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COMPARISON OF RESULTS FROM SOME WELLBORE SIMULATORS USING A DATA BANK

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ABSTRACT

Five wellbore simulators have been tested using a data bank of selected data from around the world. These simulators were programmed on the various computers available at the Institute from information published in the technical press. Comparisons are made with the measured dynamic pressure and temperature profiles or the measured output or deliverability curve.

The limitation of the simulators is demonstrated particularly with respect to the assumptions made in the methods of analysis. Some of the methods assume only pure water, others take account of solids, mainly chlorides, whilst others include the effect of gases. Some of the simulators allow for wellbore heat transfer, others allow the simulation to proceed up or down the well. The choice of a productivity index also varies from method to method.

This paper discusses these points and points the way for a simulator that includes these and other effects.

1.0 INTRODUCTION

The simulation of flow in a geothermal well has received much attention in recent literature. Bjornsson and Bodvarsson (1987), Freeston and Hadgu (1987), Gudmundsson (1987), Michaelides and Shafaee (1986), both for the analysis of downhole conditions and for prediction of the well output curve. Well bore simulators are also finding many uses for example well design, analysis of well deposition phenomena, long term well production characteristics as well as uses in the reducing the length and number of well tests. There is also potential for such simulators to be linked with Reservoir models below ground and pipe network systems above ground, to give a complete and overall geothermal system analysis from reservoir to electrical output.

However despite the number of well bore simulators that have been discussed very few model the complete system in the well. For example some choose only to use the properties of pure water, others do not model the well bore heat flow whilst others assume a single feed point. In addition whilst many have been validated for use against measured well test data, in general these data are too few and do not cover a wide enough range of geothermal conditions to make them of general use. This paper attempts to highlight this by choosing five simulators from those available, both commercially and in the literature and testing them against a wide range of data from geothermal fields with solids and gases in the geothermal fluid.

2.0 ANALYSIS

2.1 General

Most simulators are generated from the basic equations of motion using a stepwise integration technique up and down the well depending upon whether wellhead or downhole conditions are specified. They differ in the selection of closure equations used and in correlations used for parameters such as void fraction, friction factor, thermodynamic property equations (solid and gas contents effects).

The flow regimes recognised by most authors of simulators for the vertical two phase flow are bubble, slug, churn or transition, and annular and these are assumed to occur in sequence as the flow moves up the well. The flow regime maps and criteria for transition from one regime to another also vary with the author. Another feature concerns the treatment of multi feed points, some identify feed points and give them values of enthalpy and mass flow, Freeston, Hadgu (1987), Bjornsson, Bodvarsson (1987) whilst Gudmundsson (1986) uses the "pivot point" technique to account for multi feed points by running the simulator first down the well to obtain a pivot point pressure, an average feed pressure, and then calculating output curves on the basis of this position .

In the following section five simulators are described briefly and tested with data from a variety of wells. Some of the data was taken from Ambastha and Gudmundsson (1986) who carried out a similar exercise in evaluating the WF2 simulator. The simulators chosen are WF2, WELF, BARELLI, BROWN and GEOTEMP2 which we judge are representative of those currently available. However, no simulator specifically for multi feed point wells is included here. Table 1 illustrates the major limitations of each of these models.

The wells selected cover as wide a variety of conditions as possible, the points stressed in the data collection were:

1. Geometry - small and large diameter wells.
2. Depth - shallow and deep wells.
3. Fluids which have dissolved solids.
4. Fluids with gases.
5. Low and high temperature.
6. Wells with single and two phase conditions at well bottom.
7. Single feed wells.

The selected wells with their data are shown in Table 2.

It is useful to note that in the simulator WF2, the effect of dissolved solids is to change the specific gravity of the liquid phase. Although most of the simulators have an option for heat loss, the mode of inputing data is different, so in this exercise heat loss was not included in our comparison. In addition for the WF2 and Barelli simulators we use a roughness value of 1.83 x 10'^fn as a standard for this study. This number was used by Ambastha and Gudmundsson (1986)

2.2 The simulators

It is only possible to give a brief introduction to the simulators used, the reader is referred to the reference list for more detail.

