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# ANALYSIS OF WELL TEST DATA FROM INDONESIA AND ICELAND

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*ABSTRACT*

Analysis were carried out for injection tests of four high-temperature wells; namely wells KMJ-42, 43 and 45 in Kamojang, Indonesia and well KJ-13 in Krafla, Iceland. Several analysing methods were applied in order to determine transmissivity and storativity values for the reservoirs and the skin value of the reservoir/well systems. All the methods are based on a simplified reservoir model. The reservoir is assumed to be horizontal of uniform thickness and of infinite areal extent. It is also assumed homogeneous, isothermal and isotropic. Reservoir fluid is single-phase and obeys the Darcy law.

The well test data is of variable quality, and especially the data from well KMJ-43 was difficult to interpret due to short duration of injection steps. Estimated transmissivity values are similar for all the wells, or of the order of $10^{-8}$ $m^3/Pa/s$, which is typical for geothermal wells. Estimated storativity values are relatively high, especially for the wells in Kamojang. An explanation of the high storativity is that Kamojang is a vapor dominated system, but it should also be remembered that injection tests are not ideal for storativity determinations compared with interference tests. Both the Kamojang and the Krafla reservoirs are fractured reservoirs. It is therefore not surprising that the well test analysis yield negative skin values for the wells.

CONTENTS

ABSTRACT . . . . . . . . . . 3
LIST OF CONTENTS . . . . . . . . . . 5
LIST OF FIGURES . . . . . . . . . . 6
LIST OF TABLES . . . . . . . . . . 7

1. INTRODUCTION . . . . . . . . . . 9

2. WELL TESTING TO EVALUATE SINGLE PHASE RESERVOIRS . . . . 10
2.1 General Approach . . . . . . . . . . 10
2.2 Steady State Radial Flow Around a Well . . . . . . . . . . 11
2.3 Theis Solution . . . . . . . . . . 12
2.4 Transmissivity . . . . . . . . . . 13
2.5 Storativity . . . . . . . . . . 13
2.6 Skin Factor . . . . . . . . . . 14

3. WELL TEST ANALYSIS . . . . . . . . . . 15
3.1 Semilog Plot . . . . . . . . . . 15
3.2 Horner Plot Method . . . . . . . . . . 16
3.3 The Varflow Computer Program . . . . . . . . . . 16

4. ANALYSIS OF WELLS TEST DATA . . . . . . . . . . 17
4.1 Well KMJ-42, Indonesia . . . . . . . . . . 18
4.2 Well KMJ-43, Indonesia . . . . . . . . . . 19
4.3 Well KMJ-45, Indonesia . . . . . . . . . . 20
4.4 Well KJ-13, Iceland . . . . . . . . . . 22

5. DISCUSSION AND CONCLUSIONS . . . . . . . . . . 25
ACKNOWLEDGEMENTS . . . . . . . . . . 27
REFERENCES . . . . . . . . . . 28
APPENDIX A: Examples of input and output files for Varflow . . . . . . . . 42

*LIST OF FIGURES*


| Figure | | Page |
|---|---|---|
| 2.1 | A simplified model of a confined reservoir | 29 |
| 2.2 | Dynamic viscosity of water as a function of temperature | 29 |
| 4.1 | Location of wells in the Kamojang field, Indonesia | 30 |
| 4.2 | Location of wells in the Krafla field, Iceland | 30 |
| 4.3 | Pressure and flow data for the injection test of well KMJ-42 | 31 |
| 4.4 | Semi-log curves for the flow test of well KMJ-42 | 31 |
| 4.5 | Horner plot for recovery of well KMJ-42 after injection | 32 |
| 4.6 | Calculated pressure in well KMJ-42 by Varflow | 32 |
| 4.7 | Calculated pressure in well KMJ-42 by Orkustofnun programs | 33 |
| 4.8 | Pressure and flow data for the injection test of the well KMJ-43 | 34 |
| 4.9 | Semi-log curves for the flow test of well KMJ-43 | 34 |
| 4.10 | Horner plot for recovery of well KMJ-43 after injection | 35 |
| 4.11 | Calculated pressure in well KMJ-43 by Varflow | 35 |
| 4.12 | Calculated pressure in well KMJ-43 by Orkustofnun programs | 36 |
| 4.13 | Pressure and flow data for the injection test of the well KMJ-45 | 37 |
| 4.14 | Semi-log curves for the flow test of well KMJ-45 | 37 |
| 4.15 | Horner plot for recovery of well KMJ-45 after injection | 38 |
| 4.16 | Calculated pressure in the well KMJ-45 by Varflow | 38 |
| 4.17 | Calculated pressure in the well KMJ-45 by Orkustofnun programs | 39 |
| 4.18 | Pressure and flow data for the injection test of the well KJ-13 | 40 |
| 4.19 | Semi-log curves for the flow test of well KJ-13 | 40 |
| 4.20 | Horner plot for recovery of well KJ-13 after injection | 41 |
| 4.21 | Calculated pressure in well KJ-13 by Varflow | 41 |

*LIST OF TABLES*


| Table | | Page |
|---|---|---|
| 4.1 | Calculated reservoir properties for well KMJ-42 | 19 |
| 4.2 | Calculated reservoir properties for well KMJ-43 | 21 |
| 4.3 | Calculated reservoir properties for well KMJ-45 | 22 |
| 4.4 | Calculated reservoir properties for well KJ-13 | 24 |

## *1. INTRODUCTION*

The author was awarded a United Nations University (UNU) fellowship to attend the 1989 Geothermal Training Programme which lasted from April 24 to October 24, 1989 at the National Energy Authority of Iceland.

The training programme started with introductory lectures, lasting for six weeks. The topics of the lectures related to geothermal energy development i.e, geology, geophysics, geochemistry, borehole geology, drilling, logging, reservoir engineering, utilization, project economy and geothermal environmental studies.

As a part of the training programme, UNU fellows went on a field excursion from the 5th to the 14th of July, 1989. On the trip, the main geothermal fields of Iceland were visited, both high and low temperature fields. During the excursion, the fellows received lectures and seminars in the respective areas, i.e. on geothermal geological exploration, utilization and the stage of development in each geothermal project.

In the second part of the training programme, the author undertook a two months training on well logging and well testing. The author participated in well logging at several high temperature geothermal fields. The work included measurements of downhole pressure and temperature and injection well tests. The final weeks of the training were used for preparing and writing this report.

## *2. WELL TESTING TO EVALUATE SINGLE PHASE RESERVOIRS*

### *2.1 General Approach*

Well testing methods have been used for decades to evaluate groundwater and petroleum reservoirs. These methods have also been successfully applied in geothermal studies, especially for single-phase geothermal reservoirs. The tests give information on the hydrological conditions of the well/reservoir system and form a basis for future prediction on well delivery and pressure drawdown in the reservoir.

The fundamental reservoir model used in well test analysis is showed on figure 2.1. It assumes that the reservoir is horizontal of uniform thickness and of infinite areal extent, it is also homogeneous, isothermal and isotropic. Further it is assumed that the reservoir fluid is in single phase condition and that the fluid flows according to Darcy's law (McWhorter and Sunada, 1977). The model includes a production well that fully penetrates the reservoir and an observation well at a distance from the producer. Prior to the well test, the reservoir pressures are assumed uniform.

During a well test, fluid is either discharged from or injected into the production well. This will create a time-dependent pressure changes in the reservoir, which are either monitored in the production well itself (single well test) or in the observation well (interference test). To fully describe a well test the following parameters must generally be monitored or estimated:

$t$ = time since well test started.
$Q(t)$ = the flow rate from (into) the well being tested.
$P(t)$ = the pressure in the monitoring well.
$r_w$ = the radius of the production well.
$r_1$ = the radial distance between the production and the observation well.
$\mu$ = the dynamic viscosity of the reservoir fluid,
$\rho$ = the density of the reservoir fluid.

The main parameters obtained in analysing well test data are: Transmissivity, $kh/\mu$, and storativity, $\phi ch$, where:

$k$ = (intrinsic) permeability of the reservoir
$\phi$ = porosity of the reservoir rocks
$c$ = compressibility
$h$ = reservoir thickness.

In the following the basic flow equations for the reservoir system on figure 2.1 will be discussed.

*2.2 Steady State Radial Flow Around a Well*

Assume that we have a steady state radial flow toward the production well in the reservoir model on figure 2.1. If the well flow rate, Q, is constant, Darcy's low can be written as (Sullivan and McKibbin 1989, Kjaran and Elíasson 1983, Grant et.al. 1982)

$$Q = A\,v = 2\pi r h\,K\,\frac{dl}{dr} \tag{2.1}$$

where A is a cross sectional area around the well at a distance r, K is hydraulic conductivity and dl/dr is the water level gradient towards the well. Note that the flow rate Q is negative for production and positive for injection.

The hydraulic conductivity K is related with the parameters defined in previous chapter as (Todd 1980)

$$K = \frac{kg\rho}{\mu} \tag{2.2}$$

Assume that there is an observation well at distance $r_1$ from producing well, with water level at $l_1$. Assume also that the water level in the producing well is at $l_w$. Then we can solve equation (2.1) by inserting equation (2.2) and by using the boundary conditions,

$$l(r_w) = l_w \qquad l(r_1) = l_1 \tag{2.3}$$

The solution is given by (O'Sullivan and McKibbin, 1989),

$$Q = 2\pi K\,h\,\frac{l_1 - l_w}{\ln\,(r_1/r_w)} \tag{2.4}$$

This equation is known as equilibrium or Thiem solution. From Thiem solution we can find the permeability thickness, kh, of an aquifer if the water level in two wells at distances $r_1$ and $r_2$ from the production well are known, namely:

$$kh = \frac{\mu Q}{2\pi\rho g(l_2 - l_1)}\,\ln\frac{r_2}{r_1} \tag{2.5}$$

When the permeability thickness is known, the water level l, in the reservoir can be described at any distance r, by the equation

$$l(r) = l_w + \frac{Q}{2\pi Kh}\,\ln\frac{r}{r_w} \tag{2.6}$$

*2.3 Theis Solution*

The diffusivity equation describes horizontal flow of a single-phase, slightly compressible fluid through a homogeneous and isotropic porous media (Ramey and Gringarten 1982. O'Sullivan and McKibbin 1989). The equation can be written as

$$\frac{\delta P}{\delta t} = D\left[\frac{\delta^2 P}{\delta r^2} + \frac{1}{r}\frac{\delta P}{\delta r}\right] \tag{2.7}$$

where D is the reservoir diffusivity, defined as

$$D = \frac{kh}{\mu}\frac{1}{\phi ch} = \frac{T}{S} \tag{2.8}$$

where T is called transmissivity and S storativity.

Here we make the assumption that k, $\mu$, $\rho$, $\phi$ and c are independent of pressure. The initial and boundary conditions can then be stated as follows

$$\begin{aligned} P(r,0) &= P_0 && \text{for } 0 \leq r \leq \infty \\ \lim_{r\to\infty} P(r,t) &= P_0 \\ Q &= -\frac{2\pi khr}{\mu}\frac{\delta P}{\delta r} && \text{at } r = r_w \end{aligned} \tag{2.9}$$

A solution to (2.7) is given by (O'Sullivan and McKibbin 1989)

$$P(r,t) - P_0 = \frac{Q\mu}{4\pi kh}\int_t^\infty \frac{e^{-u}}{u}du = \frac{Q}{4\pi T}\int_t^\infty \frac{e^{-u}}{u}du \tag{2.10}$$

where

$$u = \frac{S}{4T}\frac{r^2}{t}$$

Equation (2.10) is called the Theis solution to the diffusivity equation.

