Proceedings Eighth Workshop Geothermal Reservoir Engineering
Stanford University, Stanford, California, December 1982
SGP-TR-60

AN EXPERIMENT IN RELATIVE PERMEABILITIES AND TWO-PHASE TRANSIENT THEORY

Malcolm A. Grant
Applied Maths Division, DSIR, Wellington, New Zealand
Richard B. Glover
Chemistry Division, DSIR, Taupo, New Zealand
Mark W. Killup
Ministry of Works & Development, Taupo, New Zealand

ABSTRACT

A series of pressure transients were observed at BR21, a high-enthalpy well. The variation in transient behaviour with enthalpy gives some indication of the form of relative permeability functions for fractured media. The consistent form of the observed transients indicates that two-phase transient observations can be used to determine reservoir parameters.

INTRODUCTION

BR21 is a high-enthalpy well in Broadlands geothermal field, New Zealand. The recent theoretical work (Sorey et al. 1980; Bodvarsson et al. 1980; Garg & Pritchett 1981) on the transient changes occurring in two-phase flow to geothermal wells requires good experimental data to check model predictions. For this purpose a test discharge was carried out at BR21, in which the transient changes in pressure, mass flow, enthalpy and gas and water chemistry were monitored with high frequency during a period of discharge with changes in flow rate and brief shutins. The test history is shown in Figure 1.

THE WELL

BR21 was drilled in 1970 to a depth of 1120m. There were circulation losses around 500m, and the casing is set at 425m. Figures 2a&b show some profiles measured at various times and under various conditions. Permeability is indicated at 500m and around 800-900m; which permeable zones were confirmed by a spinner survey during injection after the flow test. Comparison of pressures with the well cold (P1) with profiles after warmup (P2&4) indicates that the upper zone is dominant (Hitchcock 1971). During most injection tests, the upper zone is discharging and the lower injecting (T1,T19) and flowmeter or temperature profiles can be used to determine that the productivity of the upper zone is about 5 t/h.b; and the injectivity of the lower zone about the same.

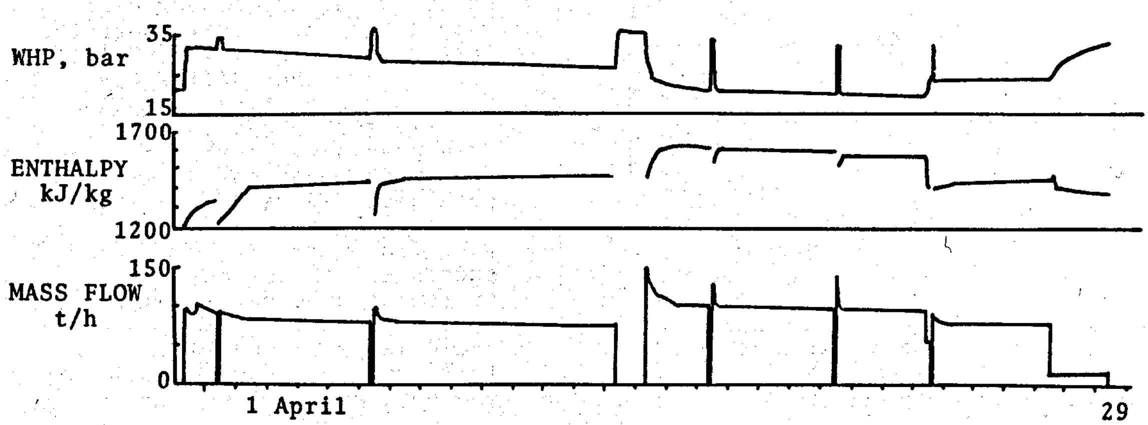

FIGURE 1. FLOW TEST HISTORY, BR21, 30 March - 29 April 1982.

