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A MULTI-FEEDZONE WELLBORE SIMULATOR

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ABSTRACT

A multi-feedzone wellbore simulator has been developed. This computer code is quite general as it enables one to compute downhole conditions in wells with an arbitrary number of feedzones during discharge or injection. The simulator is applied to flowing pressure and temperature surveys from various wells in Mexico, Iceland and Kenya. It is demonstrated that such a model can be used to estimate flow rates and enthalpies of individual feedzones.

INTRODUCTION

Most geothermal reservoirs are located in fractured rocks, with fluids entering the wells in discrete zones (feedzones). These feedzones frequently have different pressure potentials so that internal flow occurs in the well when the well is in a static condition and in some wells during discharge or injection. Examples in the literature include wells in Iceland (Stefansson and Steingrimsson, 1980), Kenya (Haukwa, 1984) and New Zealand (Grant et al., 1982, 1983). Currently there are few tools available for the design of multi-feedzone wells or for analyzing their behavior during discharge.

We have developed a multi-feed zone wellbore simulator that can handle an arbitrary number of feedzones. The simulator is quite general as it allows for calculations of downhole conditions both during fluid discharge and injection. It also has the capability of computing the conditions within the well either from wellhead to wellbottom, or from wellbottom to wellhead, depending upon whether wellhead or downhole thermodynamic conditions are known. For example, it is useful to start the computations at the bottom of the well and proceed upwards when the wellbore simulator is coupled with a reservoir model which provides reservoir conditions at specific depths (grid blocks).

The multi-feedzone wellbore simulator has many potential applications, including:

(i) designing multi-feedzone wells;

(ii) matching flowing temperature and pressure profiles in order to determine flow rates and enthalpies of individual feedzones;

(iii) investigating internal flows in wells and optimizing the operating wellhead conditions of the well to maximize productivity;

(iv) investigating the effects of multiple-feedzones on pressure transient data during well tests;

(v) coupling with a reservoir simulator to determine well productivity or injectivity changes with time.

In the present paper the multi-feedzone simulator is briefly described in terms of its mathematical formulation and solution procedures. The model is then validated using flowing pressure profiles from wells with single feedzones. Finally, the simulator is used to interpret pressure and temperature profiles of two-phase wells in Iceland and Kenya. The interpretation yields estimates of the flowrate and enthalpies of individual feedzones.

THE WELLBORE SIMULATOR HOLA

The governing equations for two-phase flow are highly nonlinear and must be solved numerically. Mixed analytical and empirical formulations do exist for various types of flow (Orkiszewski, 1967; Chisholm, 1983; Wallis, 1969). These have been used by several authors in their development of wellbore models for numerically predicting downhole pressures, given the well design and either wellhead or bottomhole flow conditions (Barelli et al., 1982; Gould, 1974; Goyal et al., 1980; Juprasert and Sanyal, 1977; Miller, 1980; Miller et al., 1981; Parlaktuna 1985; Upadhyay et al., 1977). The predictions usually compare fairly well with measured data. All of the present available codes assume that fluid enters only at the bottom of the well.

The wellbore simulator HOLA (the Icelandic word for "well") solves numerically the differential equations that describe mass, momentum and energy flow in a vertical pipeline. A detailed description of the code and its application is given by Bjornsson (1987). The mass flow is assumed to be steady state. Calculations either start at the wellhead and continue downwards in a finite difference grid, or at the wellbottom and proceed upwards. The nonlinear governing equations are solved using the Newton-Raphson iteration procedure. Frictional pressure drop and phase velocity calculations in two-phase flow are based on empirical relations given by Chisholm (1983). Pure water is the flowing fluid, but it can flow either under single- or two-phase conditions. All physical properties are assumed uniform at any given depth within the well. The program HOLA allows for multiple feedzones, variable grid spacing, pipe roughness and well radius. Heat exchange with the surrounding rocks are computed analytically.

Feedzones are assumed to occur at single grid points in the well, which is a reasonable assumption for wells in fractured, geothermal reservoirs. Two-phase mixtures are always assumed to flow upwards whereas single-phase fluid can flow either up or down. Thus, internal downflow and upflow can be computed between feed zones.

