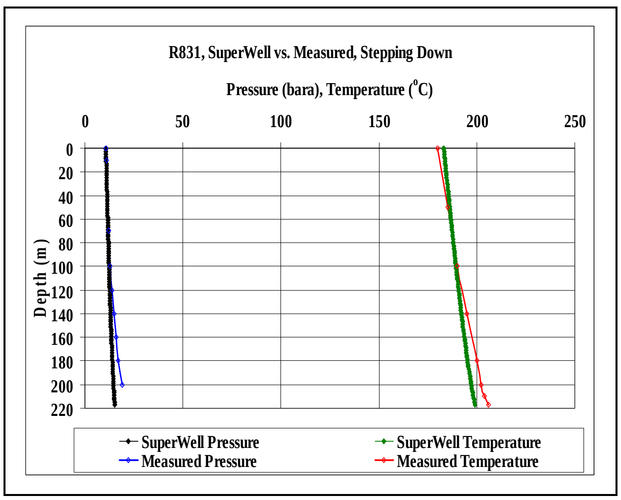

Figure 3. R831
SuperWell vs. Measured, Stepping Down

Next, the known bottom hole conditions were used to initialize the spreadsheet at depth $z = 217m$. Stepping up produced temperature and pressure profiles and calculated well head conditions. Again, these generally match the well logging test measured data, but the fit is not perfect, predicting higher well head temperature than the measured data, as shown in Figure 4.

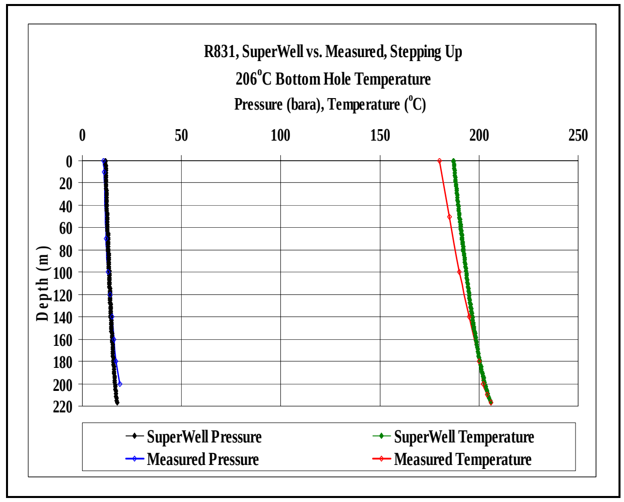

Figure 4. R831
SuperWell vs. Measured, Stepping Up
206°C Bottom Hole Temperature

To attempt a better fit to the well logging test measured data, the calculated bottom hole conditions (from Figure 3, Stepping Down) were used to initialize the spreadsheet at depth $z = 217m$. Stepping up produced temperature and pressure profiles and calculated well head conditions. Although the fit is still not perfect, the calculated well head conditions closely match the well logging test measured data, as shown in Figure 5.

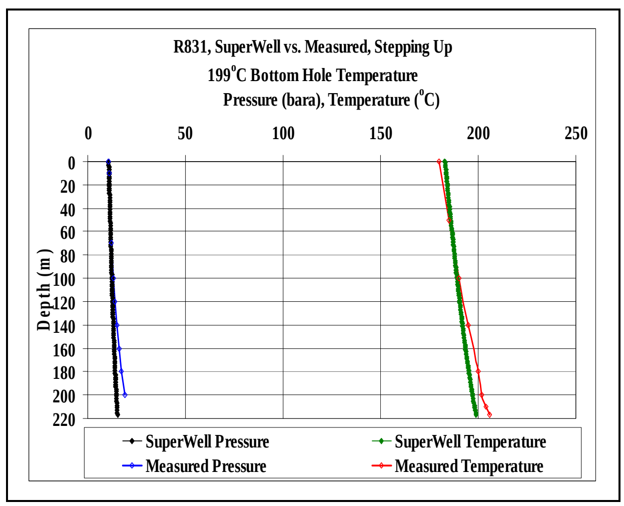

Figure 5. R831
SuperWell vs. Measured, Stepping Up
199°C Bottom Hole Temperature

Finally, both stepping up models were used to build output curves, as shown in Figure 6.