2.2.1 WF2

This simulator is described in Jaime Ortiz-Ramirez (1983), and was developed at Stanford University. It is based on the earlier work of Fandriana et al (1981) and uses the Orkiszewski (1967) approach which was developed for oil and gas flow. The model assumes one dimensional steady flow of geofluid up the well with a single feed point. The flowing parameters at the bottom or top of the well are required as input. This allows the calculations to start from the top or bottom of the well depending on the input data, one of the few simulators that have this feature.

Transition between the four flow regimes is determined by correlations used by Duns and Ros (1963) with the two phase mixture properties calculated as in Orkiszewski (1967). A heat transfer term due to Romey (1963) is included in the Energy equation. The productivity index(P.I.) is defined in terms of a linear function of mass flow and pressure drawdown

TABLE 1

No.		WF2	BROWN	WELF	BARELLI	GEOTEMP2
1	Starts from bottom	✓	✓	✓	✓	✓
2	Starts from top	✓	X	✓	X	X
3	Can handle solids	*	/	✓	✓	X
4	Can handle Gases	X	X	X	✓	X
5	Can handle two-phase at well bottom	✓	X	✓	✓	/
6	Allows change of pipe roughness	✓	X	X	✓	X
7	Can handle heat loss**	✓	X	✓	✓	✓
8	Multiple feed wells	X	X	X	X	X

*,**, See note in text

i.e. P.I. $= M_t\ (p_r - p_b)$

M_t = total mass flow

p_r = reservoir pressure

p^ = well pressure at the feed point

2.2.2 WELF

This simulator was programmed by Miller (1984). It operates with steady flow up the well and can calculate flow parameters either up or down the well depending upon the input data. Dissolved solids, multi diameter wells and wellbore heat losses can also be accounted for in the input. The heat loss calculation requires a static temperature gradient, rock thermal conductivity and distance from the well where the natural geothermal gradient is assumed to exist.

The flow regimes and transition boundaries are those used by Orkiszewski (1967) except that the churn or transition flow regime seems to be incorporated into annular flow. The frictional pressure drop calculations are based on the correlations of Chishom (1973) whilst for mixture density, hold up, etc., for the bubble, slug and annular flow regimes ,the correlations of Harmathy (1960), Griffith and Wallis (1961) respectively are used. The heat transfer term is based on the Ramey (1963) formula with the heat transfer coefficient a modified form of the well known Dittus-Boelter equation.

2.2.3 BARELLI

This model was presented by Barelli et al (1982). A programme was written based on the outline of the solution procedure given by the authors with minor additions. Study of this model is important because it included two unique points of interest not found in the other simulators, namely, inclusion of the effect of gases and the use of correlations based on global parameters. The assumptions used were 1) steady state flow with the phases in thermodynamic equilibrium 2) the dissolved solids can be represented by NaCl and the gases by CC>2 3) liquid surface tension and

TABLE2

Nr	well	field	geometry (m)	depth (m)	mass (kg/s)	BHP (bar a)	BHT (°Q	h (Kj/Kg)	%TDS	%gas
1	Wk27	Wairakei	0-424 ID=.2O12 424-608ID=.1937	608	27.5	31	231		0.6	0.01
2	Wk207	Wairakei	0-445 ID=.1988 145-1000 ID=.1504	1000	9.722	56	240			0.05-.1
3	B885	Rotorua	0-100 ID=.1O32	100	1.1944	10	162			0.02
4	ZK327	Yangbajing	0-51 ID=.32O5 51-108 ID=.2245 108-110 ID=.3112	110	21.39	9.92	151		0.3	
5	HGP-A		0-680 ID=.2245 680-1925 =.1778	925	13.9	4.2*	146+	1966		
6	MESA6	East Mesa	0-2134 ID=.2216	2134	12.9	94	198.5			
7	CP90	Cerro Prieto	0-1299 ID=.1771	1299	45	89.5	292			
8	OKOY7	Palinpinon	0-1308 ID=.2211	2600	13.2	163.9	319			
9	NG11	Ngawha	0-673.5 .1988 673.5-902 .1504	902	68.6	79.4	224.5		0.5	1.2
10	W2-1		0-1355 ID=.323	1355	34	98	225		1	2.88
11	W4-1		0-800 ID=.22O5	800	19.862	64	285	1465	9.1	0

