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Slimholes for Geothermal Reservoir Evaluation - An Overview[0]

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Introduction

The topics covered in this session include: slimhole testing and data acquisition, theoretical and numerical models for slimholes, and an overview of the analysis of slimhole data acquired by the Japanese. The fundamental issues discussed are concerned with assessing the efficacy of slimhole testing for the evaluation of geothermal reservoirs. The term reservoir evaluation is here taken to mean the assessment of the potential of the geothermal reservoir for the profitable production of electrical power. As an introduction to the subsequent presentations and discussions, a brief summary of the more important aspects of the use of slimholes in reservoir evaluation is given.

Background

Small diameter holes, usually cored, are used routinely in geothermal exploration to characterize geology and temperature distributions in geothermal reservoirs. It is then natural to inquire whether the existing core holes, or slimholes, can be used for reservoir evaluation in the same way as large diameter production wells have historically been used. Hence, it is necessary to determine if it is possible to infer the performance of large diameter (10-14 *in*) production wells from injection and flow tests performed with small diameter (3-4 *in*) slimholes. Furthermore, it is also of interest to determine to what degree the structure and extent of a geothermal reservoir can be estimated from slimhole testing.

The use of slimholes offers several potential advantages over the more conventional use of production-size wells in reservoir evaluation. When compared with the drilling of a production well, a slimhole requires a smaller drill rig and crew, smaller tools and casing, and less infrastructure such as roads and site construction. Compared to production-size wells, these features can reduce drilling costs by a factor ranging from 35 to 65 percent. The slimhole also has reduced environmental impact. More extensive testing is possible with a slimhole which leads to increased data acquisition to support the model development discussed below. Finally, extensive data for slimholes is available from foreign sites.

The types of experimental investigations which can be conducted with slimholes include injection tests, flow tests, tracer tests, and interference tests. The first two tests can provide information of fundamental importance to the prediction of the energy extraction rate associated with a production well and will be the primary subjects of subsequent discussions. The latter two tests are of importance to the description of reservoir characteristics and will be treated only briefly in this overview.

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Modeling

The results of tests, such as those listed above, are of maximum benefit when used in conjunction with mathematical models and numerical simulations of the phenomena involved. The experimental results can be used to validate the models which can, in turn, be used to predict the performance of production wells and infer details of the structure of the geothermal reservoir. The most important issue involved in the modeling of injection and flow tests is the scale-up of slimhole results for the prediction of production well behavior. Experimental data from slimholes and production wells are needed to validate the model predictions. An ideal experiment would involve a slimhole which intersects the same reservoir features as a nearby production well. It has also been suggested that a useful experimental comparison could involve initial testing of a slimhole followed by the testing of a production well created by drilling out the initial slimhole. Regardless of the particulars of the experiment, extensive slimhole data is needed to support the use of predictive models for the evaluation of geothermal reservoirs.

In the following sections, brief introductions to the fundamental aspects of the various testing methods will be given. Applications of modeling strategies will be illustrated with data acquired in field experiments conducted by Sandia National Laboratories in collaboration with other organizations.

Injection Testing

In the simplest scenario, injection testing consists of injecting fluid, at constant flow rate, into a wellbore and monitoring the transient pressure build-up during injection or the transient pressure decay after shut-in.[1] If the wellbore is represented by an infinite line source, then the pressure response is given approximately, for large time, by the Theis equation[2]

$$p(r, t) \approx -\frac{\mu Q}{4\pi k h}\left[\ln\left(\frac{r^2}{4\alpha t}\right) + \gamma\right], \tag{1}$$

where p is the pressure, r is the radial distance, t is time, μ is the viscosity, Q is the volumetric flow rate, k is the permeability, h is the thickness of the horizontal porous layer, $\alpha = k/\phi\mu c$ is the apparent diffusivity, ϕ is the porosity, c is the effective compressibility and γ is Euler's constant (0.5772157...). Although no wellbore radius appears in this idealized equation, it has been pointed out by Collins[3] that reasonable results can be obtained upon evaluation of the Theis equation at $r=a$, corresponding to conditions which exist at the physical core hole radius. If the volumetric flow rate from the core hole is constant at a value Q over the period $0 \le t \le t_s$ and is then zero for subsequent time, the core hole is said to be shut-in. Using superposition, the subsequent pressure response is[1]

$$p(t) \approx \frac{\mu Q}{4\pi k h}\ln\left(\frac{t_p + \Delta t}{\Delta t}\right), \tag{2}$$