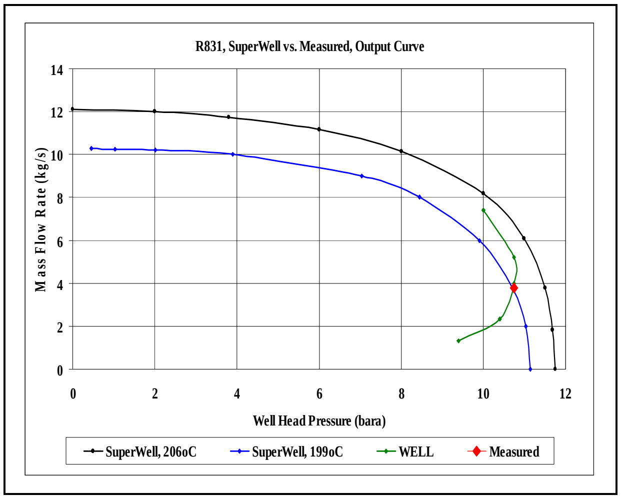

Figure 6. R831
SuperWell vs. Measured, Output Curve
206°C and 199°C Bottom Hole Temperatures

For mass flow rates above the flow test measured data of 3.80 kg/s and 10.75 bara, the output curves are generally accurate and of the right shape. In addition, the 199°C model matches the flow test measured data, as does WELL. However, the fit is not correct for flow rates below 3.80 kg/s and measured maximum discharge pressure of 10.75 bara. Also, as the flow rate and well head pressure are further lowered, the well eventually collapses, and flow ceases before the well head valve is completely closed. This type of behaviour seems to be typical of low enthalpy wells, and it indicates that the feed zone at the bottom hole may in fact be subcooled liquid, rather than saturated.

In summary for R831, the disagreement between the stepping down and the stepping up models raises suspicions about some of the well testing measured data. If the actual feed zone temperature were slightly below 200°C (saturated), rather than the recorded value of 206°C (superheated), then our two models would match, eliminating the discrepancy. The fact that the well logging test plots at standby conditions are below or slightly below the boiling point for depth curve also supports this theory. This would also make the output curve match the measured output curve even more closely above 3.80 kg/s mass flow rates. On the other hand, this does not fix the discrepancy below 3.80 kg/s and 10.75 bara between the calculated output curve and the measured output curve. This is a limitation in SuperWell; at present, it cannot handle subcooled liquids or superheated vapours. The geothermal fluids must be two-phase, that is with steam quality between 0 and 1. It may be possible to correct this problem in the future, as WELL has the capability of handling this situation.

WK232

Wairakei well WK232 was selected as a second test well, as its data had also been publicly released (Leaver and Freeston, 1987). In addition, this well is known to produce saturated or dry steam, so the steam quality in the well is much greater than 0, avoiding the problem that occurred with R831. Once again, a model of the well's geometry was entered into the spreadsheet. Then, the known well head conditions were used to initialize the spreadsheet at depth $z = 0m$. Stepping down produced temperature and pressure profiles and calculated bottom hole conditions, as shown in Figure 7.

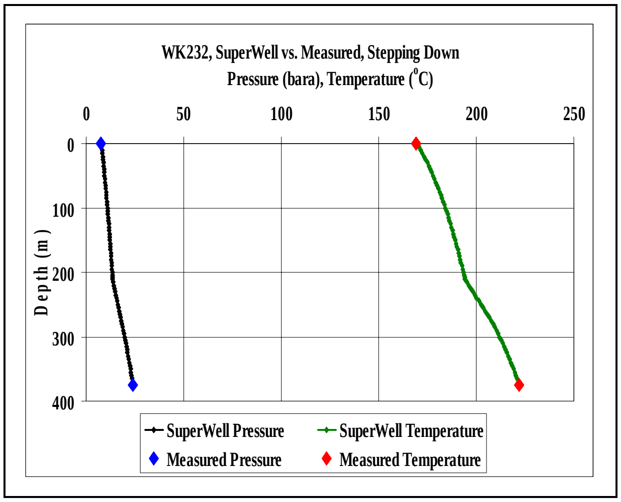

Figure 7. WK232
SuperWell vs. Measured, Stepping Down

These match the well feed temperature and pressure measured data: 222°C with a difference of 0.03°C, and 24.1 bara with a difference of 0.017 bara.

Next, the calculated bottom hole conditions were used to initialize the spreadsheet at depth $z = 375m$. Stepping up produced temperature and pressure profiles and calculated well head conditions. By making slight modifications to the bottom hole conditions, an almost perfect pressure and temperature match was achieved at the well head, as shown in Figure 8.