* - WHP; the HGP-A well was run from wellhead to bottom
\+ - WHT
BHT - Bottom hole temperature
BHP - Bottom hole pressure
TDS - Total dissolved solids
h - enthalpy

viscosity values are assumed equal to those of pure water. The model uses balance equations as the basis for calculations. Programme execution starts at well bottom and well profiles are obtained based on downhole data.

The basic equation for total pressure gradient has the same form as for other methods but since the correlations used in the solution are based on global parameters, individual terms should not be compared with flow regime dependent correlations. The following bottom hole pressure is defined as

$$Pb = Pr \; " \; K \; M_t \; " \; k_t \; M_t^{2}$$

where k^ and lç are coefficients.

2.2.4 BROWN

This simulator was developed by Bilicki, Z. et al. (1981). The model calculates flow parameters in a well based on conditions at bottom hole. A stepwise integration technique is used up the well bore and the model assumes steady one dimensional flow. A single liquid only feed point is also assumed. One unique feature of this method is that the transition boundaries between the flow regimes are based on an analytical approach utilising experimental results. Details are given in Bilicki and Kestin (1980).

The pressure gradient equation is as for the other models, however the closure equations for wall shear stress are based on Petrick's (1958) correlation and void fraction correlations, which are flow regime dependent, obtained from other sources. The wellbore heat loss is set to zero although the authors did run the programme with heat loss and demonstrated the effect on the well outnut curve.
The thermodynamic and transport properties of the fluid for pure water are based on functions developed for the 1967 International Formulating Committee. The density of the NaCl liquid solution is obtained using correlations developed by Haas (1970), for the viscosity a correlation developed by Kestin & Khalifa (1981) is used. In the vapour both the density and viscosity are those of pure water. The enthalpy of the liquid is a function of both the molality and temperature but for the vapour it is independent of temperature. The methods for obtaining these is described by the authors. The presence of noncondensible gases is discussed by the authors but they conclude that the effect on the properties of brines can be ignored.

A detailed discussion of critical flow is given and a theory developed in Bilicki & Kestin (1980b). In the programme, choking is associated with convergence of the driving pressure to zero. A drawdown factor is also used, and is the same as in the WF2 programme i.e. it has a linear form.

2.2.5 GEOTEMP2

Geotemp 2 is a multipurpose wellbore simulator developed by Sandia National Laboratories (1982) for geothermal drilling and production applications. It is designed to solve the natural and forced convection equations in the well together with conduction associated with the surrounding rock formation. It is suitable for a number of cases including:

1) gas or liquid drilling with various operations such as forward and reverse circulation.

2) Single and two phase injection or production.

3) Deviated wells.

For this study the injection/production option was used.

The correlations used for flow regime and pressure gradient are those of Orkiszewski (1967) with minor alterations, the heat flow between the fluid and surroundings is expressed using Dukler's similarity analysis (1964). The model does not consider critical flow and it uses for this option the properties for purse water. The user manual, points out that the programme could have limited use for deviated wells and also injection problems as the Orkiszewski correlations were for vertical upflow.

One interesting feature of this method is that it may be able to be used for transient wellbore conditions as it uses a transient analysis of radial heat flow to determine temperatures at selected distances from the well. The authors do not have any experience of this option.

3.0 RESULTS AND DISCUSSION

It is not possible within this paper to present all the results of the simulation exercise so a selection of the results is shown which illustrate the main points.