1. R. C. Earlougher, Jr., *Advances in Well Test Analysis*, Society of Petroleum Engineers of AIME, New York, NY, ISBN 0-89520-204-2, pg. 77, 1977.
2. C. V. Theis, "The relationship between the lowering of piezometric surface and the rate and duration of discharge using ground-water storage," Trans. AGU, 1935, pp. 519-524.
3. R. E. Collins, *Flow of Fluids Through Porous Materials*, PennWell Books, PennWell Pub. Co., Tulsa, OK, pp. 71-73, 1961.

where t_p is the time prior to shut-in and Δt is the elapsed time since shut-in. The term in parentheses is called the Horner time. For the injection response, a plot of pressure versus the logarithm of time yields a straight line from which the product *kh* (transmissivity) can be estimated. For the shut-in response, a plot of pressure versus the Horner time can be used to similarly infer a value for the transmissivity.

As an example of the application of injection testing, the data from an injection test performed on an exploratory slimhole (well number TGC 61-10) near Vale, Oregon on March 12, 1995 is considered. Pertinent details of the well completion are given in Figure 1 and the parameters for the injection test are included in Table 1. The measured pressure response at the feed zone during the

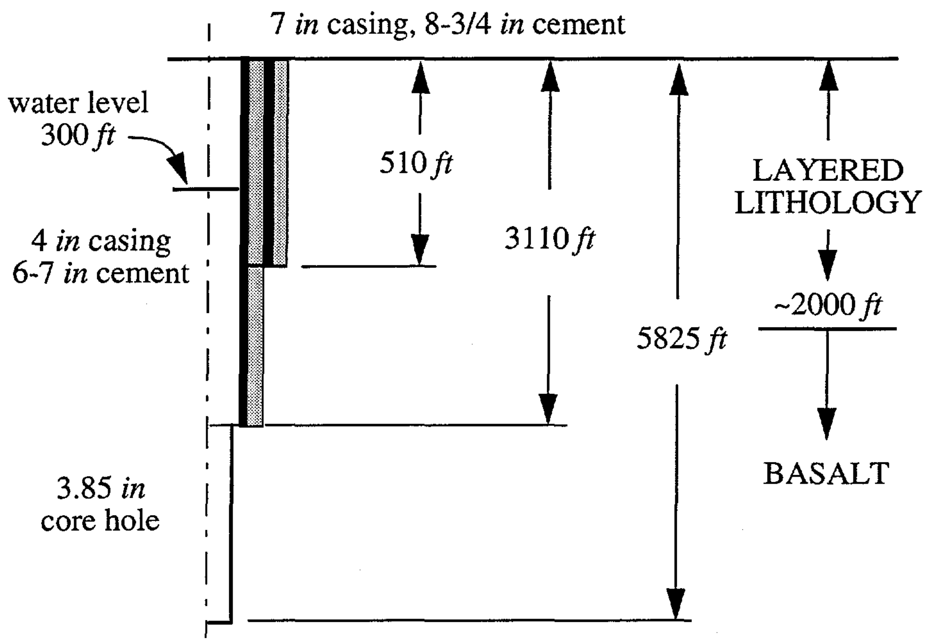

Figure 1. Exploratory slimhole. Well number TGC 61-10. Vale, Oregon.

Date	Injection Start	Shut-In	Elapsed Time (hrs)	P_{wh} (psi)	P_{dh} (psia)	Q (gpm)	T_{dh} (^oF)	Depth (ft)
3/12/95	08:39:56	10:05:49	1.431	240	1584	42	57	3109

Table 1. Parameters for injection test.

injection tests is shown in Figure 2. The corresponding pressure rise is plotted in Figure 3. Based on the slope of the curve in Figure 3, the transmissivity is estimated to be $kh \approx 0.610Da - ft$. In Figure 4, the pressure fall-off response is plotted as a function of time. A straight line fit to the late time data yields the estimate $kh \approx 0.232Da - ft$, which is 38% of the value determined from the pressure rise data. Variations of this magnitude are not uncommon in the analysis of field data. Both results are indicative of a tight formation which offers little potential for economical development.