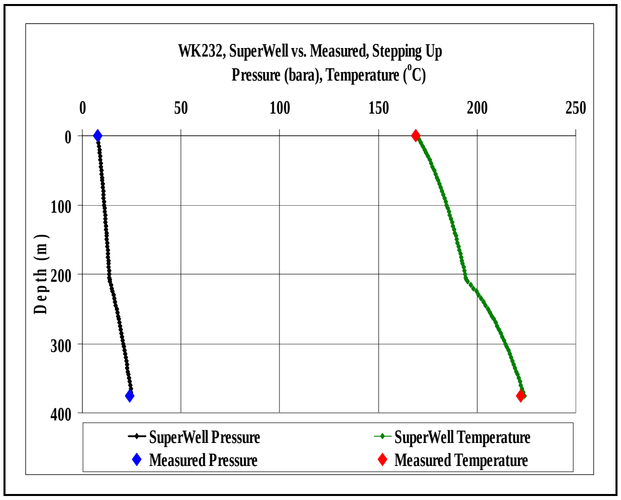

Figure 8. WK232
SuperWell vs. Measured, Stepping Up

The stepping up model was used to build an output curve for WK232. The output curve is accurate compared with the Leaver polynomial model and the measured data, as shown in Figure 9.

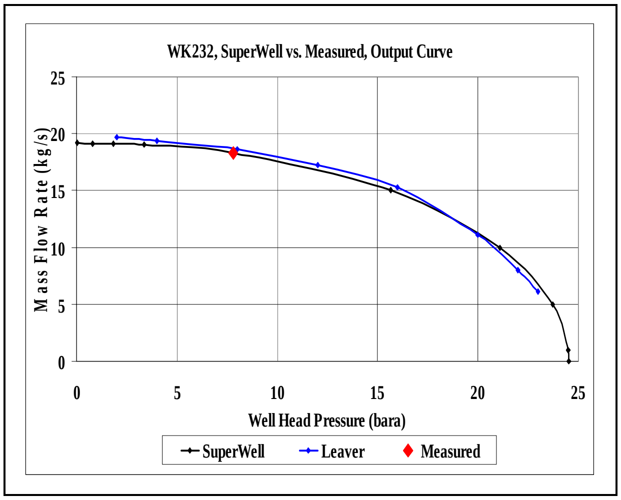

Figure 9. WK232
SuperWell vs. Measured, Output Curve

Due to its high flowing enthalpy and steam quality, this well does not collapse, and the flow ceases only when the well head valve is completely closed. This type of behaviour seems to be more typical of the geothermal wells that we prefer for electric power production, and it indicates that flashing of liquid into vapour is occurring within the reservoir.

RESULTS AND CONCLUSIONS

The main goal of this project was to develop a well bore flow simulator in spreadsheet format that provides high quality results while being easy to use. For typical, two-phase, steady state, geothermal wells, this goal has been achieved. A number of suggestions for improvements are discussed below.

SuperWell needs further testing against a wide variety of steady state, two-phase geothermal wells using field data. This will validate the robustness of the implementation of the equations of motion and state.

SuperWell can easily handle multiple and/or distributed feed and/or loss zones. Time limitations prevented the testing of these capabilities. These phenomena occur in producing geothermal wells, so testing with this type of field well data would be very useful.

To correctly identify problems that occur at low mass flow rates and pressures in wells that probably have low enthalpy, subcooled feed zones, it will be necessary to develop the equations to correctly handle the properties of subcooled liquid. In addition, a similar method must be defined for the transitions from subcooled liquid to saturated liquid and then to two-phase flow of liquid and vapour. This is a significant amount of work, but it is very important, as many of the new reservoirs that are awaiting development are liquid-dominated. In addition, the properties of water have been thoroughly studied, and they are well understood, so there is no technology barrier in the way of progress.

Another problem that will need to be addressed is the transition from two-phase flow of liquid and vapour to saturated vapour (e.g. $x = 1$) and then to superheated vapour. This is also a significant amount of work, but it is also important, as liquid-dominated reservoirs change once exploitation is underway. Their flowing enthalpies and steam qualities tend to steadily increase over time. In addition, a vapour zone may form at the top of the reservoir, and the exploitation of this very high enthalpy fluid would usually be highly desirable.