*2.4 Transmissivity*

The transmissivity parameter is a measure on how easily a fluid flows through a porous medium. It is defined as

$$T = \frac{kh}{\mu} \tag{2.11}$$

Transmissivity has the unit $m^3/Pa/s$. In chapter 3.1 we will introduce some well known methods in evaluating the transmissivity.

Note that the viscosity, $\mu$, is heavily dependent on temperature, specially at 0-100 °C. This can be seen on Figure 2.2 where the viscosity of water is plotted along with temperature. The figure shows that water viscosity decreases by almost factor 10 if temperature is raised from 5-200 °C. It is therefore important to take the temperature of the reservoir fluid into account, when transmissivity of two or more reservoirs is compared.

*2.5 Storativity*

Storativity of confined reservoirs defines the quantity of fluid the rock matrix will yield if fluid pressure is slightly reduced. The fluid is released from the rock matrix by two means;

1. Fluid in pores is compressed and expands with reduced fluid pressure. If the pore volume remains constant some fluid has to escape.

2. Pore fluid carries some fraction of the overburden weight. If pore pressure is reduced, the rock will deform a little and reduce its pore volume, hence release some fluid.

These two effects are often described by a lumped parameter called compressibility, c

$$c = \frac{\Delta V/V}{\Delta P} \qquad \text{at constant temperature} \tag{2.14}$$

where V is a unit volume of saturated rock, and $\Delta V$ denotes the volume change due to a pressure change $\Delta P$.

Well testing analysis do not determine the compressibility of a reservoir, but instead a lumped parameter of compressibility, porosity and reservoir thickness. This parameter is called storativity and is defined by

$$S = \phi ch \tag{2.15}$$

Storativity has the unit m/Pa. It means physically the volume of fluid stored/released per unit area of reservoir per unit pressure change.

*2.6 Skin Factor*

There are often local changes in reservoir properties close to a well. These changes are described with a parameter called "skin factor". The skin effect may result from drilling operation such as mud damage or mud cake around wellface, or from fractures intersecting the well. Skin effect can be described with an additional pressure drop in the wellface. The pressure drop $\Delta P_s$ due to the skin effect is often defined as;

$$\Delta P_s = \frac{Q\mu}{2\pi kh} s \qquad (2.16)$$

where s is a dimensionless skin factor.

The total pressure drop in a aquifer is then defined by equations (2.10) and (2.16) as;

$$P(r,t)_{total} = P_{Theis} + P_{skin} = \frac{Q\mu}{4\pi kh} \left[ \int_t^{\infty} \frac{e^{-u}}{u} du + 2\,s \right] \qquad (2.17)$$

Positive skin indicates lower wellface permeability than in the reservoir. This means that greater wellbore drawdown is required in order to produce the same amount of fluid than if the skin is zero. On the other hand, negative skin means less drawdown in a well than if the skin is zero. Negative skin is often caused by fracture flow into the well.

## *3. WELL TEST ANALYSIS*

In the following we will introduce few well known methods of analysing well test data. The methods are all based on the Theis solution to the diffusivity equation.

### *3.1 Semilog Plot*

Equation (2.10) can be expanded as a convergent series (Todd 1980)

$$P(r,t) = \frac{Q}{4\pi T}\left[-0.5772 - \ln u + u - \frac{u^2}{2\,2!} + \frac{u^3}{3\,3!} \ldots\right] \tag{3.1}$$

If r small and t is large, the value of u become negligible. In that case equation (3.1) can be written as,

$$P(r,t) = \frac{Q}{4\pi T}\left[-0.5772 - \ln\frac{r^2S}{4Tt}\right] \tag{3.2a}$$

or if we prefer $\log_{10}$ basis for the logarithm

$$P(r,t) = \frac{2.30\,Q}{4\pi T}\log\frac{2.25\,Tt}{r^2S} = m\log\frac{2.25\,Tt}{r^2S} \tag{3.2b}$$

If we plot the drawdown, P as a function of the logarithm of time, we find a straight line of slope m. This line can be used to determine transmissivity and storativity of the reservoir.

If we read the change in pressure during one log-cycle ($\Delta P_{10}$) from such a graph, then we have that (Todd 1980);

$$\Delta P_{10} = \frac{2.30\,Q}{4\pi T} = m \tag{3.3}$$

This equation can then be solved for the transmissivity T.

Furthermore, if we read the time $t_0$ where $P = 0$, equation (3.2) can be rearranged to give

$$S = \frac{2.25Tt_0}{r^2} \tag{3.4}$$

and the storativity can be calculated.

This method is generally called the Cooper-Jacob method of solution (Todd 1980).

If one wants to include the skin effect into this solution algorithm, equation (2.17) can be rearranged and solved for the skin factor (O'Sullivan and McKibbin, 1989)

$$s = 1.151\left[\frac{\Delta P}{m} - \log\left(\frac{kt}{\phi\mu c r_w^2}\right) - 0.351\right] \tag{3.5}$$

where $\Delta P$ is the pressure change at time t from initial production/discharge.

*3.2 Horner Plot Method*

When a well is shut down after a steady production Q, at time $\hat{t}$, the water level recovers to the initial water level prior to pumping. This recovery can be imagined as another hypothetical well at pumping rate -Q, which is superposed on the other at $t = \hat{t}$. By using equation (3.2), we known that at $t < \hat{t}$,

$$P(r,t) = \frac{2.3Q}{4\pi T} \log\frac{2.25\,Tt}{r^2S} \tag{3.6}$$

And when the well is shut off, the pressure can be defined by the two terms (Todd D.K., 1980)

$$\begin{aligned} P(r,t) &= P(r,t+\hat{t})_{\text{flow}=Q} + P(r,\hat{t})_{\text{flow}=-Q} \\ &= \frac{2.30Q}{4\pi T} \log \frac{t+\hat{t}}{\hat{t}} \end{aligned} \tag{3.7}$$

If we plot the pressure recovery as a function of $\log((t + \hat{t})/t)$, we get a straight line. By measuring the pressure change $\Delta P_{10}$ over one log cycle, we have by (3.6) that

$$T = \frac{2.30Q}{4\pi\Delta P_{10}} \tag{3.8}$$

*3.3 The Varflow Computer Program*

The semi-log and Horner plot analysis methods, often become complicated if there are many wells producing at varying flow rates from a reservoir. There are several computer programs existing, which are able to solve equations (2.10) or (2.17) for such conditions. One such program is called Varflow. It is developed at the Lawrence Berkeley Laboratory in California. Both the program and a complete users manual are published in a report (EG&G Idaho Inc. and Lawrence Berkeley Laboratory, 1982). The program code is available at Orkustofnun, and is runable on a PC-computer. This program was used to analyse the completion test data discussed in this report. A detailed description of the program will not be given, but an example of input and output files is shown in Appendix A.

The main advantage of using Varflow, is that it is compilable and runable on a PC-computer. This means that the program can be transferred with the author back to Indonesia and used there for further flow tests analysis. Another possibility in the training schedule, was to use programs existing on the Orkustofnun main-frame computer system. But since these programs are developed for the Orkustofnun hardware environment, it requires severe work to install them on other different computer systems. Therefore, all the well test analysis and plotting were performed in the PC-environment using the Varflow.

## *4. ANALYSIS OF WELLS TEST DATA*

It is customary to conduct a injection test after final completion of a geothermal well, and also sometimes after repairing or cleaning a well. The type of testing is determined by the drilling method used, availability of water for injection and degree of permeable zones encountered.

The most common procedure in injection and fall-off tests, is to inject cold water into the well at varying flow rates. The flowrate is generally increased in steps, and kept constant within each step. During pumping, pressure is measured at some constant depth, often close to zones of significant water losses.

The objective of injection and fall-off tests, is to determine some reservoir properties around a well, such as transmissivity, skin and storativity. The results of injection and fall-off tests then indicate the quality of the well; weather it will become a poor or a good producer.

In this chapter, results of pumping tests from 4 geothermal wells are presented. The wells discussed are wells KMJ-42, 43 and 45 in the Kamojang field in Indonesia, and well KJ-13 in Krafla, Iceland. A standard procedure was followed in the interpretation of the pressure data, namely:

1. Data plotted along with flow rate but obscurities omitted from it.

2. Data for each injection step plotted on a semi-log graph, such that the initial time and pressure are taken at the time when the flow was increased or decreased. This assumes that the well has established a quasi-steady state condition at the end of each flow step. Then storativity and transmissivity were computed by equations (3.3) and (3.4) in chapter 3.1.

3. Data for the recovery plotted by Horner plot method presented in chapter 3.2. Then the transmissivity was computed by equation (3.8).

4. When the approximate values of transmissivity and storativity were known, the Varflow computer program (see chapter 3.3) was used to compute the pressure response for the total flow history of the test. Then the values of transmissivity, storativity and skin were modified until reasonable match was obtained between measured and computed pressure.

5. When the results of terms 2-4 were at hand, a Orkustofnun main-frame iterative computer program was used to analyse the well test data. The program takes into

account the final radius of the production well. This should give more accurate results for well test data sampled in production wells, as are discussed in this chapter.

The well test data discussed in this report are published in Indonesian and Icelandic reports. Figure 4.1 shows location of wells in the Kamojang field, and Figure 4.2 shows location of wells in the Krafla field.

*4.1 Well KMJ-42, Indonesia*

Well KMJ-42 is an exploitation well, located at the western part of the Kamojang field (Figure 4.1). It was completed on April 1985 to a depth of 1476 m. The well was cased with 9 5/8" production casing to 795 m, and with a slotted liner to 1427 m (Pertamina III, 1985a).

An injection and fall-off test started on April 11, 1985 with a pressure gauge (Kuster) being lowered to 1350 m depth. Initial pressure at that depth was 36 $kg/cm^2$. Before the test, water was pumped into the well at a constant rate of 600 l/m for 240 minutes. In the next step the flow rate was increased to 880 l/m for 25 minutes, then to 1320 l/m for 25 minutes and finally to 1617 l/m for 55 minutes. After shut-down, the pressure recovery was recorded for 186 minutes (Pertamina III, 1985a).

The pressure and flow history of the injection test of well KMJ-42 is shown on figure 4.3. The pressure records start close to the end of the first injection step. During the next two steps the pressure increases but no pressure stabilization is seen due to the short duration of the steps. The maximum flow rate was however maintained for much longer time and pressure was fairly stable when pumping was stopped. The pressures recovered fast when injection was stopped. Some irregularities are however seen in the fall-off curve. For example the pressure increased for a while about 100 minutes after injection was stopped. The pressure increase is probably due heat recovery, and might mark the time when cross-flow starts in the well.

The injection test data from well KMJ-42 was analysed with semi-log and Horner plots, and with Varflow and Orkustofnun computer programs. Figures 4.4 and 4.5 show the curves that were chosen in the semi-log and Horner plot analysis. The curves show linear trends, but some deviations are seen, especially for the short flow steps and the fall-off. The best matches with the pressure history using the computer programs are shown on figures 4.6 and 4.7. The matches are reasonably good but not perfect. Pressure is not matched at the end of the initial step, and the pressure increase during the fall-off, can of course not be matched. The pressure stabilization during the maximum injection is also hard to match.