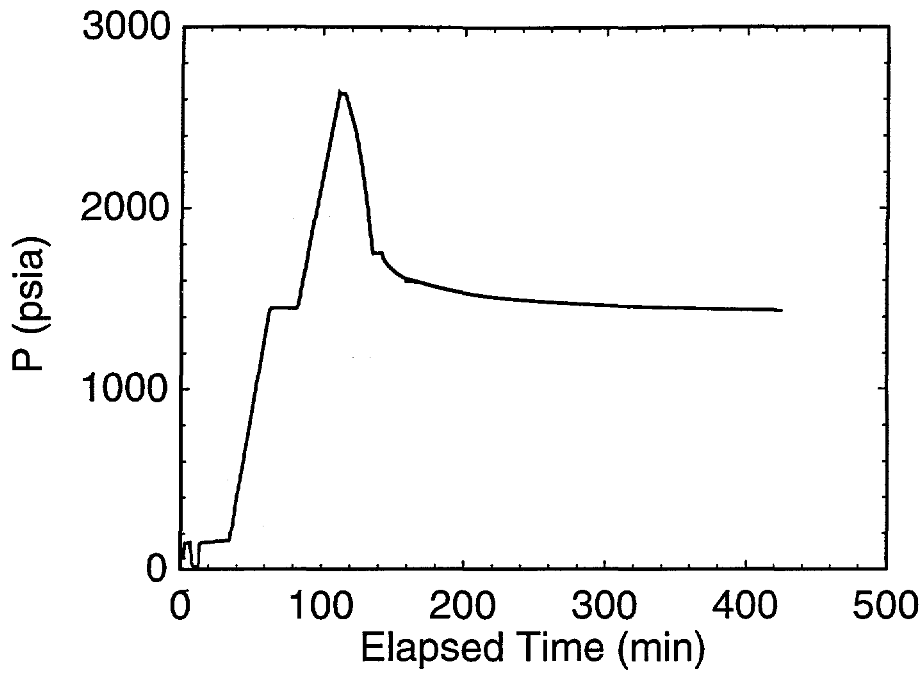

Figure 2. Downhole pressure for injection test. Well No. TGC 61-10.

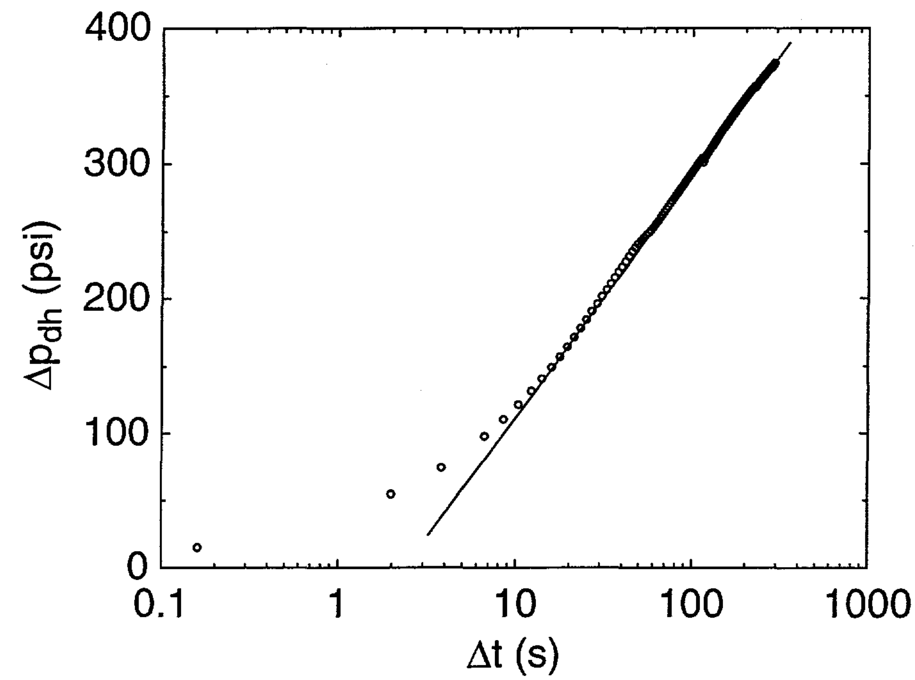

Figure 3. Pressure rise for injection test. Well No. TGC 61-10.