The addition of a modelling method for down hole pumps would help with the efficient exploitation of liquid-dominated reservoirs. Many of these reservoirs have high enthalpy but do not flow strongly; this is often caused by high content of dissolved solids. These resources can make significant contributions to the growth of geothermal energy in the Western USA and other parts of the world.

For wells in which fluids enter the well as subcooled liquids and flash in the slotted liner or production casing, we would like to model the location where flashing first occurs, as this is a likely location for scaling deposition. While scaling cannot be completely avoided in wells that have this problem, it can and must be controlled.

Corrections for dissolved gases and solids would also be good things to have. Some of the simulators that were studied by Hadgu (1989) contain methods of handling dissolved gases and solids, but they seem to be much too computationally intensive for incorporation into spreadsheets. At any rate, they would violate our goals of simplicity and ease-of-use. In order to make progress in these areas, it would probably be a good idea to find and use streamlined correlations for dissolved gases and solids prior to spreadsheet implementation.

In summary, the spreadsheet format is very popular among geothermal professionals. Tools that can accept, calculate, output and plot information compatible with this format will be adopted because they improve user productivity. There are still a number of improvements that can be made to SuperWell. There may be other useful tools that can be crafted into the spreadsheet format so that they can be used more efficiently.

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Dr. Sadiq Zarrouk, my advisor, helped me with the selection and supervision of this project; he was right there, from start to finish.

Greg Ussher and Peter Barnett of Sinclair Knight Merz provided valuable direction regarding the key problems to be solved and features to be included in this project to make it useful for geothermal reservoir engineers.

During this project, I talked with many people at Boart Longyear, Century Resources, Contact Energy, and GNS Sciences. They broadened my knowledge of the well test analysis problems faced by geothermal professionals in the field and of the challenges that lay ahead of me during the course of this project.

Electronic steam table functions from Paul Bixley of Bixley Geothermal Consultants and Roland Horne of Stanford University were used in this project for computing the properties of saturated water with respect to pressure, and these functions were extremely helpful.

This was the first time that I had ever lived in a foreign country. The entire staffs of Grafton Hall, the Geothermal Institute, and the University of Auckland went above and beyond the call of duty to make my stay in New Zealand both productive and pleasant.

REFERENCES

BRENNAND, A.W. AND WATSON, A. (1987): Use of the ESDU compilation of two-phase flow correlations for the prediction of well discharge characteristics. Proceedings of the 9th NZ Geothermal Workshop, Geothermal Institute, The University of Auckland, Auckland, 65-68.

ENGINEERING SCIENCES DATA UNIT (1971): v. 5a. ‘Two phase flow: guides to pressure drop related problems,’ and v. 5b. ‘Two phase flow: pressure losses in pipes.’ Engineering sciences data, Fluid mechanics, internal flow sub-series, London.

FREESTON, D.H. AND HADGU, T. (1987): Modelling of geothermal wells with multiple feed points: a preliminary study. Proceedings of the 9th NZ Geothermal Workshop, Geothermal Institute, The University of Auckland, Auckland, 59-64.

HAALAND, S.E. (1983): ‘Simple and explicit formulas for the friction factor in turbulent flow’. Transactions of the ASIVIE Journal of Fluids Engineering 103: 89-90.

HADGU, T. (1989): ‘Vertical two-phase flow studies and modelling of flow in geothermal wells.’ Department of Mechanical Engineering, The University of Auckland, Auckland.

KARAALIOGLU, H. (1998): ‘A comparison of two well bore simulators using field measurements.’ Geothermal Institute, The University of Auckland, Auckland.

LEAVER, J.D. AND FREESTON, D.H. (1987): Simplified prediction of output curves for steam wells. Proceedings of the 9th NZ Geothermal Workshop, Geothermal Institute, The University of Auckland, Auckland, 55-57.

ROTORUA GEOTHERMAL TASK FORCE (1985): ‘Technical report of the Rotorua geothermal task force.’ Oil and Gas Division, Ministry of Energy, Wellington.

SUBARKAH, F. (2001): ‘Analysis of production test for DRJ-21 well at Darajat, Indonesia.’ Geothermal Institute, The University of Auckland, Auckland.

SUGANDHI, A. (1997): ‘Analysis of well measurements for well DRJ-5A, Darajat, Indonesia.’ Geothermal Institute, The University of Auckland, Auckland.

SUTOYO (2001): ‘Production simulation of Ngawha geothermal field, New Zealand.’ Geothermal Institute, The University of Auckland, Auckland.