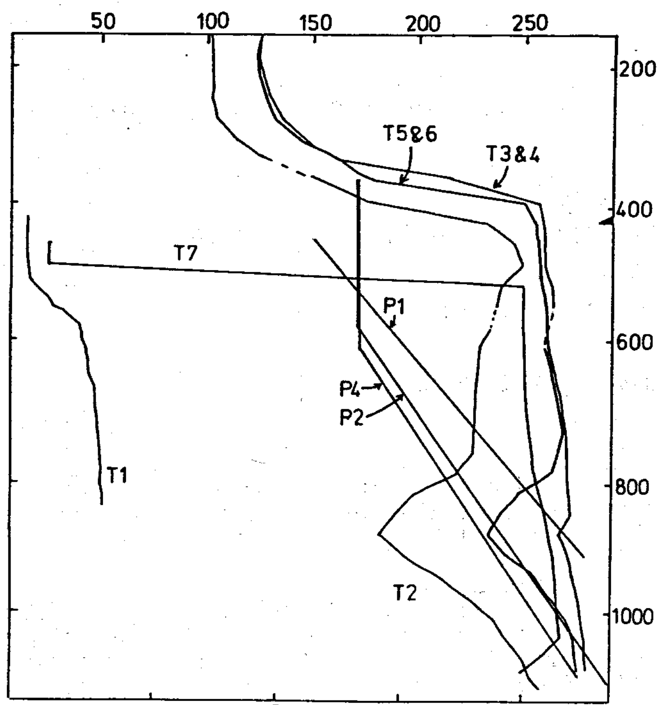

FIGURE 2A. 1970 Profiles.
P1 12/6, immediately after injection.
T2 16-17/6; T3,P2 3/7; T4 6/7; T5 3/9;
P4 21/10; T6 22/10. T7 injecting 1971.

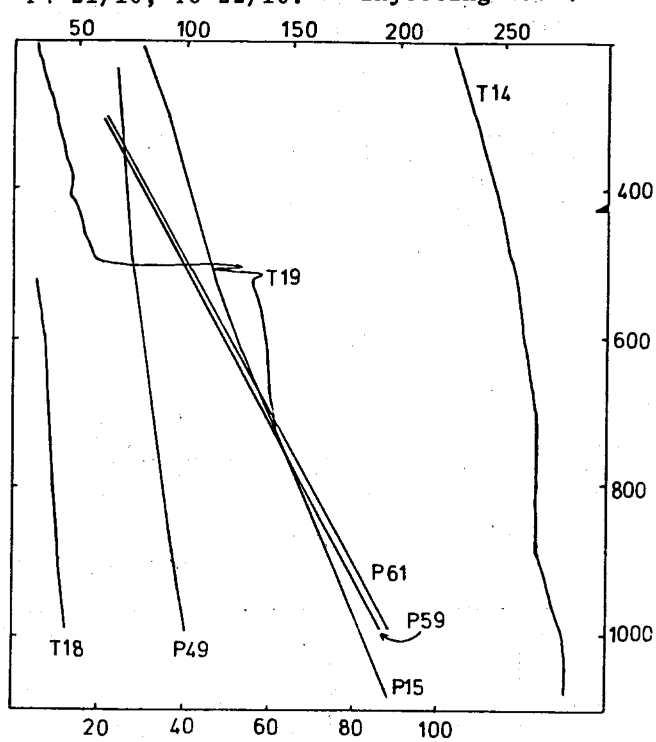

FIGURE 2B 1982 Profiles.
T14,P15 17/3 bleeding; P49 26/4 flowing 90 t/h; P59 21/5 injecting 6.7 l/s;
T18,P61 21/5 injecting 21.4 l/s;
T19 21/5 injecting (continuous log).

It is not possible to make an immediate comparison between the two zones from this result, because one cannot immediately compare injection and discharge results. The injectivity of a permeable zone in fractured rock is commonly about equal to its productivity, or considerably greater. (See, eg., Baca - Garg & Riney 1982.) In the case of BR21 there is fortunately one injection period (T18, P61) when the upper zone was accepting water. Comparing this with the profile P59, there is an incremental injectivity of over 50 t/h.b. The much higher injectivity must result from the upper zone beginning to accept water, and its injectivity must be at least ten times that of the lower zone.

The upper zone at 500m is thus the dominant producing zone, and its parameters are used for the interpretation of the transients. Stable pressure is 46-47 bar. Temperature is unobservable because there is a permanent upflow in the well (eg T14 showing 270° water entering at 900m). Chemical geothermometers indicate 255-258°, which is saturated with the 1-2 bar gas partial pressure present. T3&4 show 263° in 1970, when pressure was higher. A reservoir temperature of 255° is now assumed.