The wellbore simulator computes mass, energy and momentum balances explicitly, assuming steady state mass flow. In the portions of the well between feedzones the thermodynamic conditions in the next grid node can be readily computed based upon the known conditions in the last known grid node and the constant mass flow between the adjacent nodes. At nodes containing a feedzone, mass and energy balance calculations are performed using the specified mass rate and enthalpy of the feedzone in question. This allows for the determination of mass and energy flow to be used as inlet conditions for the next interzonal section of the well. This procedure can be followed using either the known wellhead conditions and computing down the well or known bottomhole conditions for calculations up the well to the wellhead.

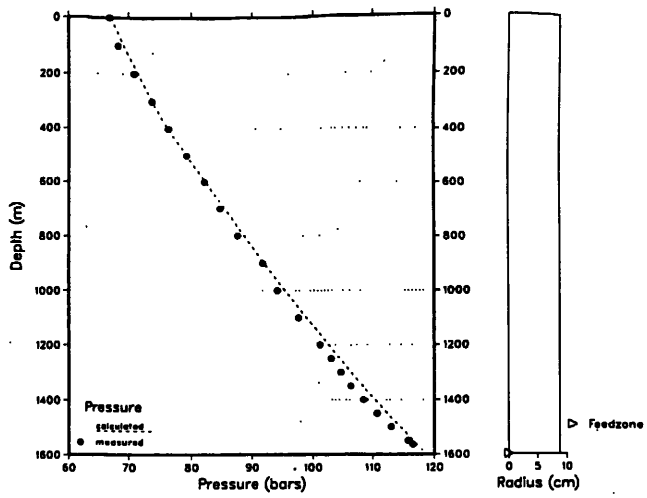
VALIDATION OF THE SIMULATOR

The simulator HOLA has been validated against many published downhole temperature and pressure profiles in flowing wells with single dominant feed zones. A few examples are given here using well data from the Cerro Prieto, Mexico and Svartsengi, Iceland geothermal fields. In matching the downhole pressure and temperature profiles, the wellhead pressure, enthalpy and flowrate are specified and the calculations proceed down to the bottom of the well. Also, inputed are the wellbore geometry and the reservoir temperature with depth.

It should be noted that the inner diameters of the casing and liner are used to specify the wellbore geometry. This neglects flow in the annulus between the liner and the sides of the borehole and may cause some inaccuracies in computations involving single-phase steam and two-phase flow. These effects should be insignificant for single-phase liquid flow where the liquid density dominates the pressure gradient.

Figures 1 and 2 show calculated and measured flowing pressure profiles for wells M-51 and M-91, respectively, at Cerro Prieto, Mexico. The well data are taken from Goyal et al. (1980).

Figure 1 shows calculated and measured flowing pressure profiles for well M-51, the well geometry (to the right) and the specified wellhead parameters. The match is satisfactory. The simulator predicts two-phase slug flow along all of the well interval shown, which is in agreement with the results of Goyal et al. (1980). In Figure 2, which shows measured and

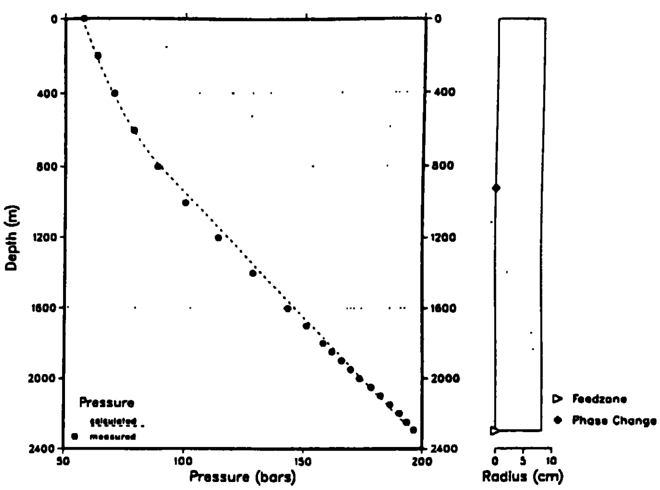


CERRO PRIETO, Well M-51
Wellbore calculations during discharge
Measurements from feb-20-1978