The reservoir parameters for well KMJ-42 calculated from the analyses are summarized in table 4.1. Transmissivity values vary between 0.5 - 2.6x$10^{-8}$ $m^3/Pa/s$. Taking into account the scattering of the data and the short duration of flow steps, the best estimate for the transmissivity is considered the Varflow value. The transmissivity of well KMJ-42 is therefore expected to be in the range of 1.5x$10^{-8}$$m^3/Pa/s$. The storativity estimates vary between $10^{-4}$ - $10^{-7}$ m/Pa, with the main frame value by far the lowest. The pressure stabilization during the maximum injection indicates very high storativity. It is therefore estimated that the storativity of well KMJ-42 is of the order of $10^{-4}$ - $10^{-5}$ m/Pa. This is several orders of magnitude higher than expected for a liquid dominated reservoir, which is not surprising as Kamojang is a vapor-dominated system. The computer analyses yield a negative skin factor (-2 and -2.5). Negative skin is generally explained with fracture flow into the well.

**Table 4.1:** Some calculated reservoir properties of well KMJ-42.

| Analysis method | Total Flow ($m^3/s$) | Change in flow ($m^3/s$) | $kh/\mu$ ($m^3/Pa/s$) | $\phi ch$ (m/Pa) | Skin | Figure number | Curve number |
|---|---|---|---|---|---|---|---|
| Semi-log | 0.010 | 0.010 | 0.6x$10^{-8}$ | 4.1x$10^{-4}$ | | 4.4 | 1 |
| | 0.015 | 0.005 | 2.6x$10^{-8}$ | 1.1x$10^{-4}$ | | 4.4 | 2 |
| | 0.022 | 0.007 | 0.6x$10^{-8}$ | 1.0x$10^{-4}$ | | 4.4 | 3 |
| | 0.027 | 0.005 | 1.4x$10^{-8}$ | 0.3x$10^{-4}$ | | 4.4 | 4 |
| | 0.000 | -0.027 | 0.5x$10^{-8}$ | 17 x$10^{-4}$ | | 4.4 | 5 |
| Horner | 0.000 | -0.027 | 0.5x$10^{-8}$ | | | 4.5 | |
| Varflow | | | 1.7x$10^{-8}$ | 1.0x$10^{-4}$ | -2.5 | 4.6 | |
| Main Frame | | | 0.7x$10^{-8}$ | 3.6x$10^{-7}$ | -2.5 | 4.7 | |

*4.2 Well KMJ-43, Indonesia*

Well KMJ-43 was drilled as an exploitation well. It is located at the center part of the Kamojang field (Figure 4.1). Drilling was started on April 1985 and completed on May 1985. The total depth of the well is 1523 m. It was completed with a 9 5/8" production casing to 728 m and 7" slotted liner to 1156 m (Pertamina III, 1985b).

An injection and fall-off test was undertaken in May 1985 with a Kuster pressure gauge placed at 1020 m in the well. Initial pressure was 42 $kg/cm^2$. In the first flow step, water was injected at 800 l/m for 366 minutes. In the second injection step, flow rate was increased to 1000 l/m for 30 minutes, then to 1400 l/m for 6 minutes, then reduced to 1200 l/m for 18 minutes, and finally increased to 1500 l/m for 57 minutes. Pressure recovery after shut-down was measured for 91 minute (Pertamina III, 1985b).

The pressure and flow history of the injection test of well KMJ-43 is shown on figure 4.8. Pressure recording starts at the end of the first injection step. The subsequent steps are of very short duration. Only a slight pressure increase is observed and it is difficult to distinguish between the individual injection steps in the pressure response. Some irregularities are seen early in the fall-off curve.

The injection test data from well KMJ-43 is of a poor quality, mainly due to the short duration of the injection steps. All interpretation results will therefore be highly unaccurate. The data was analysed with semi-log and Horner plots, and with Varflow and Orkustofnun computer programs. Figures 4.9 and 4.10 show the curves that were chosen in the semi-log and Horner plot analysis. The pressure increase for each step is close to linear on the semi-log plots but the fall-off curve is far from linear. The best matches with the pressure history using computer programs are shown on figures 4.11 and 4.12. The matches are very poor and they only simulate the general trends in the pressure data.

The reservoir parameters calculated from the injection data are summarized in table 4.3. The calculated values differ greatly for the different analysing methods, and the main conclusion must be that the injection data from well KMJ-43 is not interpretable.

### *4.3 Well KMJ-45, Indonesia*

Well KMJ-45 is an exploitation well. It was drilled from October to December 1986 to a depth of 1489 m. The well is located at the southern part of the Kamojang field (Figure 4.1). The well was completed with 9 5/8" production casing down to 902 m depth, and a 7" liner to 1472 m (Pertamina III, 1986).

An injection and fall-off test was carried out on December 13, 1986. A Kuster pressure gauge was positioned at 1375 m depth. Initial pressure was 37 $kg/cm^2$. Prior to the pressure recording, water was pumped into the well at 600 l/m flowrate for 660 minutes. In the next step, injection was increased to 900 l/m for 55 minutes, then to 1200 l/m for 55 minutes, and finally to 1500 l/m for 175 minutes. After shut-in, pressure recovery was measured for 300 minutes (Pertamina III, 1986).

**Table 4.2:** Some calculated reservoir properties of well KMJ-43.

| Analysis method | Total Flow ($m^3/s$) | Change in flow ($m^3/s$) | kh/$\mu$ ($m^3/Pa/s$) | $\phi$ch (m/Pa) | Skin | Figure number | Curve number |
|---|---|---|---|---|---|---|---|
| Semi-log | 0.013 | 0.013 | $0.4x10^{-8}$ | $35x10^{-4}$ | | 4.9 | 1 |
| | 0.017 | 0.004 | $0.6x10^{-8}$ | $1.1x10^{-4}$ | | 4.9 | 2 |
| | 0.023 | 0.006 | $2.1x10^{-8}$ | $11 x10^{-4}$ | | 4.9 | 3 |
| | 0.020 | -0.003 | $34 x10^{-8}$ | $311x10^{-4}$ | | 4.9 | |
| | 0.025 | 0.005 | $114x10^{-8}$ | $19 x10^{-4}$ | | 4.9 | |
| | 0.000 | -0.025 | $0.2x10^{-8}$ | $5.8x10^{-4}$ | | 4.9 | 4 |
| Horner | 0.000 | -0.025 | $0.3x10^{-8}$ | | | 4.10 | |
| Varflow | | | $2.2x10^{-8}$ | $1.5x10^{-4}$ | -2. | 4.11 | |
| Main Frame | | | $0.9x10^{-8}$ | $2.9x10^{-7}$ | -2.7 | 4.12 | |

The pressure and the flow history of the injection test of well KMJ-45 is shown on figure 4.13. The pressure records start close to the end of the first step. The data was analysed with semi-log and Horner plots, and with pressure history matching. Figure 4.14 shows the semi-log plots. The pressure steps are fairly linear on the semi-log scale but the fall-off curve shows a stable pressure in the well the first few minutes after pumping was stopped. This can not be explained unless there has been an offset between the clock in the Kuster pressure gauge and the clock used for the flow data. The data indicates that the offset is about 5 minutes. The fall-off data was corrected for the time offset and then a Horner plot drawn. The plot is shown on figure 4.15. The best pressure history matches are shown on figures 4.16 and 4.17. An excellent match was obtained with the Varflow (figure 4.16), but the main fraim match could have been improved if a higher storativity value had been chosen. (figure 4.17).

The reservoir parameters calculated for well KMJ-45 are summarized in table 4.3. The injection steps lead to a relatively low transmissivity values, but based on the Horner plot and the Varflow matching the true transmissivity value for KMJ-45 is estimated to be $7x10^{-8}$ $m^3/Pa/s$. The different methods show all very high storativity values except the main-frame simulation. The poor matching with the main-frame program indicates that to low storativity was used in the matching. Therefore it is concluded that the storativity of well

**Table 4.3:** Some calculated reservoir properties of well KMJ-45.

| Analysis method | Total Flow ($m^3/s$) | Change in flow ($m^3/s$) | kh/$\mu$ ($m^3/Pa/s$) | $\phi$ch (m/Pa) | Skin | Figure number | Curve number |
|---|---|---|---|---|---|---|---|
| Semi-log | 0.010 | 0.010 | $0.7x10^{-8}$ | $0.5x10^{-4}$ | | 4.14 | 1 |
| | 0.015 | 0.005 | $3.0x10^{-8}$ | $0.2x10^{-4}$ | | 4.14 | 2 |
| | 0.020 | 0.005 | $0.9x10^{-8}$ | $4.1x10^{-4}$ | | 4.14 | 3 |
| | 0.025 | 0.005 | $0.5x10^{-8}$ | $1.7x10^{-4}$ | | 4.14 | 4 |
| | 0.000 | -0.025 | $1.0x10^{-8}$ | $1.3x10^{-4}$ | | 4.14 | 5 |
| Horner | 0.000 | -0.025 | $7.6x10^{-8}$ | | | 4.15 | |
| Varflow | | | $7.2x10^{-8}$ | $2.1x10^{-4}$ | -1.6 | 4.16 | |
| Main Frame | | | $3.0x10^{-8}$ | $9.1x10^{-7}$ | -2.8 | 4.17 | |

KMJ-45 is of the order of $10^{-4}$m/Pa. Negative skin in the Varflow match indicates fracture flow in the vicinity of the well.

*4.4 Well KJ-13, Iceland*

Krafla geothermal field is located in the NE-Iceland, about 10 km northeast of Lake Mývatn. Well KJ-13 is one of several wells in the Krafla field (Figure 4.2). It was initially drilled in 1980 to a depth of 2050 m. The well was completed with a 9 5/8" production casing to 1065 m and a 7" slotted liner to the bottom of the well. The well was not a good producer. In 1983 it was decided to perform a directional drilling (side track) in the well KJ-13. Drilling operation began in July 1983, when the old production casing was opened at 880 m depth and a new directional well drilled to the east. The objective of this directional drilling was to intersect the Hveragil gully, which is a believed to be an upflow zone between the upper and the lower part of Krafla reservoir (Bodvarsson et.al. 1982, Ármannson et.al. 1987). The drilling was successful and the well produced over 10 kg/s of high pressure steam for the first weeks of discharge but declined then in a few months to a flow rate of 3-4 kg/s of steam. Well logging indicated that scaling was the main reason for the reduced flow rate (Gudmundsson et.al., 1989).

A rig cleaned the well in June 1989. When cleaning was completed, an injection test was conducted in the well. An electronic pressure gauge was lowered to a depth of 880 m and the pressure then recorded continuously at surface. Water was pumped into the well during drilling at 20 l/sec, then the flow was increased to 30.8 l/sec, then decreased to 19.4 l/sec and finally shut off (Gudmundsson et.al., 1989).

The pressure and flow history of the injection test of well KJ-13 is shown on figure 4.18. The pressure records start just before the flow was increased from 20 l/s to 30.8 l/s. The 20 l/s pump rate had been maintained constant for several hours. The pressure records show clearly a step like response to the different injection steps, with few non-theoretical deviations. The pressure is, for instance, decreasing at the end of the first step and some pressure transients are seen at the beginning of the second and the third step. The last effects are believed to be caused by transients in the injection rates, whereas the decreasing pressures at the beginning of the pressure curve are due to temperature stabilization of the pressure gauge, and therefore not real pressure changes.

The injection test data from well KJ-13 was analysed with semi-log and Horner plots, and with pressure history matching. Figures 4.19 and 4.20 show the semi-log and Horner plots. All the curves show linear trends. The best match with the pressure history using the Varflow code is shown on figure 4.21. The match is reasonably good. The main discrepancy is that the program does not match the final pressures during the fall-off and it does of course not match the non-theoretical behavior at the beginning of the second and the third step.