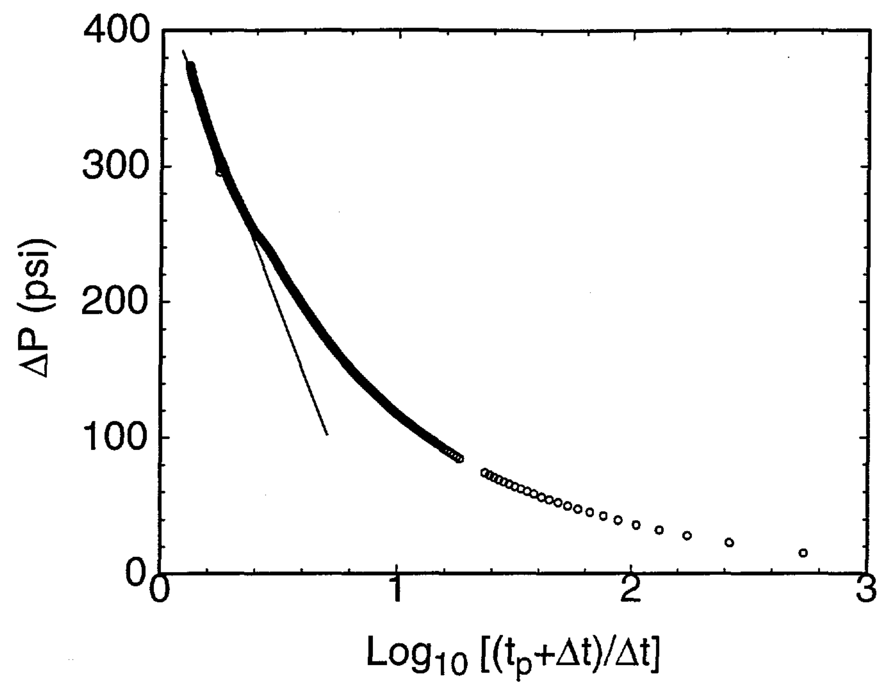

Figure 4. Pressure fall-off response for injection test. Well No. TGC 61-10.

A simpler measure of the ability of a zone in a formation to accept or produce fluid is the injectivity or productivity of the zone. These terms are also referred to as the injectivity index or productivity index. The injectivity or productivity I is defined by

$$\dot{m} = \pm I(P_{RES} - P_{DH}), \tag{3}$$

where $\dot{m}$ is the mass flow rate, P_{RES} is the reservoir pressure, and P_{DH} is the downhole pressure. The minus sign corresponds to injection and the plus sign to production. Based on the information in Table 1, for Well No. TGC 61-10, and an estimated downhole pressure of 1475 *psi*, the injectivity is 0.35 *kg/s/bar*. This value is quite small when compared with the injectivity of a potentially good production well, and is consistent with the low transmissivity measured for the slimhole. A current area of investigation is concerned with the relation between the injectivity of a slim hole and the injectivity of a production well. Numerical simulations have been used to determine scaling rules to relate the two injectivities[4].

Flow Testing

When a slimhole can be induced to flow, the wellhead pressure versus flow rate characteristics of the well can be determined. The measurement of total flow rate is typically accomplished through use of a flash tank to separate vapor and liquid in the two-phase exit flow, a James tube to determine the exit enthalpy, and a weir box or liquid flow meter to determine the liquid flow rate.[5] A

4. J. W. Pritchett, "Preliminary Study of Discharge Characteristics of Slim Holes Compared to Production Wells in Liquid-Dominated Geothermal Reservoirs," Sandia National Laboratories, Contractor Report, SAND93-7028, June 1993.

James tube is simply a straight section of pipe with a 6 *mm* diameter pressure tap located 6 *mm* from the exit to measure the "lip pressure." The tube diameter is selected so as to result in a lip pressure of several *psig* to insure critical flow in the James tube. When this condition is obtained, the total enthalpy and mass flow rate are related by James' formula

$$\frac{\dot{m}h^{1.102}}{Ap_l^{0.96}} = 1680, \tag{4}$$

where p_l is the lip pressure in *Pa*, A is the tube cross-sectional area in cm^2, $\dot{m}$ is the mass flow rate in *kg/s*, and h is the total enthalpy in *kJ/kg*. Assuming flashing occurs at atmospheric conditions, the combined mass and energy conservation equation is

$$\dot{m} = \dot{m}_w\left(\frac{h'_{fg}}{h'_g - h}\right), \tag{5}$$

where $\dot{m}_w$ is the liquid mass flow rate, h'_{fg} is the enthalpy of vaporization, and h'_g is the saturated vapor enthalpy. Both enthalpies are evaluated at atmospheric pressure, as indicated by the primes. Simultaneous solution of the last two equations allows the mass flow rate and total enthalpy to be determined.

