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THE MEASUREMENT OF PERMEABILITY BY INJECTION TESTS

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ABSTRACT

In fractured geothermal reservoirs, injection tests should normally be interpreted by using formation fluid viscosity, not injected water viscosity. Some injection tests cannot be simply related to formation permeability because injection increases permeability.

INTRODUCTION

Injection of cold water is frequently used as a testing procedure for geothermal wells, as for example in a completion test at the end of drilling. The injectivity so measured is a fairly reliable indicator of the well's production. The precise evaluation of injection tests and pressure transients however poses some problems as to what fluid properties should be used. A test measures transmissivity kh/μ. As the viscosity of cold water is up to ten times greater than that of hot water, kh estimates are sensitive to the assumption used.

Using standard homogeneous porous medium models, injection testing has been analysed by Tsang & Tsang (1978), Bodvarsson & Tsang (1980), O'Sullivan & Pruess (1980), Mangold et al. (1981), Garg & Pritchett (1981) and Bodvarsson et al. (1981). These show a variety of results, with injected fluid properties being appropriate at some times - specifically during the buildup with injection - and not at other times.

Experience, in fractured reservoirs, shows a different conclusion. Formation fluid properties should be used. (Sigurdsson & Stefansson 1977, Ramey 1979, Grant et al. 1982). Although cold water is so much more viscous than hot water, the author at present knows of no case where injection of cold water required significantly greater back-pressure than the drawdown caused by discharging an equal mass flow from the same well.

Sometimes it is observed that a well accepts water for injection markedly more readily than it produces fluid for discharge. kh/μ for injection is several times greater than for production. To explain such observations it is neccesary to assume a genuine increase of permeability with injection, due either to hydraulic fracturing or to thermal contraction of rock and opening of fractures. Detailed tests in New Zealand have shown both mechanisms to occur, in different wells.

OBSERVATIONS

Given the many uncertainties remaining about geothermal reservoirs, and in particular the problems involved with the fractured nature of the permeability, theoretical conclusions are best checked against observations of actual practice as frequently as possible. It should be quite simple to determine the fluid properties controlling a well test: simply assemble a list of wells in which good-quality tests have been made of both injection and discharge transients, and compare. In practice there seem to be remarkably few such data available. There are some, and these are reviewed below.

NEW ZEALAND

It is standard practice in New Zealand to measure the injectivity of a well at completion. Thus a large number of injectivities and injection transients have been measured. There is a smaller library of discharge results. Table 1 lists the productivities and injectivities of the wells of Ngawha field. All the wells produce water at 210°-230°, from fractured greywacke.

TABLE 1. NGAWHA WELLS

Well no.	inj.	prod.
	--- t/h.b	---
NG2	5	9
NG3	22	2
NG4	110	200
NG8	>8	12
NG11	42	25
NG18	10	1.5-4

If the injection results reflected the properties of injected fluid, the productivity should be about ten times greater than the injectivity. In fact it is about the same, or less. Had the injection results been evaluated with cold water properties, a gross overestimate of the productivity would have been calculated.

Table 2 lists a similar set of comparisons for Broadlands wells. All measurements were made in 1970-71. In some cases productivity is taken not from a flowing profile but from an 'immediate shut' profile, ie 5-15 minutes shut, so that productivity is over-estimated. All wells were flowing with excess enthalpy, and produce from a reservoir of fractured volcanic rock at 245^{o}-300^{o}.

TABLE 2. BROADLANDS WELLS

Well no.	inj.	prod.
	---t/h.b---	
BR9	20	1-1.5
BR13	4-9	3.3
BR18	8	2.2
BR22	14	12
BR23	26	11
BR25	21	35
BR27	9	5.5
BR28	50	15

As with Ngawha, productivity is equal to or less than injectivity, not much greater.

A comparison of injection and discharge transients is reported by Grant (1980) for well KA28, Kawerau. As the well is two-phase, it is neccesary to make some assumption about relative permeabilities. Using fracture-flow permeabilities, consistency between injection and discharge results is obtained assuming that the injection test measures formation fluid properties. Use of cold water properties would give incompatible results. A series of tests at BR28 provide a similar result. Using the same method of calculation as KA28, two discharge tests give kh = 5.9 and 9.8 d-m. Four tests injecting water at 155^{o}-160^{o} give kh = 8.7 -15 d-m, using formation dynamic viscosity. Using the injected fluid viscosity would triple the kh estimates.

ICELANDIC OBSERVATIONS

Sigurdsson & Stefansson (1977) report tests on six early Krafla wells. In two, KG-8 and KJ-9, both injection and production transients were analysed. They are roughly consistent if the injection tests reflect formation fluid viscosity. If injected water properties are used, the injection test provides an overestimate of kh.

Bodvarsson et al (1981) report the analysis of injection tests in two Krafla wells. A theoretical analysis shows that cold water properties are appropriate. For well KG-12 values obtained for transmissivity kh/μ are in the range 1.2-2.4×10^{-8} m^3/Pa.s, and a similar value for KG-13, which correspond to kh of about 15 d-m, using cold water viscosity. The old field of Krafla has generally poor permeability. The production history of KG-12 is shown by Stefansson & Steingrimsson (1980). Treating the mass flow decline as a flow at constant pressure, a kh of 0.1 d-m is found. The injection test did not predict the well performance. If hot fluid properties were used to evaluate the injection test, 1.5 d-m is found. It is still neccessary to assume some other effect - either stimulation during the injection test or a genuine decline in permeability under production.

VAPOUR SYSTEM

An extreme case of contrast between injected and reservoir fluid is provided by injection into a vapour-dominated reservoir. For four wells in the vapour-dominated reservoir of Kamojang, Indonesia, the following comparison was made: first, kh was evaluated from discharge measurement, usually from a decline analysis. (see, eg. Grant 1979, or Grant et al. 1982) Then, and injection test was evaluated to find kh/μ. Dividing the two gives the dynamic viscosity μ as found by the injection test. The values found lay in the range 200-500 μPa.s, ie corresponding to liquid water at temperatures of 55^{o}-120^{o}C. In this case the injection test reflected the properties of neither reservoir fluid nor injected fluid, but of water of intermediate temperature.

CONCLUSIONS

Permeability or injectivity as found by the injection of cold water into a geothermal reservoir in fractured rock reflects not the properties of the injected fluid, but usually something near the properties of reservoir fluid. Use of the injected fluid viscosity to evaluate injection tests results in a gross overestimate of permeability.

Given that theoretical calculations for a homogeneous medium indicate that injected fluid properties should apply, this conclusion is of great interest. For some reason the fractured medium acts, for injection, in a manner very different from a homogeneous one. One possible reason is that conductive heat transfer from block to fissure significantly changes the radius occupied by heated injected fluid (over that for a homogeneous medium) (Bodvarsson 1982). It is also possible that the formation permeability is effectively temperature-dependent. The normal result of long-term injection is that injectivity increases substantially, so that the cooling of the reservoir may have opened fissures wider. Injection-production cycling at BR23 confirms this hypothesis (Grant et al. 1982), but this cannot be the entire explanation since it would produce a random increase in permeability in injection wells, depending upon the local fracture geometry; whereas the injectivity/productivity comparisons show reasonable uniformity.

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