3.1 Temperature and Pressure Profiles

3.1.1 N.Z. Wairakei Wk 207.

This a relatively deep well with a liquid feed and a fluid that has a low gas, and dissolved solids content. Figures 1 and 2 give the response of the simulators for the pressure profile, and temperature profile. Only the results from four simulators are presented as the GEOTEMP2 gave a 'choked' well. The Brown simulator is currently programmed only to give pressure information at regime boundaries and as stated earlier can only be used with a liquid feed. The flash horizon is predicted satisfactorily by all simulators (Figure 1) and the wellhead pressures (Figure 2) are satisfactory except for the BARELLI model which gives lower values for both temperature and pressure as measured.

3.1.2 N.Z. Rotorua R885.

This is a shallow low enthalpy well with a liquid feed at the bottom. The gas and dissolved contents are low. Figure 3 shows the pressure profile for this well, there is a relatively wide range of wellhead pressures predicted, 3 bar (GEOTEMP2) to 5 bar (WELF), the other three gave a satisfactory wellhead pressure. The BROWN programme gave a sudden decrease of pressure at the bubble-slug transition which might indicate this transition is not very smooth. The temperature values, which are dependent upon the pressure, for both the GEOTEMP2 and WELF results are significantly different than the measured value. This is not surprising as at these low pressures small differences in pressure give large changes in temperature, e.g. 1 bar change in pressure results in about 10°C change in saturation temperature.

3.1.3 China Yanbajin ZK327.

Figure 4. This well is a large diameter shallow well (9-5/8" liner and 13-3/8" production casing) with a low enthalpy and high production and again it is liquid fed with a 0.3% T.D.S. . No result was obtained for the GEOTEMP2 simulator as a choke occurred. All the other models gave higher pressures above the flashing horizon than measured. This would seem to indicate that the T.D.S. content may be higher than specified.

3.1.4 Italy W2-1.

This is one of the wells Barelli et al (1982) used to develop their simulator and as this well is characterised by a high gas content it is not surprising that this particular simulator matches the measured data reasonably well. The well is a large diameter of 13-3/8". The pressure and temperature profiles are shown in figures 5 and 6 respectively. Flashing takes place near the bottom and the simulators apart from BARELLI predict flashing to occur at around 500m. This demonstrates the effect of neglecting gas in the modelling process. The Ngawha 11 well has a similar characteristic and is predicted