The reservoir parameters for well KJ-13 calculated from the well test analysis are summarized in table 4.4. The semi-log and the Horner plots give transmissivity values close to $1x10^{-8}$ $m^3/Pa/s$ whereas the pressure history matches give three to four times lower values. The true values are believed to be within this range, but probably closer to the pressure history values or of order of $2.5\text{-}3x10^{-8}$ $m^3/Pa/s$. The storativity values are in the range of $10^{-5}$ - $10^{-6}$ m/Pa or somewhat higher than the values for the wells in Kamojang. The well has a negative skin indicating fracture flow between the well and the reservoir.

**Table 4.4:** Some calculated reservoir properties of well KJ-13

| Analysis method | Total Flow ($m^3/s$) | Change in flow ($m^3/s$) | $kh/\mu$ ($m^3/Pa/s$) | $\phi ch$ ($m/Pa$) | Skin | Figure number | Curve number |
|---|---|---|---|---|---|---|---|
| Semi-log | 0.031 | 0.011 | $0.9x10^{-8}$ | $7.3x10^{-5}$ | | 4.19 | 1 |
| | 0.019 | -0.012 | $1.0x10^{-8}$ | $4.7x10^{-5}$ | | 4.19 | 2 |
| | 0.0 | -0.019 | $0.9x10^{-8}$ | $7.3x10^{-5}$ | | 4.19 | 3 |
| Horner | | -0.012 | $1.2x10^{-8}$ | | | 4.20 | |
| Horner | | -0.019 | $0.6x10^{-8}$ | | | 4.20 | |
| Varflow | | | $3.9x10^{-8}$ | $0.2x10^{-5}$ | -2 | 4.21 | |
| Orkustofnun*) | | | $3.4x10^{-8}$ | | -2.5 | | |

*) *From Gudmundsson et.al., 1989.*

## *5. DISCUSSION AND CONCLUSIONS*

The methods used in this report to analyse well test data are all based on a very simplified reservoir model. The results should therefore be viewed with that in mind. All the methods give similar transmissivity values for the wells. The scattering between the different methods is partly due to different execution of the well tests. The data from Kamojang could be improved if injection steps of longer duration were applied and if more accurate pressure gauges were used, both with respect to the pressure values and the time determinations. It is, for instance, obvious in the data from well KMJ-45 that a time offset of 5 minutes was between the Kuster clock and the clock used for the injection steps. Some of the data also indicates transients in the injection rates at times when the rates are supposed to be constant.

The data analysis give high storativity values, especially for the wells in Kamojang. Storativity determinations from injection test data are not considered very accurate. Storativity is generally determined from interference test where the pressure response is monitored in an observation well at some distance from the well being produced or injected. The storativity determined from single-well test are therefore only indicative for the true storativity. The high storativity values for the wells in Kamojang wells are believed to be real, and due to the fact that Kamojang is a vapor dominated reservoir. High storativity for KJ-13 can also be explained by two phase conditions in the Krafla reservoir close to the well.

The Kamojang and the Krafla reservoir are both fractured reservoirs as most geothermal systems in the world. This can be seen from the well test analysis as negative skin values. The pressure data from the wells considered in this work could not be matched unless assuming a negative skin. This also shows that the assumption of the reservoir being a porous medium is not totally correct. Further limitations of the model for use in geothermal applications are assumptions such as it being isothermal and isotropic. Despite of these shortcomings of the model it has been successfully applied for many years in geothermal well test analysis in predicting transmissivity values for reservoir/well systems.

The main conclusions of the work described in this report are:

1. The transmissivity of the Kamojang and Krafla wells is of the order of $10^{-8}$ $m^3/Pa/s$.

2. Estimated storativity for the wells is of the order of $10^{-4}$ m/Pa for the wells in Kamojang and of the order of $10^{-6}$ m/Pa for the well in Krafla. Storativity is not determined very accurately from single-well test. It is however believed that the high storativity in Kamojang is real and due to the fact that the system is vapor dominated.

3. The wells have negative skin values. Fracture feeds are therefore dominant in the wells. This is not surprising as both Kamojang and Krafla are fractured reservoirs.

4. The well test data used in this report would have lead to more accurate analysis if a different approach had been used during the well tests. Minimal flow step duration should be 1-1.5 hours per step. The data from well KMJ-43 suffers especially due to short duration steps. The pressure gauge should be positioned as close to the main feed zone as possible, in order to minimize thermal effects in the recorded pressure curve.

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Finally, my thanks to the 1989 UNU fellows for their understanding and companionship during my stay in Iceland.

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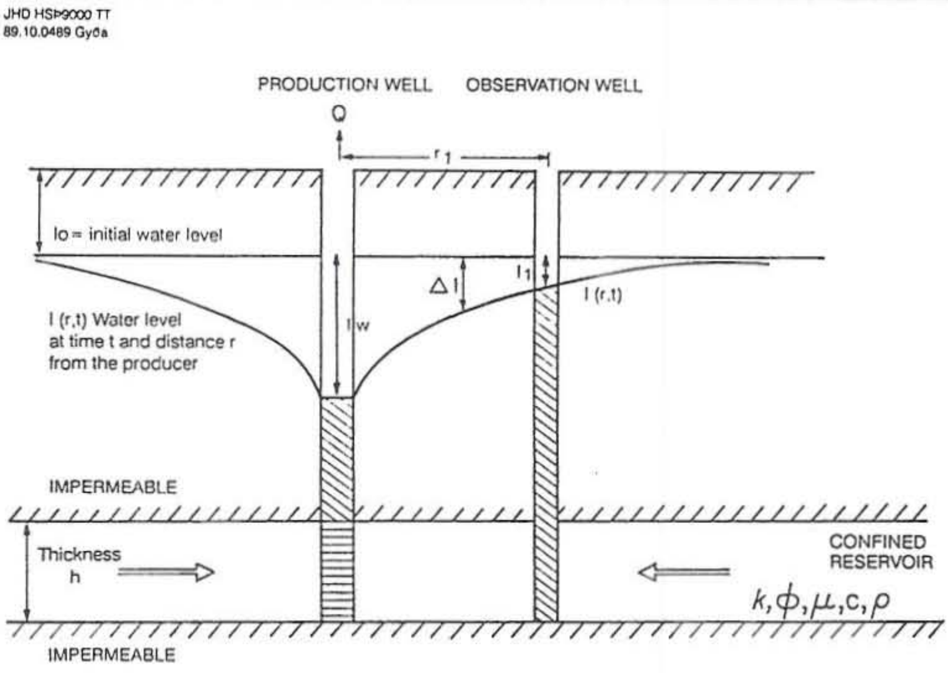


FIG 2.1 A SIMPLIFIED MODEL OF A CONFINED RESERVOIR.