Wellhead pressure (bar abs.)	:	67.00
Wellhead temperature (C)	:	282.84
Wellhead dryness	:	0.222
Wellhead enthalpy (kJ/kg)	:	1590.00
Wellhead total flow (kg/s)	:	33.00

Feedzone no:	Depth (m)	Flow (kg/s)	Enthalpy (kJ/kg)
1	1600.0	33.00	1622.8

Figure 1. Calculated and measured pressures in well M-51, Cerro Prieto, Mexico.



CERRO PRIETO, Well M-91
Wellbore calculations during discharge
Measurements from FEB-8-1976

Wellhead pressure (bar abs.)	:	57.00
Wellhead temperature (C)	:	272.22
Wellhead dryness	:	0.115
Wellhead enthalpy (kJ/kg)	:	1380.00
Wellhead total flow (kg/s)	:	34.00

Feedzone no:	Depth (m)	Flow (kg/s)	Enthalpy (kJ/kg)
1	2300.0	34.0000	1417.9

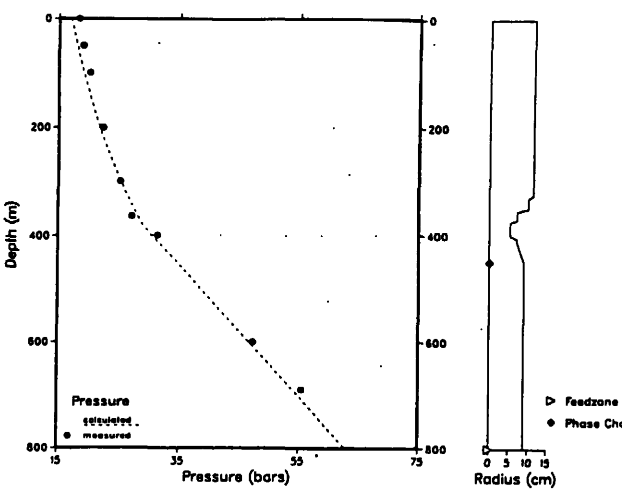
Figure 2. Calculated and measured pressures in well M-91, Cerro Prieto, Mexico.

calculated flowing pressures for well M-91, the match is also reasonable. The simulator predicts slug flow in most of the two-phase section (above 900 m depth) and bubble flow in the 50-75 m interval above the flashing level.

Figure 3 shows measured and calculated pressure profiles for well 4 in Svartsengi, Iceland. The data are taken from Parlaktuna (1985). The well produces brine, with a total dissolved solids content of about 21,000 ppm. Silica scaling is common in Svartsengi wells at the flashing level, and the wells are frequently cleaned in order to maintain production. In December 1978, a caliper measurement was conducted in the well indicating scaling at and above the flashing level. The modified well geometry due to scaling was specified directly in the input data for HOLA, as shown in the schematic well diagram in Figure 3. It should be noted that there is a small difference between the calculated and measured pressure gradients in the the liquid region below 350 m depth. This difference is due to the high liquid density of the brine.

FEEDZONE CONTRIBUTIONS

One of the most practical applications of a multi-feedzone wellbore simulator is to use it for estimating flowrates and enthalpies of the different feedzones in a well. This information is often difficult to gain by other methods. A possible alternative is to measure the wellbore flowrate by flowmeters, also called spinners (see for example Solbau et al., 1983), but this is difficult in high temperature geothermal wells.