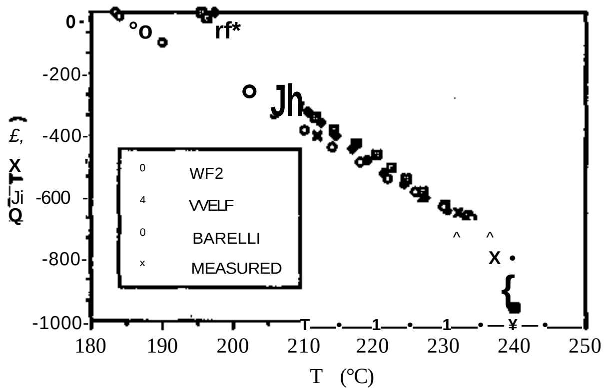

FIG.1 WELLWK207 TEMPERATURE PROFILE

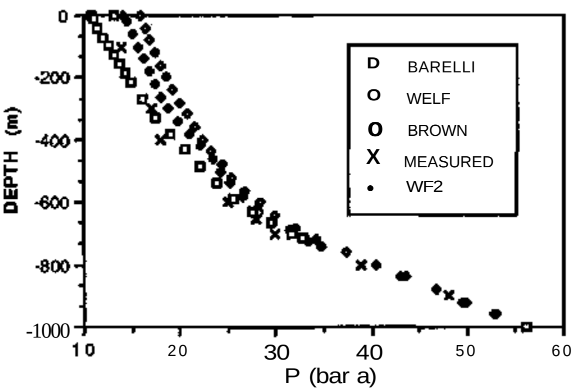

FIG.2 WELL WK207 PRESSURE PROFILE

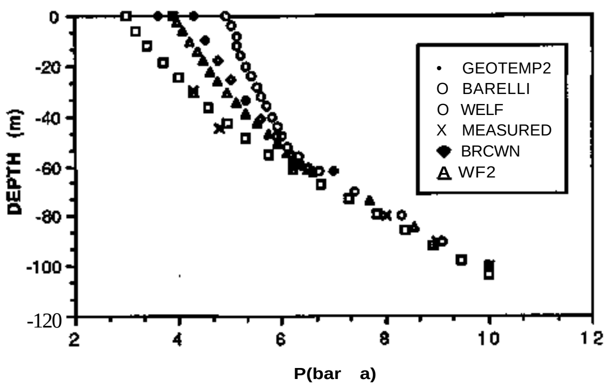

FIG.3 WELL B885 PRESSURE PROFILE

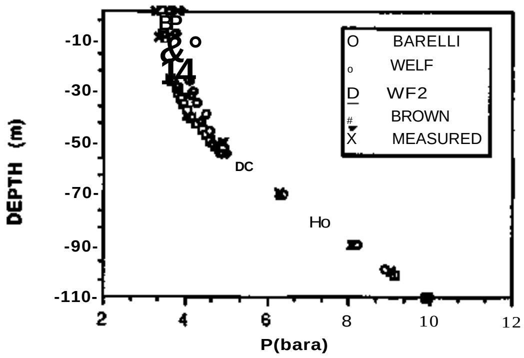

FIG.4 WELLZK327 PRESSURE PROFILE

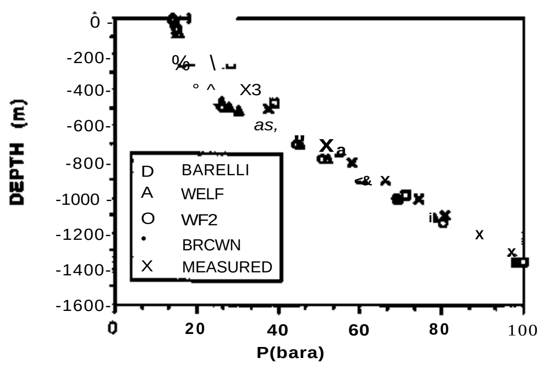

FIG.5 WELL W2-1 PRESSURE PROFILE

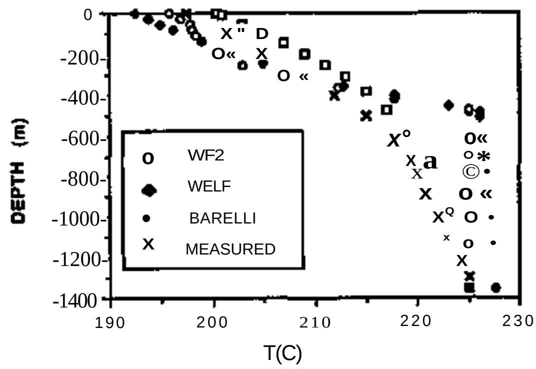

FIG.6 WELL W2-1 TEMPERATURE PROFILE

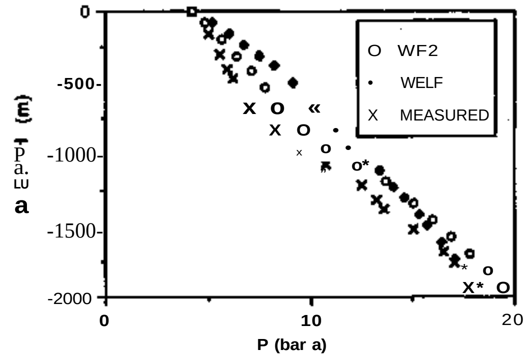

FIG.7 WELLHGP-A PRESSURE PROFILE

satisfactorily by the BARELLI simulator. For both these wells the GEOTEMP2 method failed due to a choked well.