If the reservoir fluid is in the liquid state and heat loss in the wellbore is negligible, the total enthalpy can be identified with the reservoir enthalpy h_r, which is estimated from the saturated liquid enthalpy evaluated at the temperature and pressure of the feed zone. The total mass flow rate is then determined from a modified form of Equation (5)

$$\dot{m} = \dot{m}_w\left(\frac{h'_{fg}}{h'_g - h_r}\right). \tag{6}$$

This equation can be used to estimate the total mass flow rate when downhole conditions are known and critical flow cannot be established in the James tube.

When the well is flowing, additional information regarding the characteristics of the well can be obtained from PTS (pressure, temperature, spinner) surveys to determine, respectively, the distributions with depth of pressure, temperature, and potential feed zones. These measurements can then be compared with numerical simulations of the wellbore flow. Simulations of this type require the simultaneous solution of mass, momentum, and energy conservation relations for single and two-phase flow. These relations are supplemented with a model for frictional pressure loss, a slip model which relates the vapor and liquid velocities in the two-phase region, and a model for heat transfer with the surrounding formation.

As an illustration of the measurements and analyses described above, an analysis of the flow data from the slimhole test well (Well No. SNLG 87–29) at Steamboat Hills, Nevada, has been performed. The slimhole geometry is illustrated in Figure 5 and the parameters pertinent to the flow

5. M. A. Grant *et al.*, *Geothermal Reservoir Engineering*, Academic Press, New York, NY, 1982.

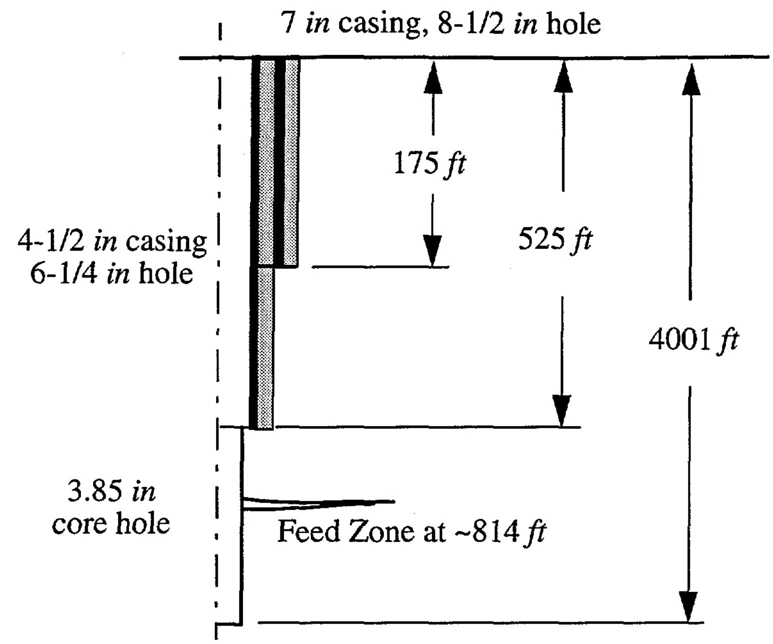

Figure 5. Exploratory slimhole. Well number SNLG 87-29. Steamboat Hills, Nevada.

tests are summarized in Table 2. Reading from left to right, the columns in the table refer to the test series, diameter of the James tube, volumetric liquid water flow rate through the weir box, wellhead pressure, James tube lip pressure, water temperature in the weir box, and water temperature at the feed zone in the well. An asterisk following the feed zone temperature indicates the value at the assumed major feed zone for cases with more than one potential feed zone. The analysis to be presented assumes a single feed zone. In Figures 6-8, a typical spinner survey, temperature distribution, and pressure distribution are illustrated for a production rate of 7.1 *kg/s*. In Figure 9, the wellhead pressure is plotted versus mass flow rate for the cases listed in Table 2.

In Figures 7-9, numerical simulations are compared with the experimental data. The two simulation programs used were GEM[6] and WFSA.[7] In GEM, the two-phase flow regime can be modeled assuming no slip or using the two-phase slip models of Hughmark[8] or Orkiszewski.[9] In Figures 8 and 9, the Orkiszewski model is used. In Figure 9, three models are compared with the experimental data. The closest fit to the data is obtained with the WFSA simulation package which uses a slip model based on a combination of the Hughmark and Orkiszewski models.