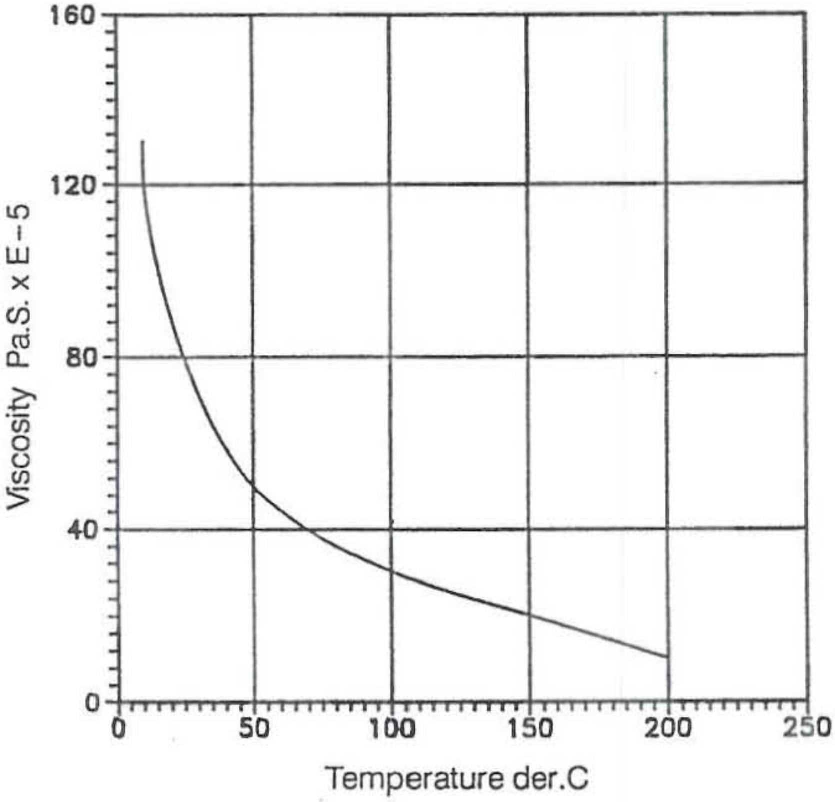


Fig. 2.2 Dynamic viscosity of water as
a function of temperature

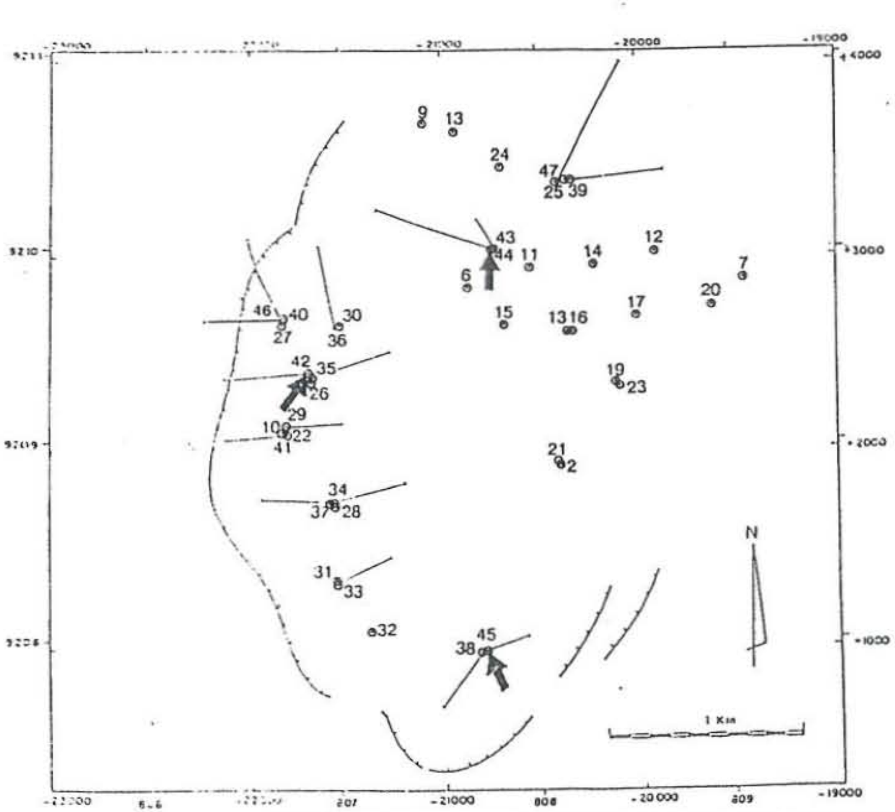


Fig. 4.1 Location of wells in the Kamojang field, Indonesia

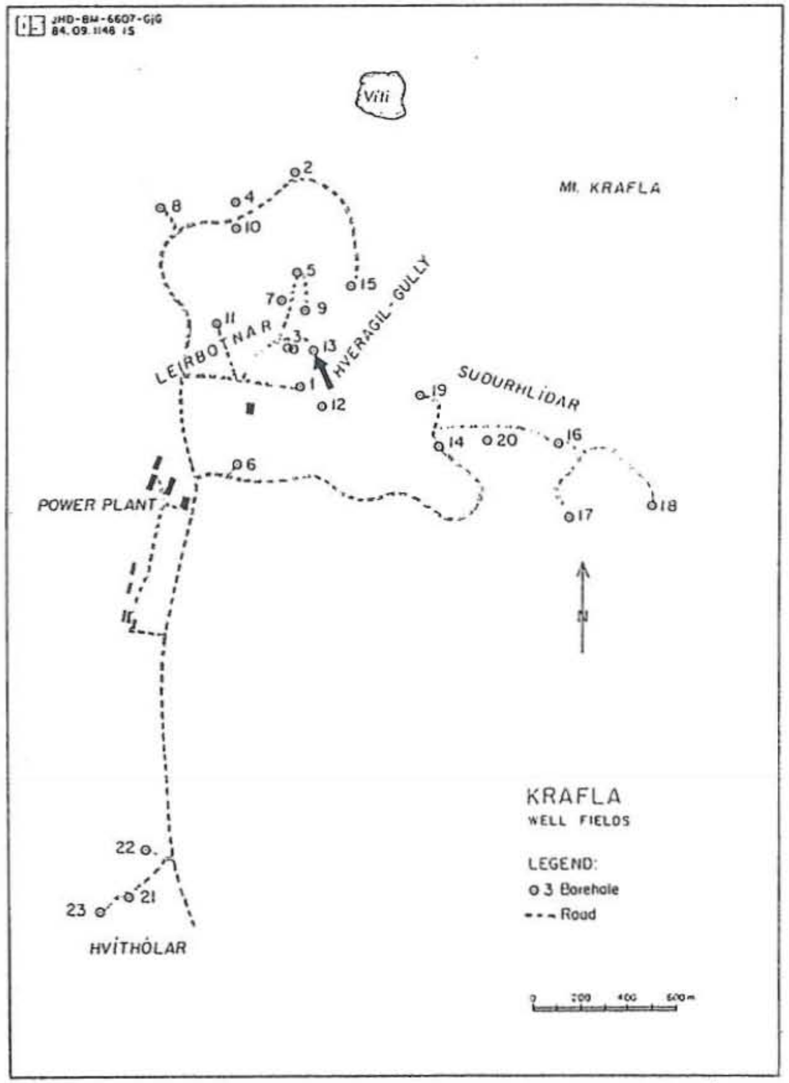


Fig. 4.2 Location of wells in the Krafla field, Iceland

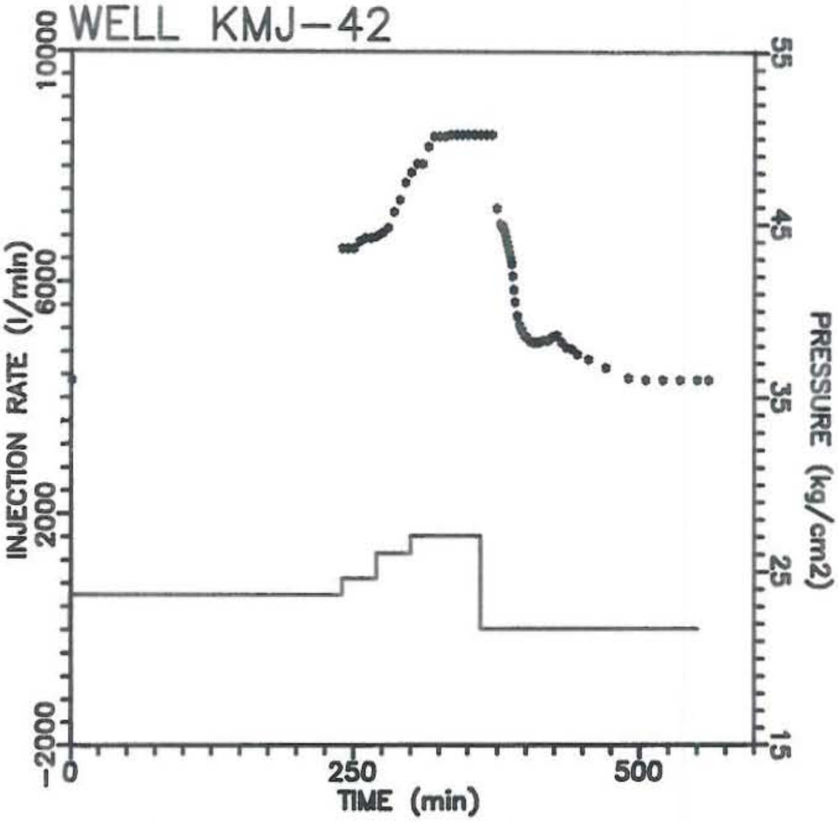


Fig.4.3 Pressure and flow data for the injection test of well KMJ-42, Indonesia

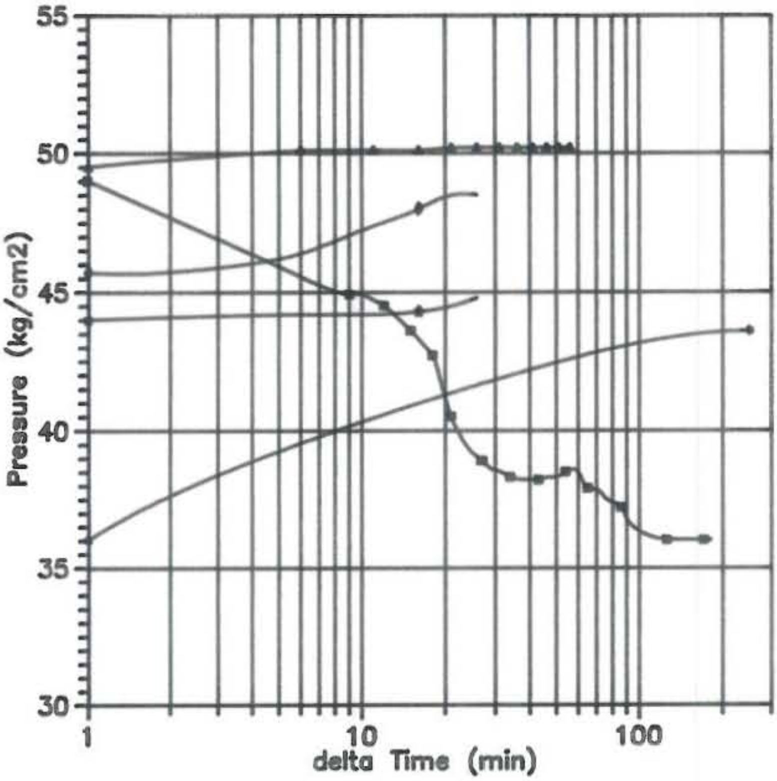


Fig.4.4 Semi-log curves for the flow test of well KMJ-42

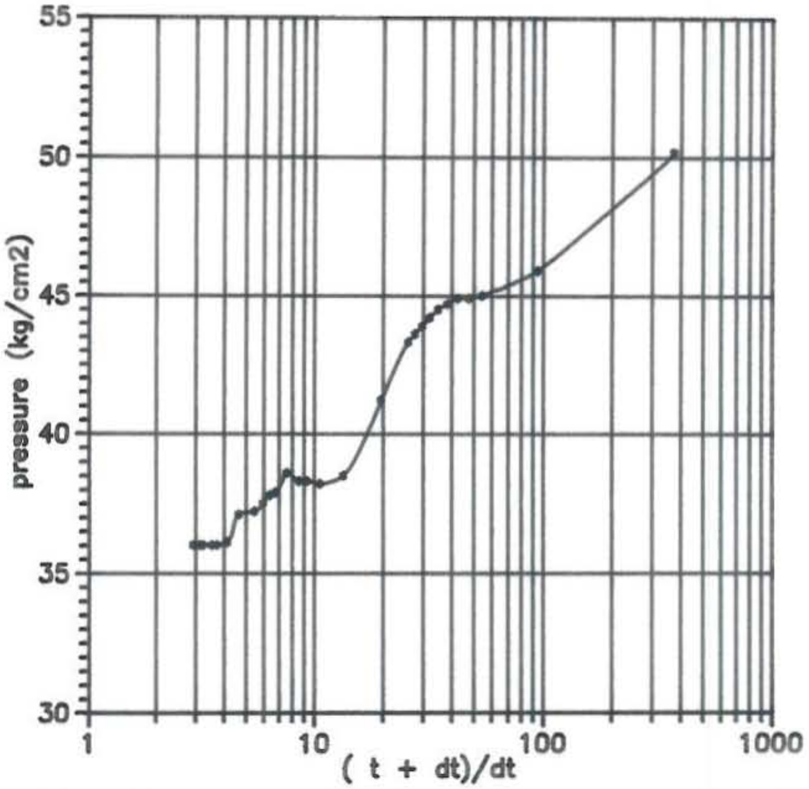