3.1.5 Hawaii HGP-A

This is a deep high enthalpy well with a two phase feed. The BROWN programme is therefore excluded. The WF2 simulator showed choking conditions when run from the bottom. It was therefore decided to run the simulators from wellhead to bottom, hence the match points at zero depth on Figure 7. Only the WELF and WF2 were successful in analysing this well although both gave higher pressures in the well than measured.

3.2 Output Curves

One of the major uses of a wellbore simulator is to be able to predict the output curve of a well. In this exercise we use the simulators to predict the output curve given the well bottom conditions. Rotorua well 715 was chosen, it is a shallow, small diameter low enthalpy well, 122m deep, 4 ins casing with a liquid feed of 167°C. Maximum output was measured at 4.3 kg/s with a wellhead pressure of 4.5 bar and an enthalpy of 720 kJ/kg. Because of the high permeability of the reservoir a drawdown factor of zero was chosen, dissolved solids and gas content are low and were ignored. Figure 8 shows the results using the various simulators with the data specified. The BROWN model gives the best fit to the measured data. GEOTEMP2 gave larger flows at low WHP and higher flows at high W.H.P. All the other simulators gave higher W.H.P.'s than measured with WELF unable to predict the correct shape of curve.

3.3 Prediction of flow regimes

One other subject for comparison of the simulators is their ability to correctly predict flow regime transitions. Unfortunately, flow regime data are not available except for Rotorua wells where a pressure transducer was used at the wellhead which gave an indication of the flow behavior. Nevertheless, the predictions of the simulators can also be compared with one another. All the simulators with the exception of BARELLI predict flow regimes, the predictions for two wells have been selected for this exercise and are shown in figures 13 and 14.