Svartsengi, well 4
Wellbore calculations during discharge
Measurements from dec-1978

Wellhead pressure (bar abs.)	:	17.00
Wellhead temperature (C)	:	204.31
Wellhead dryness	:	0.082
Wellhead enthalpy (kJ/kg)	:	1030.00
Wellhead total flow (kg/s)	:	30.00

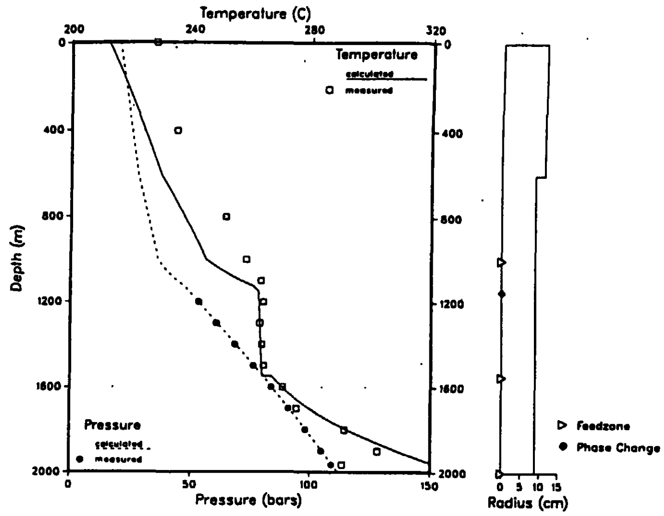
Feedzone no:	Depth (m)	Flow (kg/s)	Enthalpy (kJ/kg)
1	800.0	30.00	1043.5

Figure 3. Calculated and measured pressures in well 4, Svartsengi, Iceland.

The wellbore simulator HOLA can be used to estimate internal flowrates in geothermal wells, given the measured downhole pressure and/or temperature profiles. Simulation begins at the wellhead, where all the flow parameters are known. Downhole profiles are then calculated down to the first feedzone encountered. The interpretation begins at that point by specifying the feedzone flowrate and enthalpy. Calculations then proceed to the next feedzone, where new feedzone parameters are specified. This continues down to the lowest feedzone, for which parameters need not be specified since they can be computed from the specified wellhead conditions and the flowrate and enthalpies of all of the other feedzones. The flow values and enthalpies of the individual feedzones are then varied in a trial and error fashion until the calculated downhole temperature and pressure profiles match the measured ones.

Figure 4 shows calculated and measured downhole profiles for well NJ-7 in the Nesjavellir field, Iceland. The data were provided by B. Steingrimsson (personal communication, 1987). During the measurements the well discharged 23 kg/s of steam/liquid mixture, with a total fluid enthalpy of 1360 kJ/kg. Feedzones are located at depths of 1000, 1550 and 2000 m.

The constant, 260 °C temperature at the depth interval 1100-1600 m in well NJ-7 indicates flow of single-phase liquid with an enthalpy of approximately 1150 kJ/kg. This enthalpy



Nesjavellir, well NJ-7
Pressure and enthalpy during discharge
6-feb-1986

Wellhead pressure (bar abs.)	:	20.00
Wellhead temperature (C)	:	212.37
Wellhead dryness	:	0.239
Wellhead enthalpy (kJ/kg)	:	1360.00
Wellhead total flow (kg/s)	:	23.00

Feedzone no:	Depth (m)	Flow (kg/s)	Enthalpy (kJ/kg)
1	1000.0	14.50	1500.0
2	1550.0	8.40	1150.6
3	2000.0	0.10	1526.2

Figure 4. Calculated and measured downhole profiles in well NJ-7, Nesjavellir, Iceland.

is substantially lower than that measured at the wellhead, and requires discharge of high enthalpy fluid from the feedzone at 1000 m depth. It also indicates that the liquid water at 1100-1600 m depth is flowing upwards in the well from the feedzone at 1550 m depth. Below 1550 m the temperature increases rapidly, which is most likely due to small upward flow from the deepest feed, resulting in a near-static water column in thermal equilibrium with the surrounding rocks.

The initial reservoir pressure and temperature at 1000 m depth in well NJ-7 are approximately 80 bars and 260°C, respectively (Stefansson, 1985). Liquid water at these thermodynamic conditions has an enthalpy of 1100 kJ/kg. In order to match the data, a higher enthalpy is required, suggesting two-phase conditions in the reservoir at that depth.