TRANSIENT OBSERVATIONS

BR21 was opened on 30/3, and flowed at a slowly declining rate until 13/4, was shut for a day, flowed again until 23/4, then throttled slightly, throttled again on 27/4, and finally shut on 29/4. Each flow period was interrupted by brief shutins. The available data thus covers:

- two openings, one from one day shut
- two throttlings
- a number of closures and reopenings
- in addition a long buildup in 1971

All measurements were made with Kuster gauges using three-hour clocks. The same gauge was used through the 1982 test to minimise error. The transient results are thus defined by one or several consecutive runs showing a transient record within each run, and then possibly a number of later runs from which only one datum point is obtained. Figure 3 shows the downhole pressure history during the first two-week flow period. There are four successive three-hour runs, followed by ten later observations. There is some calibration problem present. To avoid jumps in the record, the second to fourth runs have been decreased by one bar, and all subsequent runs increased by three bars. The latter lies outside the normal range of calibration error. Figure 4 shows the pressure buildup recorded in 1971 when the well was shut after 8 months' flow.

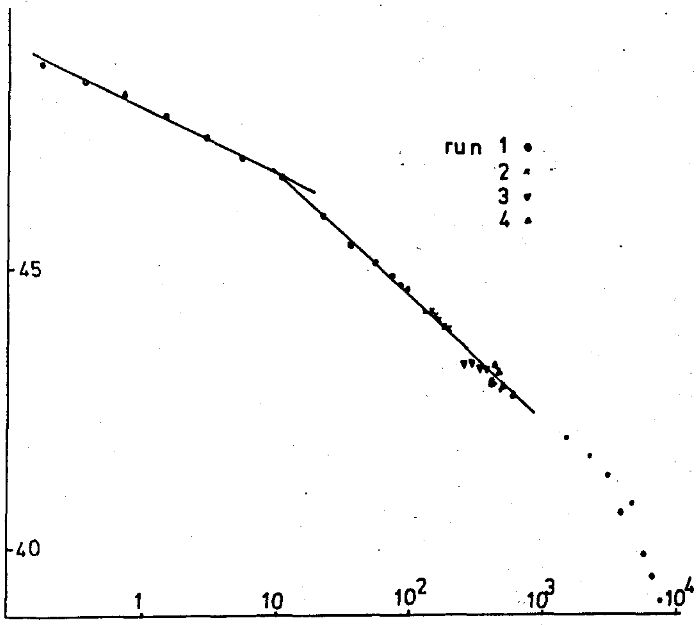

FIGURE 3. Pressure drawdown during first flow period. Pressure in bars, time in minutes.

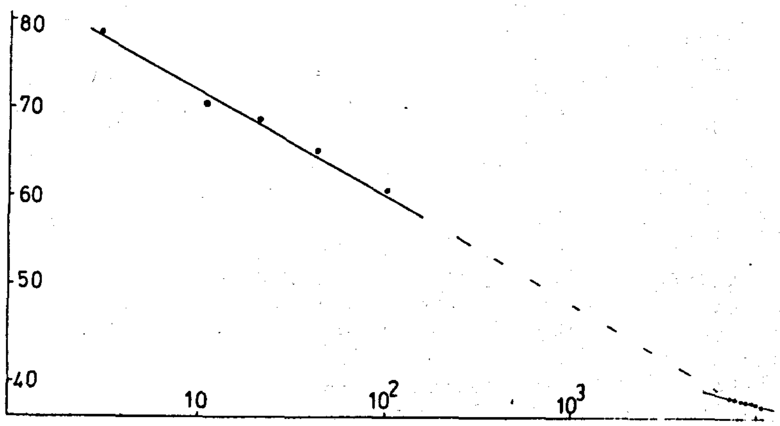

FIGURE 4. Pressure buildup at bottomhole, Horner plot. Pressure in bars.

The two results shown in Figures 3 and 4 are the longest records which are not affected by previous changes in flow rate. All other transients were recorded during the flow test, with a history of prior flow changes, and so only a short period after each flow rate can be simply interpreted. For this reason most other transients rely upon a single 3½-hour record.