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6. R. C. Dykhuizen and R. R. Eaton, "Modeling of Geothermal Wells With GEM," Sandia National Laboratories, Albuquerque, NM, Internal Memo, Jan. 8, 1993.
7. T. Hadgu, "Vertical Two-Phase Flow Studies and Modelling of Flow in Geothermal Wells," Ph.D. Thesis, Univ. of Auckland, New Zealand, 1989.
8. G. A. Hughmark, "Holdup in Gas-Liquid Flow, "Chem. Engr. Prog., **58**(4), 1962, pp. 62-65.
9. H. Orkiszewski, "Predicting Two-Phase Pressure Drops in Vertical Pipe," J. Petr. Tech., 1980, pp. 829-838.

Series	J. Tube (*in*)	Q_w (*gpm*)	p_{wh} (*psig*)	p_l (*psig*)	T_w (°*F*)	T_b (°*F*)
1.a	2.9	103	35	5.8	192	325
1.b	2.9	50	41	1.2	179	325
1.c	2.9	65	40	1.3	184	325
1.d	2.9	81	38	2.5	188	325
1.e	2.9	95	34	4.4	194	325
1.f	2.9	101	32	5.1	194	325
2.a	2.9	49	35	1.7	178	325
2.b	2.9	63	36	1.7	178	325
2.c	2.9	66	36	1.7	178	325*
2.d	2.9	96	31	5.5	178	325*
3.a	1.939	46	36	3.6	170	325*
3.b	1.939	60	37	7.8	173	325*
3.c	2.9	84	36	3.6	183	325*
3.d	2.9	103	33	5.4	183	325*
3.e	2.9	51	38	1.5	184	325*
3.f	2.9	71	38	2.0	184	325*
4.a	2.9	105	33	6.4	190	325*

Table 2. Basic parameters for flow tests.
Well No. SNLG 87-29, Steamboat Hills, Nevada.

Note on productivity and injectivity

As mentioned in the previous section, the productivity can also be used to characterize the overall performance of a producing well. As with the injectivity, numerical studies[4] have shown that it is possible to determine scaling rules to relate the productivity of a slimhole to that of a production well. The ongoing work also shows promise of relating the injectivity and productivity. This approach has potential for the evaluation of production wells from slimhole data without flow testing the slimhole. In the simplest scenario, the injectivity of a slimhole is taken to be equal in magnitude to the productivity of the slimhole. The productivity of a production well is then inferred from the productivity of the slimhole through the use of scaling arguments. Even if the injectivity and productivity of the slim hole are not equal, it may be possible to devise rules to relate the two and, hence, allow the prediction of productivity for a production well.

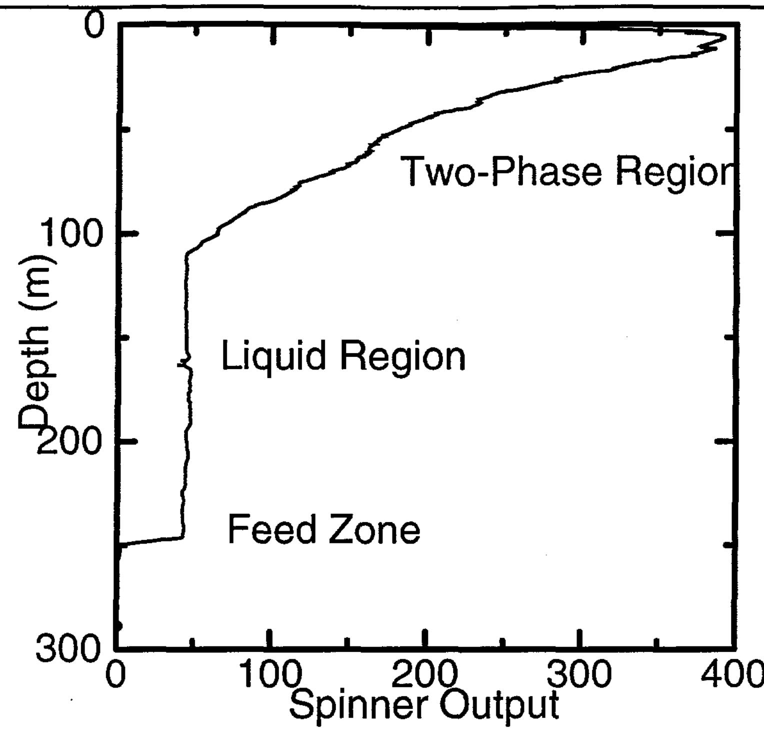

Figure 6. Spinner response versus depth while flowing 7.1 *kg/s*.
Well number SNLG 87-29. Steamboat Hills, Nevada.