Fig.4.5 Horner plot for recovery of well KMJ-42 after injection

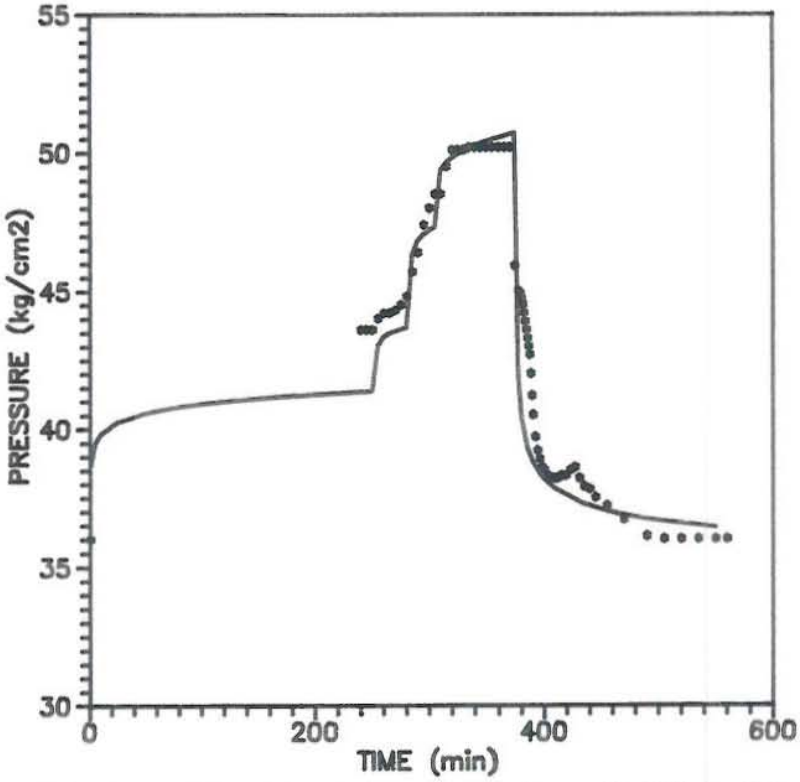


Fig.4.6 Calculated pressure in well KMJ-42 by Varflow

# Well KMJ-42

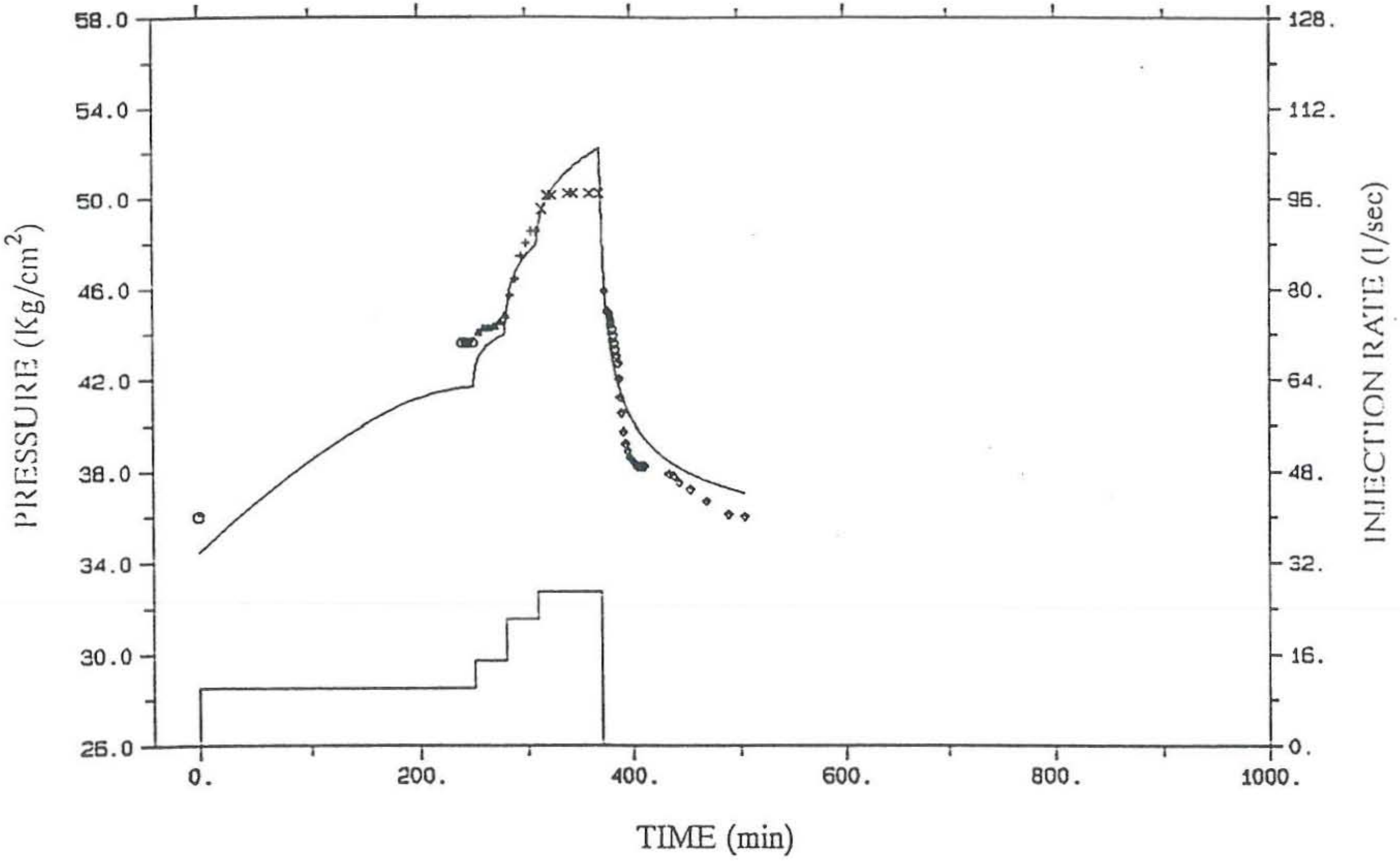


Fig. 4.7 Calculated pressure in well KMJ-42 by ORKUSTOFNUN program

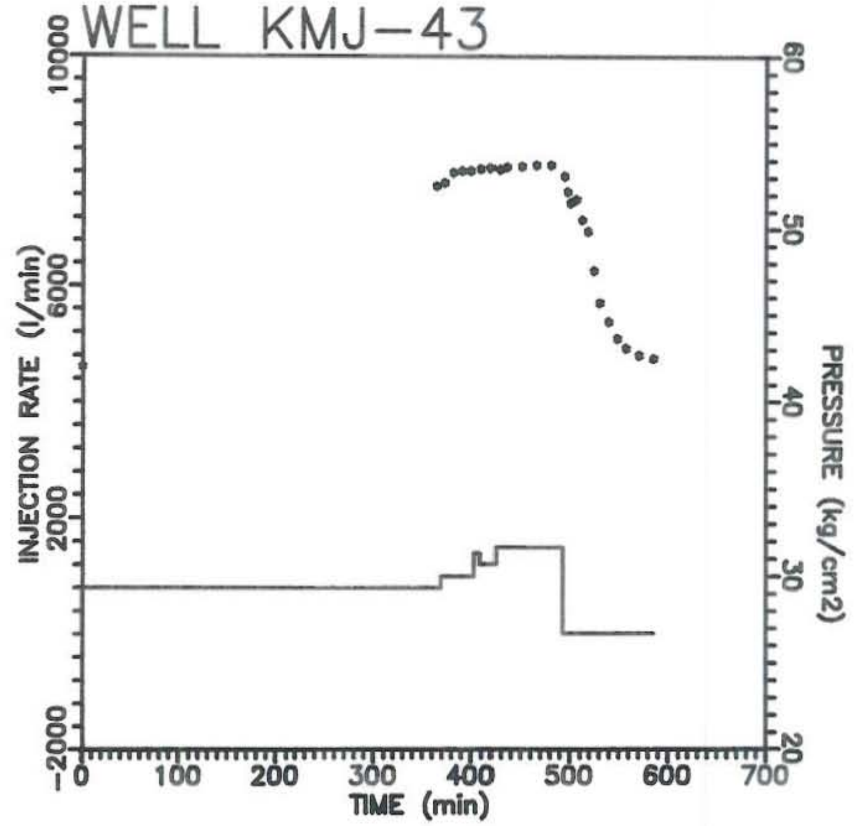


Fig.4.8 Pressure and flow data for the injection test of well KMJ-43

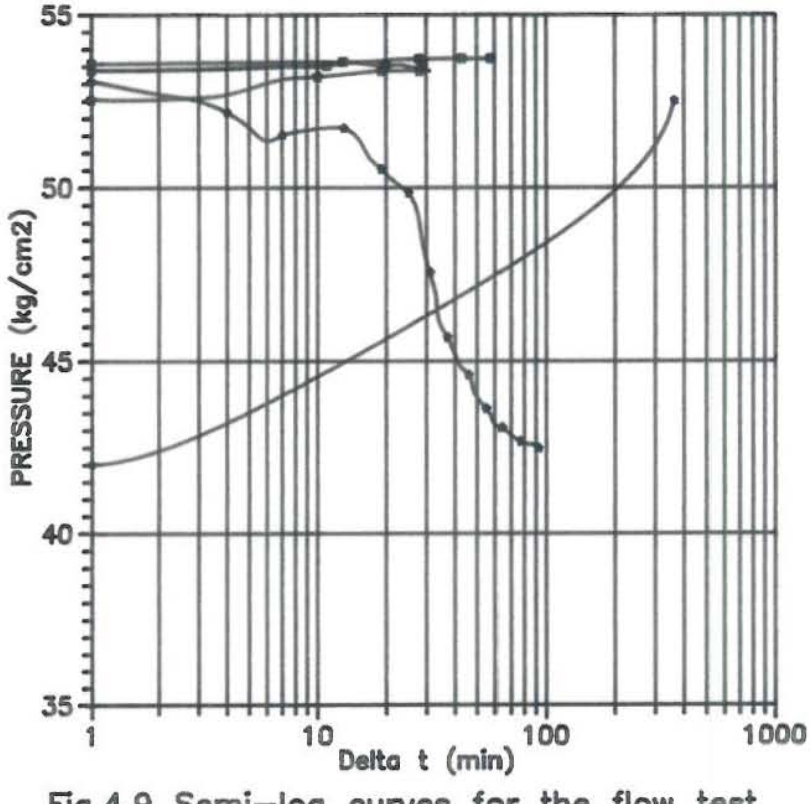


Fig.4.9 Semi-log curves for the flow test of well KMJ-43

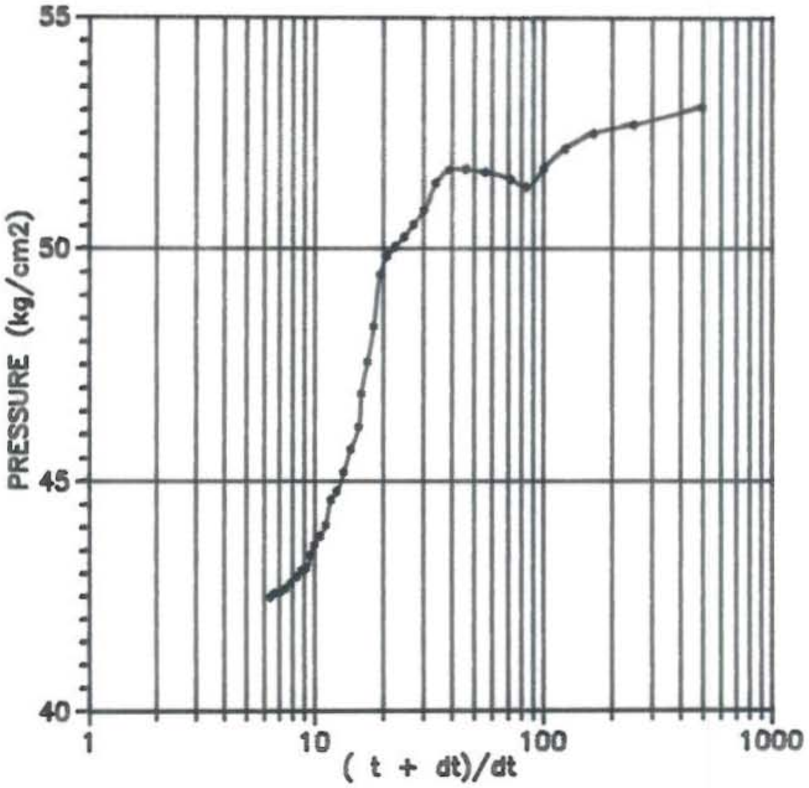


Fig.4.10 Horner plot for recovery of well KMJ–43 after injection