Figures 3 and 4 show what is a persistent feature of the results: two straight lines. The first begins a few seconds after the flow change, and is replaced by the second line at a fraction of an hour. Sometimes only one line is present, as is shown in Figure 5. These two straight lines gave considerable problems in interpretation. Type-curve matches were tried, which showed that

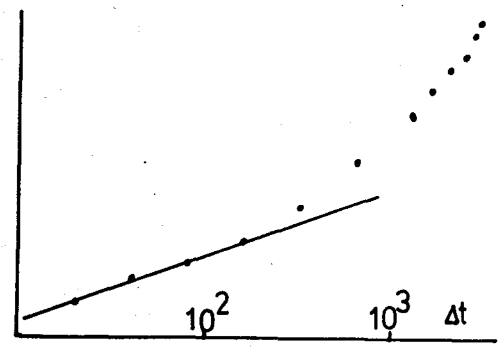

FIGURE 5. Pressure buildup after shutin, 20/4/82.

the early slope is not an artifact of storage and/or skin. Because a straight line develops so quickly, no useful purpose was served by such matching. The reservoir is of course fractured, so there is the possibility that the early slope is in fact the transition period of a fractured medium. The full transient would show two parallel lines joined by a flatter transition, but the first line can be easily obscured by storage effects. However, for this interpretation the ratio of the two slopes must be less than 2:1, and it is in fact about 3:1. Also, the enthalpy transient is interpreted as due to a fractured medium, and the relaxation time of the blocks is 400 hours (Grant & Glover, in prep.).

As the two lines are not always present, it was decided in the end to ignore the problem of their significance, and proceed to the object of the test, the variation of the transient behaviour with discharge enthalpy of the well. Table 1 lists the results of the pressure buildups during the 1982 tests, the 1971 buildup and the two drawdowns. The mass flow and enthalpy given is that just before shut, for the buildups, or midway through the straight-line period, for the drawdowns. Where two straight lines are present, both are given. From the enthalpy, k_{rw}/k_{rg} is computed. Then, assuming the fracture-flow relative permeabilities $(k_{rw}+k_{rg}=1)$, kh_{ff} is computed. See the Appendix for details. Figure 6 shows the values of kh_{ff} plotted against k_{rw}/k_{rg}. Unfortunately there are no transients in which the discharge enthalpy is equal to downhole water, from which an unambiguous interpretation of kh can be made. According to the results of Sorey et al. (1980), there should be a marked overrecovery

TABLE 1 SHUTINS AND OPENINGS

Date	W t/h	H_t kJ/kg	m bar/cy.	kh_{ff} d-m
---- openings ------				
30/3	96	1200	1.2	7.2
		1300	2.2	4.1
14/4	131	1500	8.5	2.3
------shutins-------				
31/3	89	1333	1.3	8.1
			3.0	3.4
5/4	74	1413	.80	12.6
			2.7	3.8
13/4	73	1440	1.1	9.1
			3.8	2.6
16/4	100	1620	2.2	7.8
			5.4	3.2
20/4	97	1590	1.8	9.3
1971	55	1975	2.7*	10.4
			7.2*	3.9

*Bottomhole data corrected to 500m

in saturation at wellface during shutin. It was hoped that this would produce a discharge of liquid water on reopening. Although discharge enthalpy was markedly lower at each reopening than at the preceeding shut, it was never as low as liquid water.

The variation of kh_{ff} is equivalent to the variation of $k_{rw}+k_{rs}$, since

$$kh_{ff} = (k_{rw}+k_{rs}).kh$$

If the fracture-flow relative permeabilities do apply, kh_{ff} should be constant over variations in enthalpy, and will in fact be equal to kh. If some other form of relative permeability applies, kh_{ff} varies proportionately to $k_{rw}+k_{rs}$.

Both early and late slopes show no well-defined trend, within the considerable scatter of ±30%. Within this scatter, the results are consistent with the fracture flow permeabilities, but the data are few and this result correspondingly tentative. The kh value indicated for BR21 is 3 d-m from the late slopes and 9 d-m from the early.

At the top of Figure 6 is shown the form of variation that would be given by a porous medium obeying the Corey relative permeabilities. It is not consistent with either the early or late slope data. Over the range of observation, the Corey relative permeabilities attain a maximum value of $(k_{rw}+k_{rs})$ of about 0.4. The greatest variation in relative permeability is then in the range of single-phase and nearly single-phase flow, which unfortunately the BR21 results do not span. Rather than data covering a range of two-phase flow conditions, the most important test of relative permeability forms would be provided by a comparison of single-phase and two-phase results.

There does not seem to be any major inconsistency between the results of the buildups and the two drawdown tests.