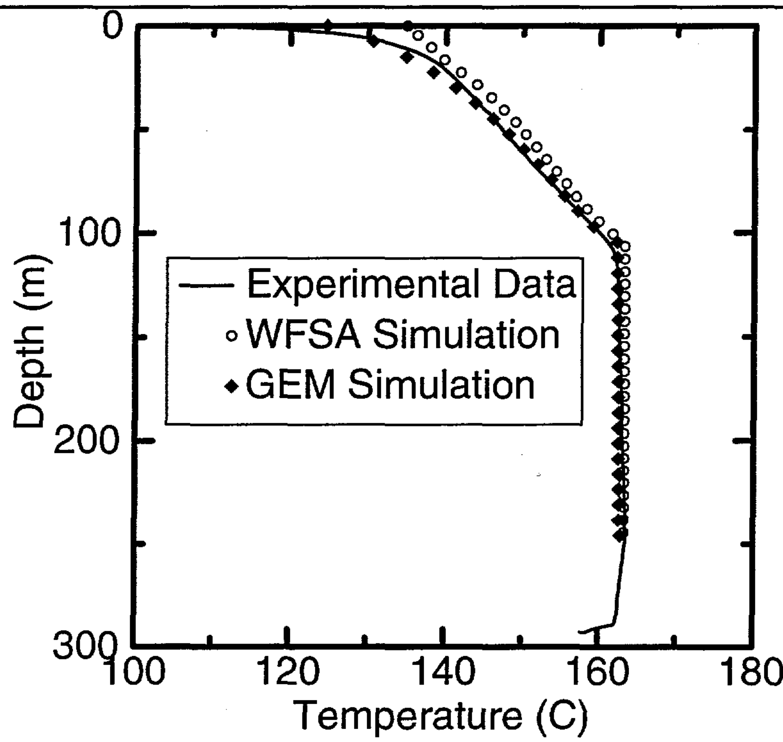

Figure 7. Temperature versus depth while flowing 7.1 *kg/s*.
Well number SNLG 87-29. Steamboat Hills, Nevada.

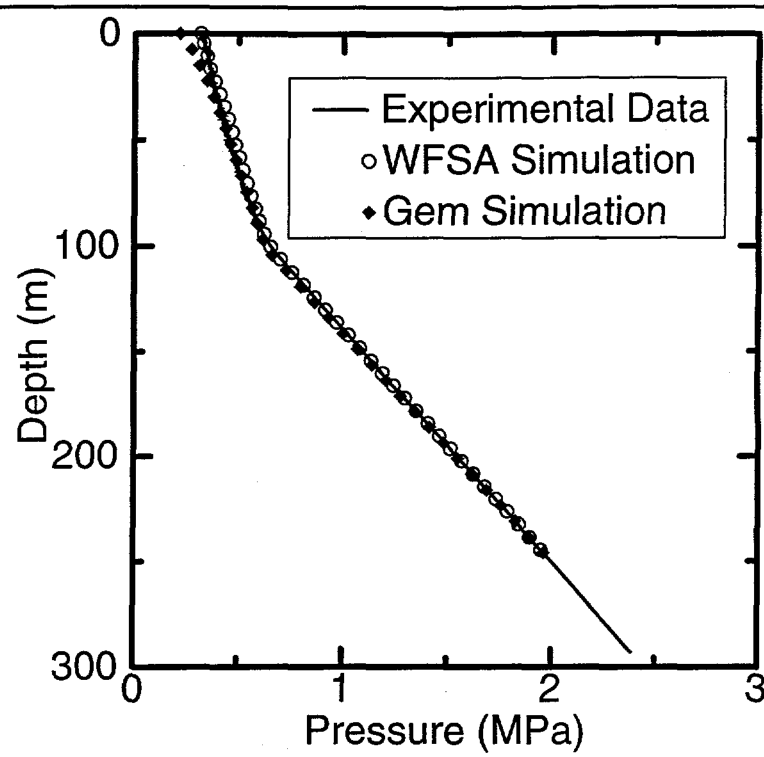

Figure 8. Pressure versus depth while flowing 7.1 *kg/s*. Well number SNLG 87-29. Steamboat Hills, Nevada.