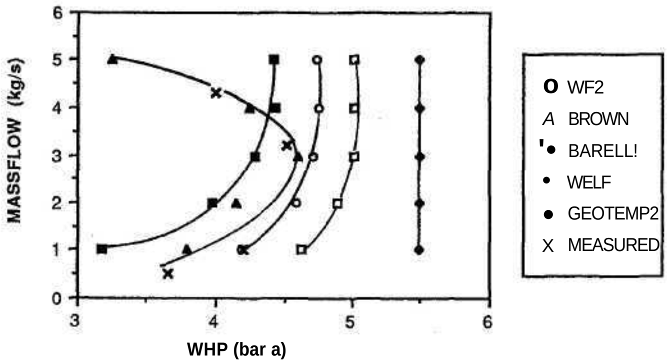

FIG.8 COMPARISON OF SIMULATORS : OUTPUT OF ROTORUA WELL 715

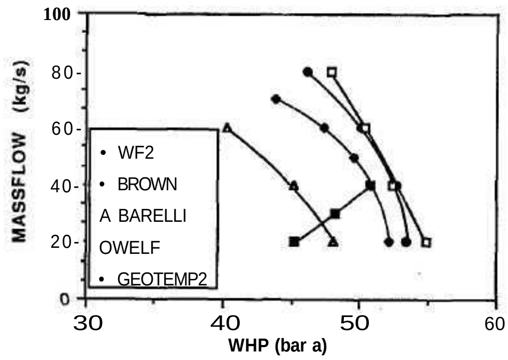

FIG.11 GEOMETRY: 0-600 m 95/8" CASING 600-1520 m 7" LINER

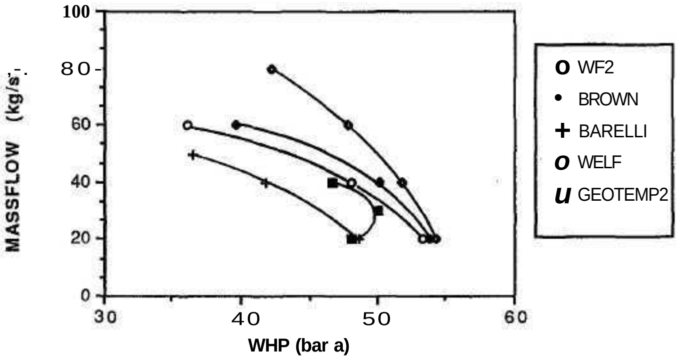

FIG.9 COMPARISON OF SIMULATORS BASED ON CASE DATA

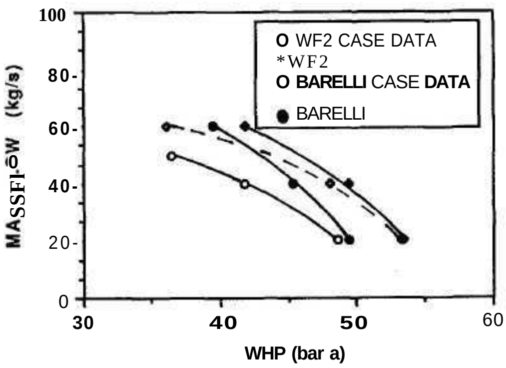

FIG.12 PIPE ROUGHNESS USED: 4.6E-5 m

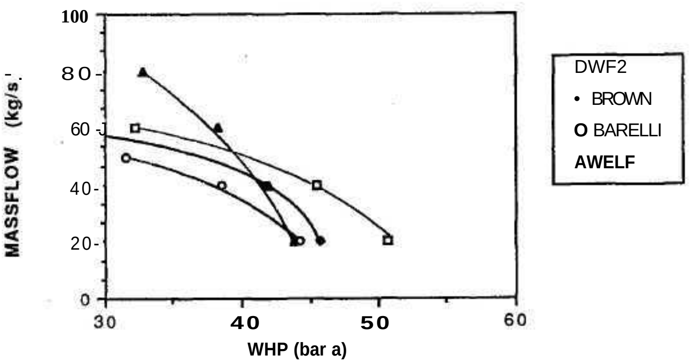

FIG 10 DISSOLVED SOLIDS CONTENT IN TOTAL FLUID : 10 PERCENT

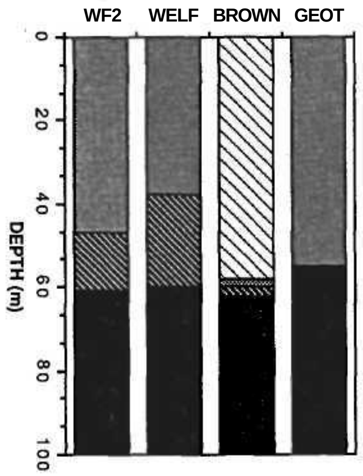

FIG.13 PREDICTION OF FLOW REGIMES FOR WELL B885

• ANNULAR
• CHURN
H SLUG
B3 BUBBLE
• LIQUID

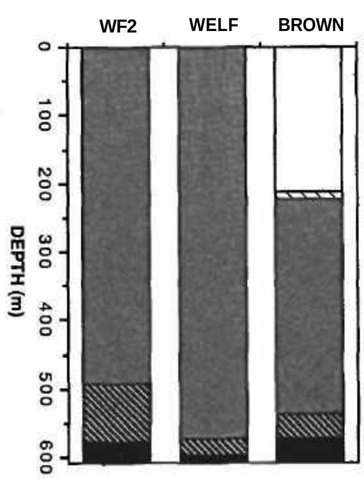

FIG.14 PREDICTION OF FLOW REGIMES FOR WELL WK27

The location of the flashing horizon is approximately the same for all models. However in the two phase region the predictions are very much in variance. WF2 and WELF show similar predictions because they both use the same correlations. This should also be true for GEOTEMP2 , however there is small changes when compared with the other two. The BROWN simulator gives a very different picture. For most cases WELF, WF2 and GEOTEMP2 predict slug flow at the wellhead. The BROWN simulator predicted slug, churn and annular flows depending on the input conditions .