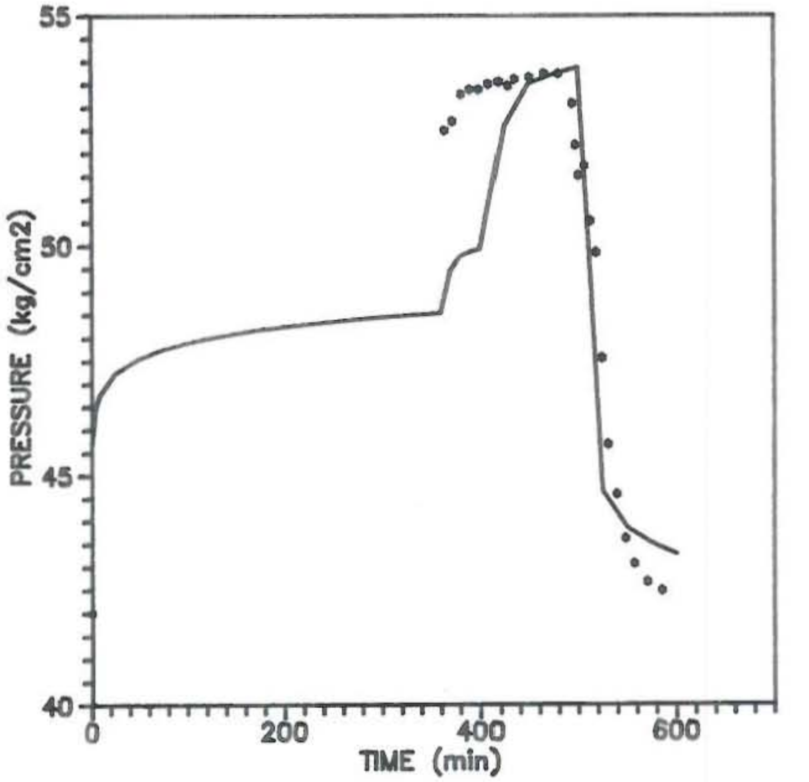


Fig.4.11 Calculated pressure in well KMJ–43 by Varflow

# Well KMJ-43

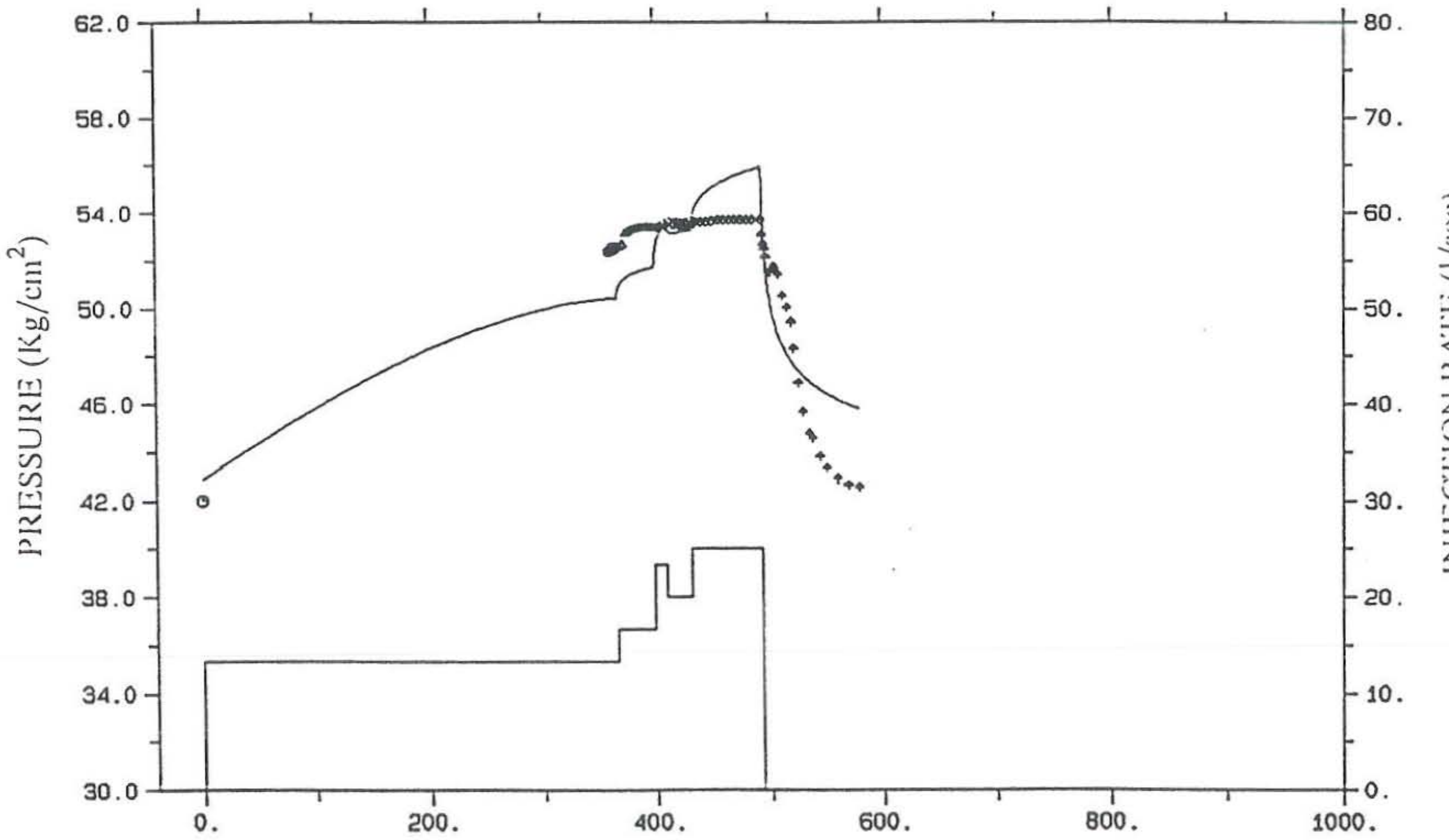


Fig. 4.12 Calculated pressure in well KMJ-43 by ORKUSTOFNUN program

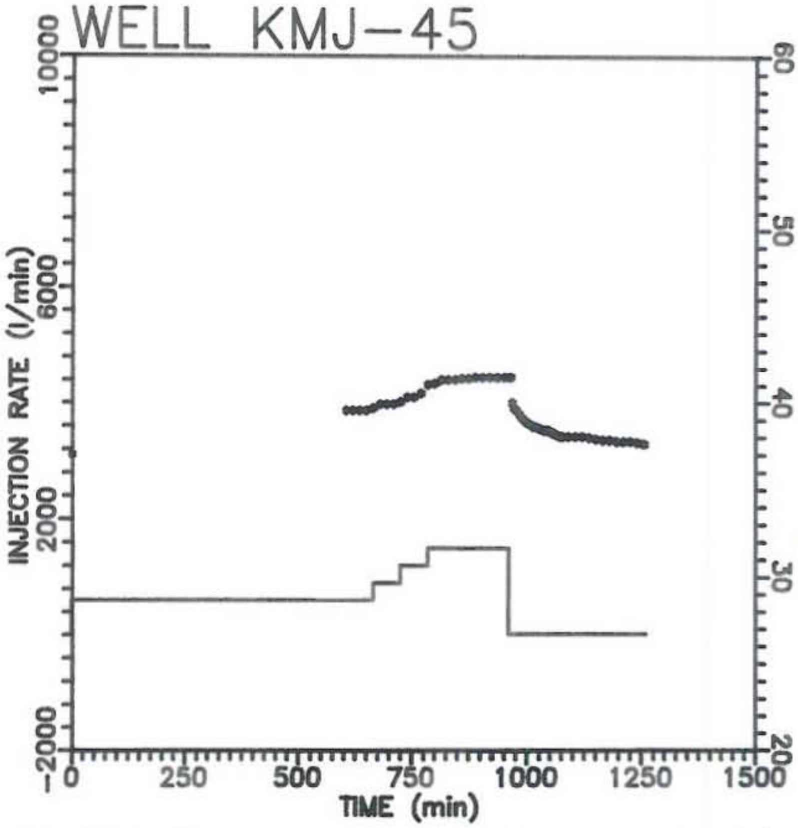


Fig.4.13 Pressure and flow data for the injection test of well KMJ-45

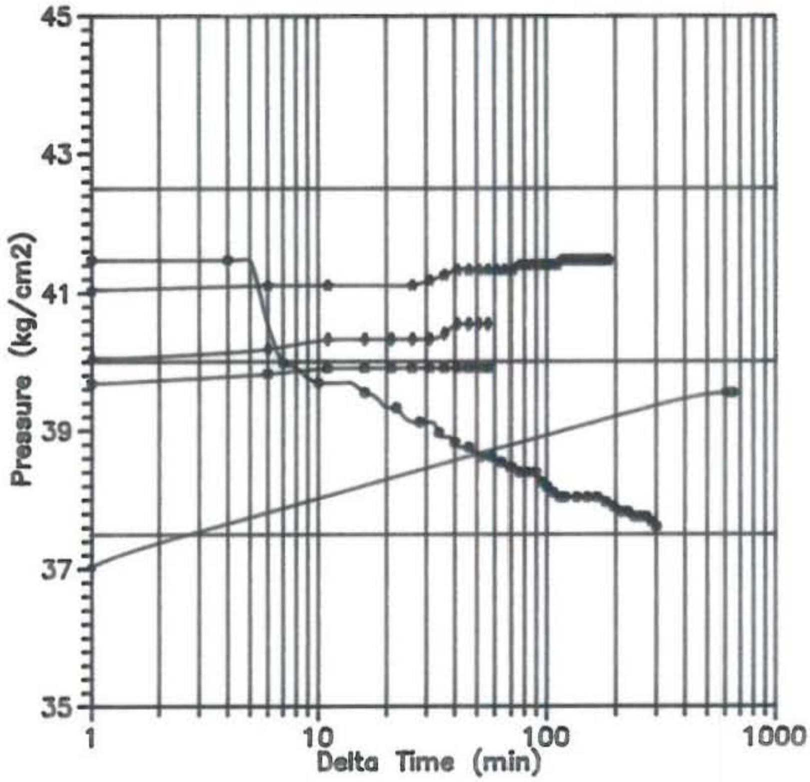


Fig.4.14 Semi-log curves for the flow test of well KMJ-45

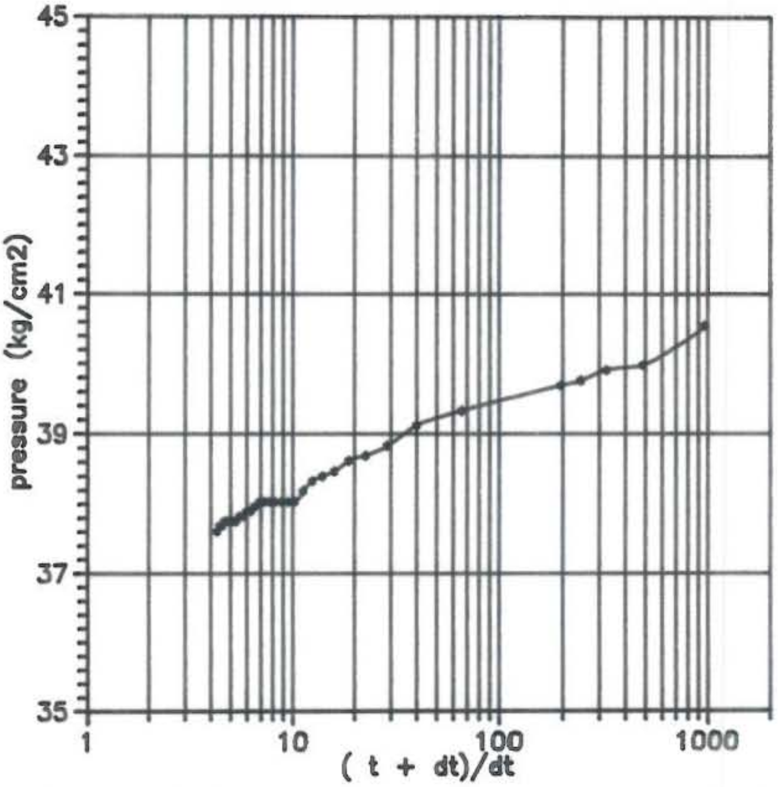


Fig.4.15 Horner plot for recovery of well KMJ−45 after injection. Time scale corrected for offset