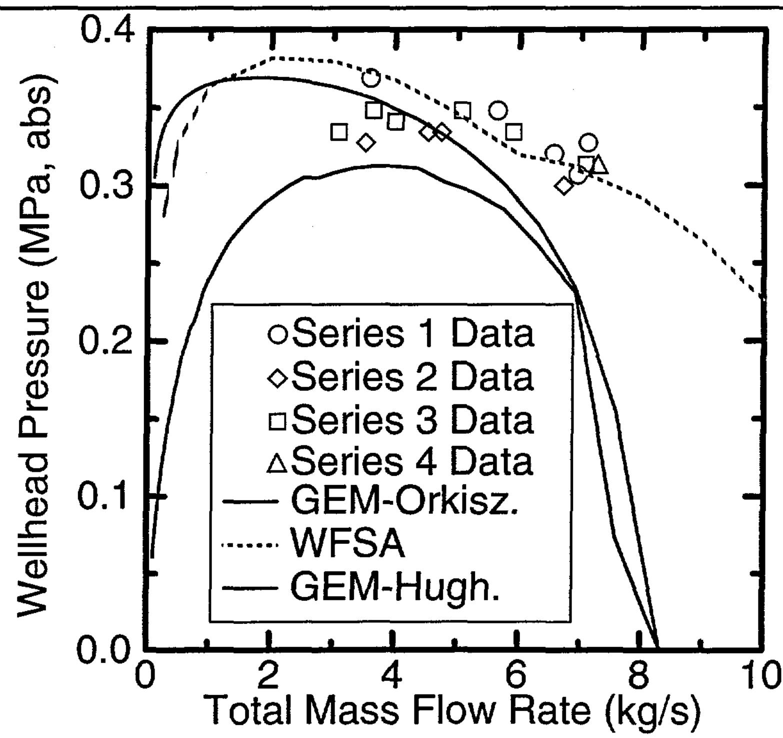

Figure 9. Wellhead pressure versus mass flow rate. Well number SNLG 87-29. Steamboat Hills, Nevada.

Reservoir Modeling

Although not specifically a topic of concern to the current discussion, the numerical simulation of the geothermal reservoir is of significance to a complete understanding of the dynamics of the coupled system consisting of the wellbore, reservoir, and power plant. Slimhole data obtained from interference, tracer, production, and injection tests together with corehole data can be used to infer reservoir characteristics for detailed simulations of the geothermal reservoir. An approach which incorporates two of these processes was recently reported in a study by Hadgu *et al.*[10] who coupled the reservoir simulator TOUGH[11] with the wellbore simulator WFSA.[7] The coupled reservoir-wellbore simulation allows accurate, integrated, modeling for the potential exploitation of a geothermal resource. The work demonstrated that meaningful results can be obtained from the coupled simulation for time periods of interest to the practical investigation of a geothermal system. The investigations that have been done so far are preliminary and the method needs to be improved to provide a complete interfacing of the two simulators. Field data is also needed to validate the numerical simulation procedure. It is also important to extend the method to include the surface gathering system and the power generation cycle. A complete, coupled, simulation of the entire geothermal system can be of significant value in developing efficient strategies for the development of the resource.

Concluding Remarks

Numerical simulations of the thermal-hydraulics of slimholes have shown good agreement with experimental data obtained in exploratory wells. Simulations have also been used to relate predicted production well performance to the predicted performance of a slimhole. At this stage, a good experimental comparison between a slimhole and a production well which share the same feedzone is needed to fully validate the numerical simulation procedure. There is evidence that injection data obtained with slimholes can be used to infer the performance of a production well. However, it is believed that flow testing of slimholes is preferable to injection testing for the determination of production well performance. Injection testing of slimholes is, however, still useful for the initial screening of potential geothermal resources. Finally, additional experimental and numerical studies are needed to understand fully the dynamics of a coupled wellbore-reservoir system.

Acknowledgment

The author wishes to express his appreciation to John T. Finger, of Sandia National Laboratories, for his contributions to this paper.

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10. T. Hadgu, *et al.*, "Coupled Reservoir-Wellbore Simulation of Geothermal Reservoir Behavior," Geothermics, Vol. 24, No. 2, 1995, pp. 145-166.
11. K. Pruess, "TOUGH User's Guide," Report LBL-20700, Lawrence Berkeley Laboratory, Berkeley, CA, 1987.