For Rotorua wells the three simulators WF2, WELF and GEOTEMP2 predicted slug flow at wellhead whilst at higher flows BROWN gave churn and annular flow patterns. The wellhead transducer records are in agreement with the results from BROWN. It should also be noted that the regime boundaries used in the BROWN model are close to those used on the maps of Taitel et al (1980) and McQuillan and Whalley(1985).

3.4 Response of simulators to changes in some parameters

For this exercise the simulators were to be used to draw the output curve given well bottom conditions. The well bore parameters were altered to study the effect of a model on the output curve. The basic data, based on an existing well were :

Depth	1500m
Internal Diameter	0.164m
Bottomhole Pressure	150 bar (static pressure)
Bottomhole Temperature	295°C

In addition the following assumptions were made :

Pipe roughness	1.8×10^{-4}m
Drawdown factor	22000 Pa.s/kg
No Heat loss	
No dissolved solids or gas	

The simulators were first run with the basic data, Figure 9. The chosen well has a single phase feed with high temperature and pressure with flashing occurring in the well. The drawdown factor was chosen based on a discharge history at low flows. At high flows this may not be satisfactory, however for this exercise it is sufficient for purposes of comparison.

GEOTEMP2 gave low output and choked at flows above 40 kg/s. The other four gave similar shapes with WELF giving outputs some 50% higher in the middle W.H.P. range than BARELLI, which gave the lowest predicted output. The BROWN and WF2 gave similar curves choking at about 80 kg/s whilst WELF, WF2 and BROWN predicted a maximum discharge pressure of 5.6 bar at approximately the same flow rate, the other two gave values nearer 50 kg/s.

The sensitivity of the simulator outputs is tested by varying a number of parameters. In all bottomhole pressure and temperature, % T.D.S., drawdown factor, pipe roughness and a stepped well were changed. Figure 10 shows the effect of adding a 10% by weight solids content. GEOTEMP2 does not have an option for varying the solids content. All the others account for solids although in different ways. A high solids content generally reduces output, in addition it could cause deposition leading to a reduction in flow area, which for our case we assumed to remain constant. The calculated mass flow for a given W.H.P. was reduced from the base data, Figure 9, for all simulators. As expected, however the magnetude of the reduction was different for each one. The effects on the outputs of BARELLI and WF2 were minimal, for WELF the reduction was uniform for all flow rates whilst for the BROWN simulator the reduction was more pronounced at higher flow rates, which is logical. The results for a stepped well i.e. a 7 ins diameter liner and a 9-5/8" diameter production casing were then assessed Figure 11. The outputs are as expected, greater than the base data with more significance at the higher flows. GEOTEMP2 gave a completely different view with an indication that over the flow range tested it appeared to be working in the lower part of the standard output curve. As part of the study on diameter changes, a 9-5/8" well cased to 1520m was run and showed output similar to Figure 11.

Finally the effects of variation in pipe roughness were tested. Only the BARELLI and WF2 simulators allowed changes to be made. Friction losses become important at high mass flow and high steam qualities. The roughness values were reduced from the standard of 1.8×10^{-4} to 4.6×10^{-5} m. The results are shown in Figure 12. As expected the outputs are higher with the reduced friction losses in the well bore and demonstrates that the choice of an appropriate roughness value could be important.

4.0 CONCLUSIONS

1. None of the simulators chosen for this study is capable of giving satisfactory answers for the wide variation of well designs, fluid chemistry, etc., that are drilled in geothermal fields worldwide.

2. Some of these simulators are more suited to a particular set of conditions than others, e.g. BROWN gives good answers, when checked against measured data for shallow, low enthalpy wells with a liquid feed but for deep wells at high mass flows choking occurs at a W.H.P. below the measured values and is limited in that with the version tested it cannot handle high enthalpy feeds.

3. WELF gave similar outputs to WF2 in many situations, however it is insensitive at low flows.

4. BARELLI is the only one tested that is capable of handling fluids with gas however it appears to underpredict when used on very deep or high enthalpy wells and gave unreliable results for low enthalpy shallow wells.

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