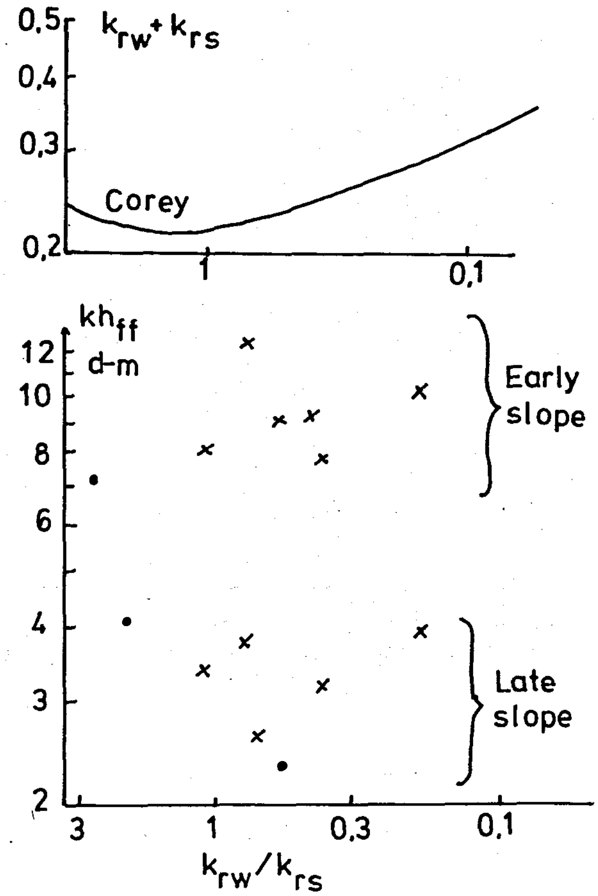

FIGURE 6. Above: variation of $k_{rw}+k_{rs}$ with k_{rw}/k_{rs}, for Corey relative permeabilities. Below: variation of kh_{ff} for BR21 with k_{rw}/k_{rs}.

The drawdowns (denoted by dots) fit into Figure 6 consistently. As the pressure buildup data are easier to interpret - they generally give better straight lines and there is a single unique value of mass flow and enthalpy to use - it is normally easier to use buildup data for well test analysis.

The pressure falloff when the well was reopened after each brief shutin was more difficult to interpret. The brief closure produces sharp radial gradients in saturation around the well, so that the pressure transient on reopening propagates outward into a radially inhomogeneous medium. It is also difficult to allow for the effect of the preceeding closure, by a simple Horner plot or two-rate analysis, because of the different viscosities created by the differing enthalpies. This applies also to the two throttlings. No attempt was made to allow for the effect of the preceeding closure, and all the falloffs were plotted as MDH plots. The effect of the preceeding flow change should then appear as a flattening of the curve. Table 2 lists the results of these falloffs. They appear to vary more strongly with enthalpy than those of Table 1, although this result is strongly dependent on one result (20/4).

TABLE 2 REOPENINGS.

Date	W t/h	H_t kJ/kg	m bar/cy.	kh_{ff} d-m
31/3	94	1225	1.4	6.2
5/4	100	1280	.95	11.0
		1400	2.3	5.7
16/4	55	1560	6.9	1.3*
20/4	51	1550	11.9	.69

*Result dubious - plot erratic.

The well was twice throttled, and transient changes measured. This was done primarily to observe the expected fall in discharge enthalpy, analagous to that expected after shutin. The pressure transient suffers from difficulty in analysis because of the change in enthalpy and hence in viscosity. It was decided to compute kh proportionally to the change in the product $(W\nu_t)$, not just to the change in mass flow W. This gave results reasonably consistent with those of Table 1, and are shown in Table 3.

TABLE 3 THROTTLINGS

Date	W_1 t/h	W_2	H_{t1} kJ/kg	H_{t2}	m b/cy	kh_{ff} d-m
23/4	93	51	1562	1404	1.5	5.5
					3.3	2.5
27/4	72	12	1406	1380	.99	8.0

SATURATION

From observations of pressures and enthalpy, it is possible to determine the relative permeabilities as functions of each other, but not their dependence on saturation. The saturation is unobservable from these data. It can in theory be determined from chemical transient data, as the transient changes in chemical composition of the discahrge involve a balance between the fluxes of fluid flowing and the amounts in storage in the porous medium. A major object of the chemical analysis was to obtain such estimates of saturation. Six were obtained, one for each shutin period and one for the first period of flow. Two results were discarded, and the remainder give saturations of 12-40%, surprisingly low. These apply only to the fracture medium, not to the entire fracture-block medium. It is not known what to make of these saturation estimates. For further discussion see Grant & Glover (in prep.).