The calculated pressure and temperature profiles shown in Figure 4 are obtained by assuming an enthalpy of 1500 kJ/kg for the feedzone at 1000 m depth. The calculated results show that most of the produced fluids are flowing from the feedzone at 1000 m. The remaining 30% come from the feedzone at 1600 m, with negligible flow from below (2000 m feedzone).

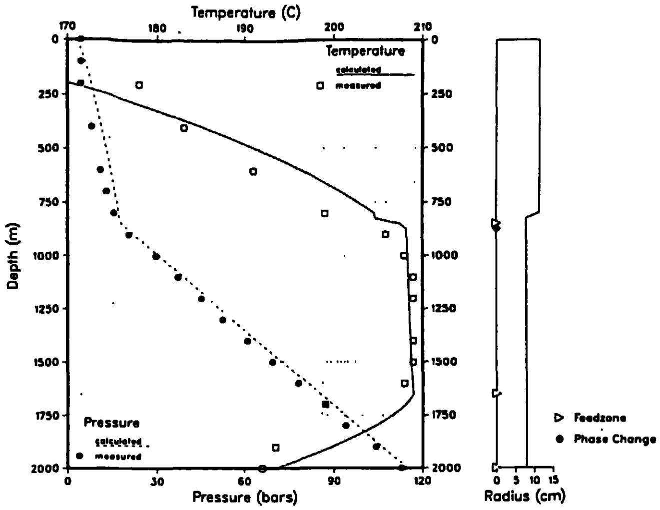
The assumed 1500 kJ/kg fluid enthalpy at 1000 m depth is uncertain; it is only necessary that this enthalpy must be higher than the wellhead enthalpy, since colder fluid is flowing from below and mixing with the discharge from the uppermost feedzone. This makes the estimated feedzone parameters shown in Figure 4 nonunique. Independent information such as geochemical data may help in determining relative contribution of feedzones, hence, making the parameter determination more unique.

Figure 5 shows calculated and measured downhole profiles for well OW-201 in the Olkaria geothermal field, Kenya. The data are taken from Haukwa (1984). Two major feedzones are present in the well, one at 800-900 m and the other at 1600 -1700 m depth.

These test data are interpreted in a similar manner to those for well NJ-7. A high enthalpy feedzone is present at 850 m in the well. Single-phase liquid with 900 kJ/kg enthalpy flows both up and down from a feedzone at 1650 m depth. A slight outflow of fluids occurs at the feedzone at 2000 m. The enthalpy of the upper feedzone is not precisely known, but is estimated to be around 1300 kJ/kg. The match between calculated and measured profiles is reasonable and the results indicate that a majority of the discharged fluid is coming from the feedzone at 850 m depth, which is consistent with other well information (C. F. Haukwa, personal communication, 1986).

CONCLUSIONS

A multi-feedzone wellbore simulator has been developed. The simulator allows for calculations of downhole pressure, temperature and vapor saturation conditions in wells with an arbitrary number of feedzones. It can simulate well conditions during both discharge and injection. The computer code can be applied to various problems, including the design of multi-feedzone wells, evaluation of internal flow and relative contributions of feedzones and studies of productivities and injectivities of wells.



Olkaria, well OW-201
Wellbore calculations during discharge
Measurements from 22-oct-1984

Wellhead pressure (bar abs.)	:	3.00
Wellhead temperature (C)	:	133.54
Wellhead dryness	:	0.332
Wellhead enthalpy (kJ/kg)	:	1280.00
Wellhead total flow (kg/s)	:	35.50

Feedzone no:	Depth (m)	Flow (kg/s)	Enthalpy (kJ/kg)
1	850.0	33.0000	1330.0
2	1650.0	2.8000	901.6
3	2000.0	-0.3000	827.7

Figure 5. Calculated and measured downhole profiles in well OW-201, Olkaria, Kenya.

The simulator was validated by comparing computed pressures and temperatures to actual data from three wells, each one with a single dominant feedzone. Most of the measured data were matched reasonably well.

The simulator was also used to match flowing profiles in two wells which show effects of two or more feedzones. Flowrates and enthalpies of individual feedzones were estimated, thus giving important information on the characteristics of each well feedzone.

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