MEASUREMENT AT BR2

Because of the importance of a comparison between single-phase and two-phase transients on the same well, a test was made (9-10 Nov 82) on well BR2. This well is very well documented (see Grant et al. 1982) and has in the past flowed at high enthalpy. At present it produces liquid water at 245°-248°C from its primary feedpoint at 450m. A buildup after one day's flow at 240 t/h gave kh = 20 d-m.

A pressure buildup in 1968 at discharge enthalpy 1480 kJ/kg gave

$$kh/\nu_t = 2.6\text{x}10^{-5}\text{m.s}, \quad kh_{ff} = 8\text{d-m}.$$

By contrast using the Corey permeabilities gave kh = 34d-m, so this comparison implies that the actual result lies between the fracture and Corey relations. In fact $k_{rw} + k_{rs} = 0.4$ at the observed value of $k_{rw}/k_{rs} = 0.4$.

The constancy of the BR21 results with varying enthalpy implies that this value of $k_{rw}+k_{rs}$ applies over most of the range of the BR21 test, ie k_{rw}/k_{rs} between 0.2 and 3.

CONCLUSIONS

Observations of pressure transients at different discharge entahlpies has shown some systematic variation of kh estimates with enthalpy, consistent with relative permeability functions lying between the 'fracture-flow' and Corey expressions. This conclusion is sensitive to the small amount of data.

When a well discharges at high and variable enthalpy, the pressure buildup after a flow period provides the simplest data to interpret, as drawdown data is often affected by changes of flow rate or enthalpy. The form of the transients observed at BR21, with early and late slopes, was surprisingly stable over 11 years, indicating that such form relfects real propoerties of the reservoir rather than artifacts of the well or high enthalpy.

ACKNOWLEDGEMENTS

We are very appreciative of the time and trouble taken by the measurements team of the Ministry of Works and Development, Wairakei to collect the data used.

REFERENCES

Bodvarsson, G.S., M.J.O'Sullivan & C.F. Tsang, 1980 "The sensitivity of geothermal reservoir behaviour to relative permeability parameters" 6th Workshop, pp224-237

Garg,S.K. & J.W.Pritchett, 1981 "Buildup analysis for two-phase geothermal reservoirs" GRC Trans v5 pp287-290.

Garg,S.K. & T.D.Riney, 1982, "Reservoir definition and conceptual model" in report LBL-14132, Lawrence Berkeley Lab

Grant, M.A. & R.B.Glover, in prep. "Two-phase heat and mass transfer experiment at well BR21, Broadlands".
Grant, M.A. & M.L.Sorey, 1979, "The compressibility and hydraulic diffusivity of a water-steam flow" Wat. Resour. Res. v15 pp684-686.
Grant, M.A., I.G.Donaldson & P.F.Bixley, 1982, "Geothermal Reservoir Engineering" Academic Press.
Hitchcock, G.W. 1971, Internal report.

NOTATION

kh	permeability-thickness
k_r	relative permeability
H	enthalpy
k_r	$= k_{rw}+k_{rs}$
W	mass flow
m	log slope of pressure transient
ν	kinematic viscosity

Subscripts

w	water
s	steam
ff	assuming fracture-flow relative permeabilities

APPENDIX

Transients are calculated following the formulation of Grant & Sorey (1979) or Grant et al. (1982). Given enthalpies of discharge, water and steam (the latter at reservoir temperature), the reservoir dryness is $X = (H_t-H_w)/H_{sw}$.

$$\frac{k_{rw}}{k_{rs}} = \frac{\nu_w}{\nu_s} \cdot \frac{H_s-H_t}{H_t-H_w}$$

$$= \frac{\nu_w}{\nu_s} \left(\frac{1}{X} - 1 \right)$$

If fracture relative permeabilities are valid

$$k_{rw}+k_{rs} = |k_r| = 1$$

and $$\nu_t = \nu_{tff} = X\nu_s+(1-X)\nu_w$$

For any other relative permeability

$$\nu_t = \nu_{tff}/|k_r|$$

Given log slope m

$$kh_{ff} = |k_r| . kh = 2.303 W \nu_{tff}/4\,m.$$

For the calculation of the throttling transients

$$kh_{ff} = (2.303/4\,m)((W\nu_{tff})_1 - (W\nu_{tff})_2)$$

At 255°C H_w=1110, H_s=2798 kJ/kg
ν_w= .812 ν_s= .137 x10^{-6}m^2/s