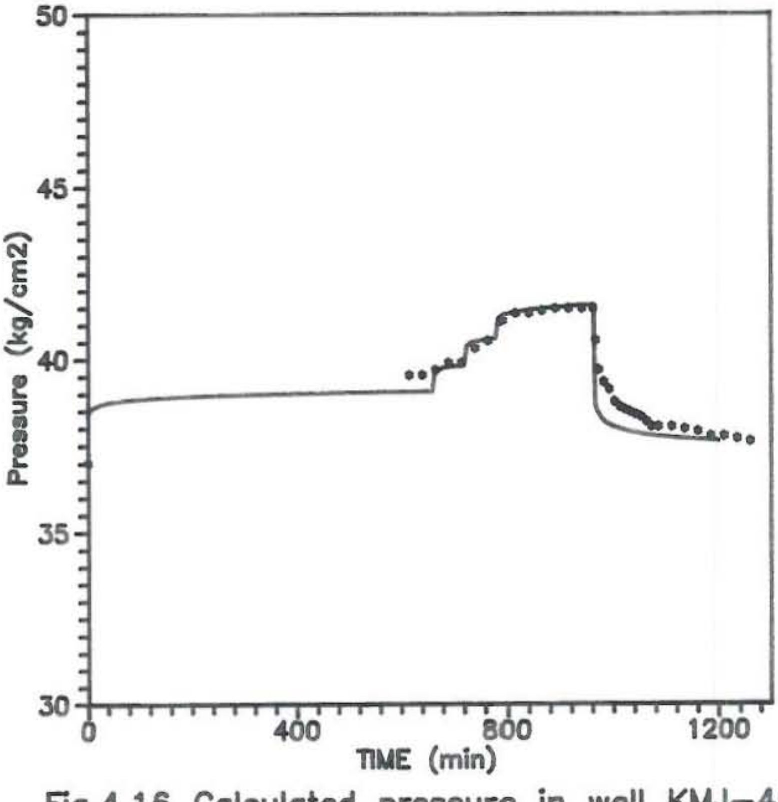


Fig.4.16 Calculated pressure in well KMJ−45 by Varflow

# Well KMJ-45

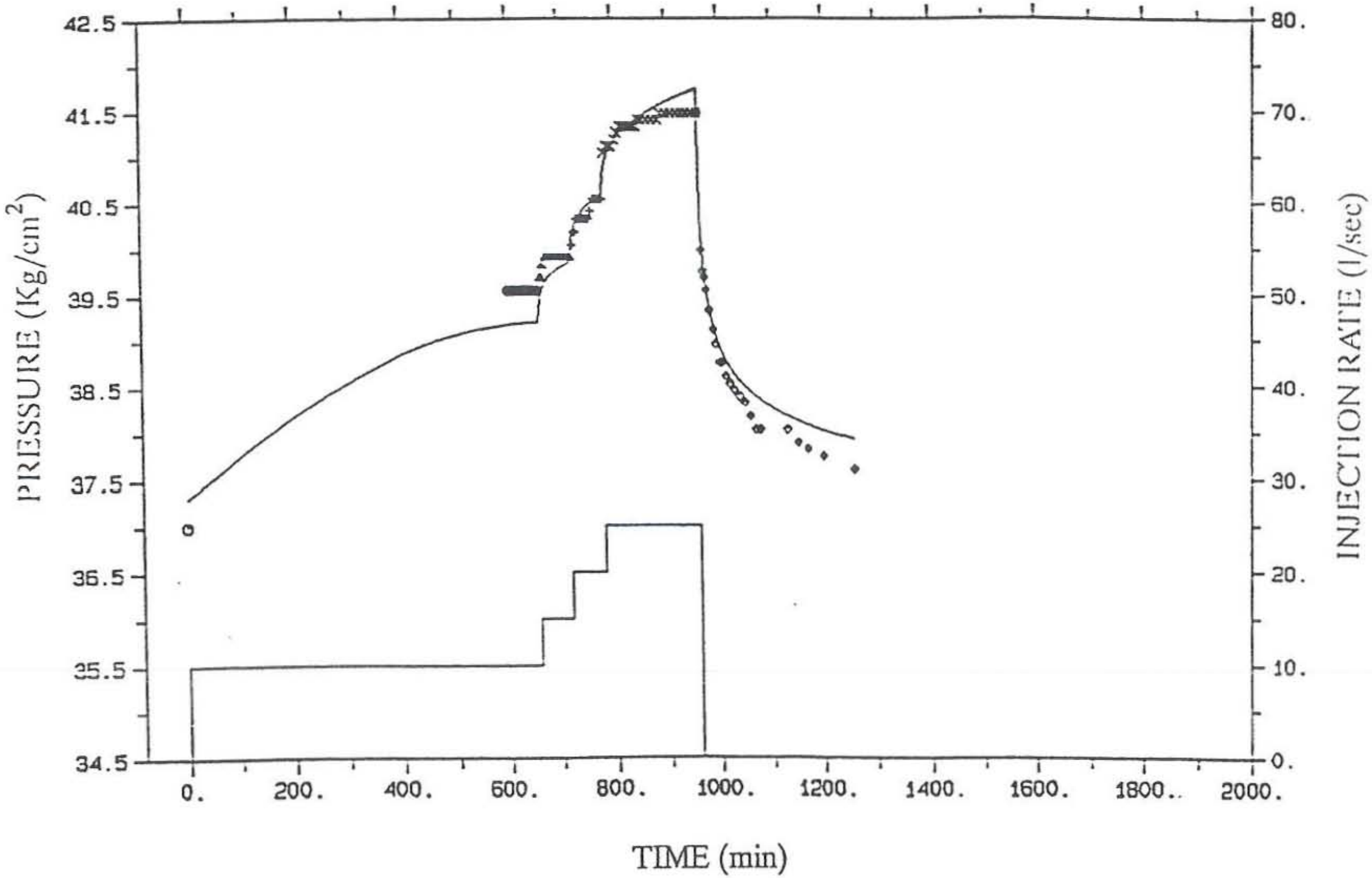


Fig. 4.17 Calculated pressure in well KMJ-45 by ORKUSTOFNUN program

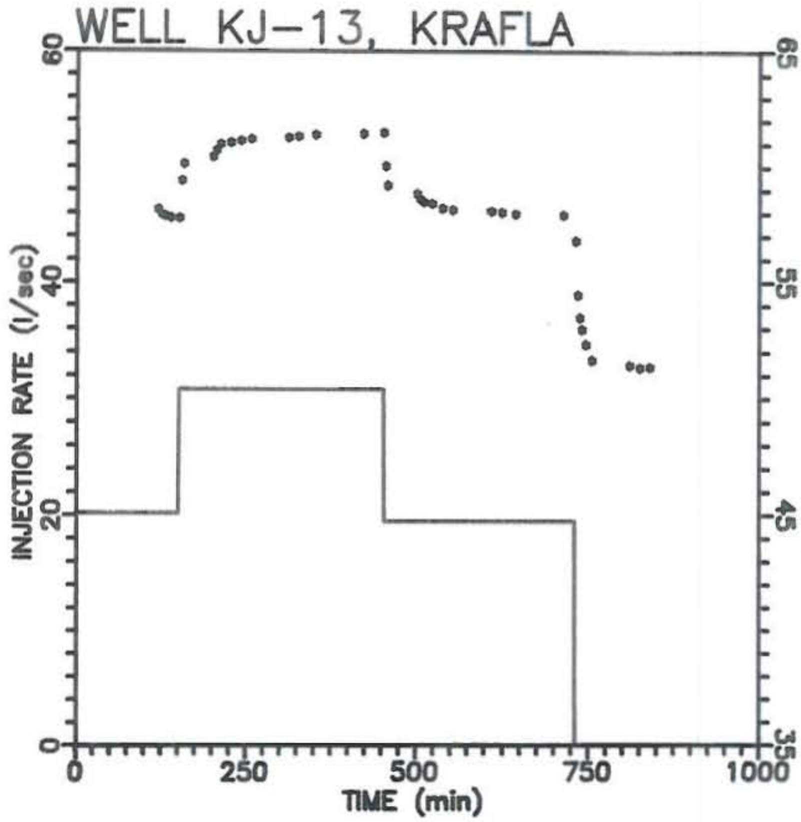


Fig.4.18 Pressure and flow data for the injection test of well KJ-13, Iceland

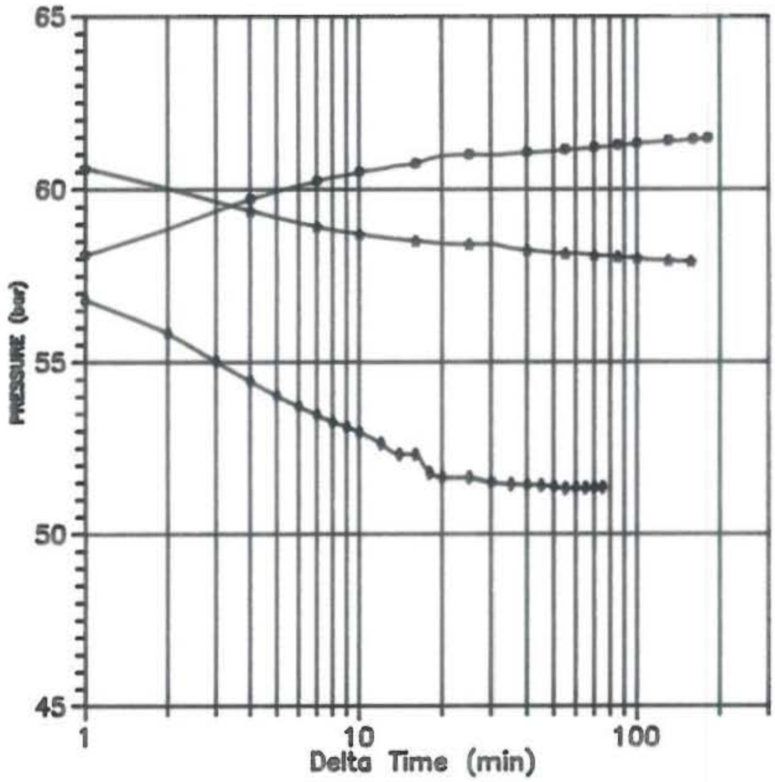


Fig.4.19 Semi-log curves for the flow test of well KJ-13

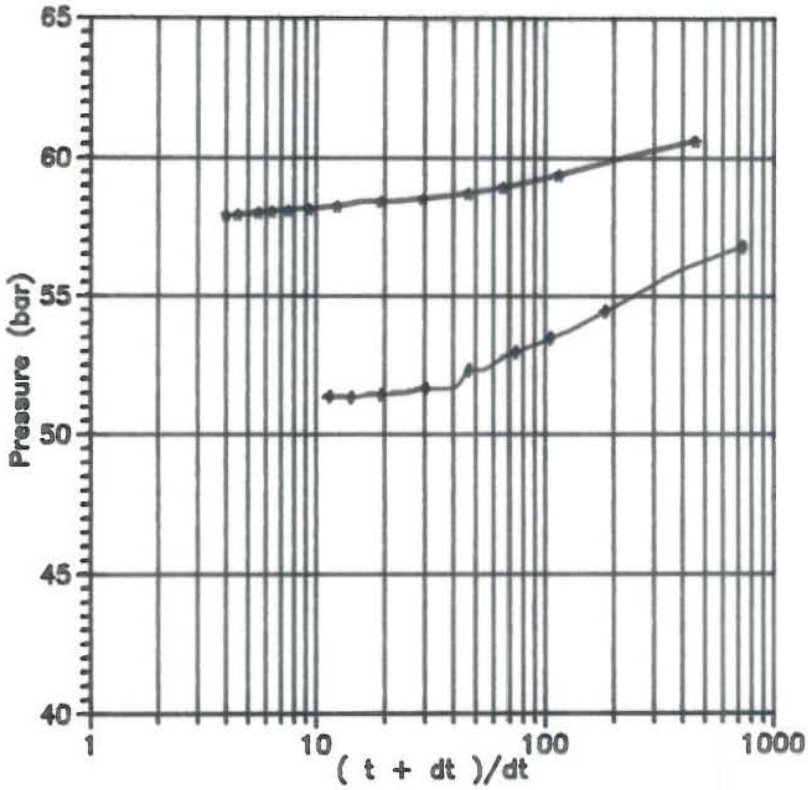


Fig.4.20 Horner plot for the recovery of well KJ–13 after injection

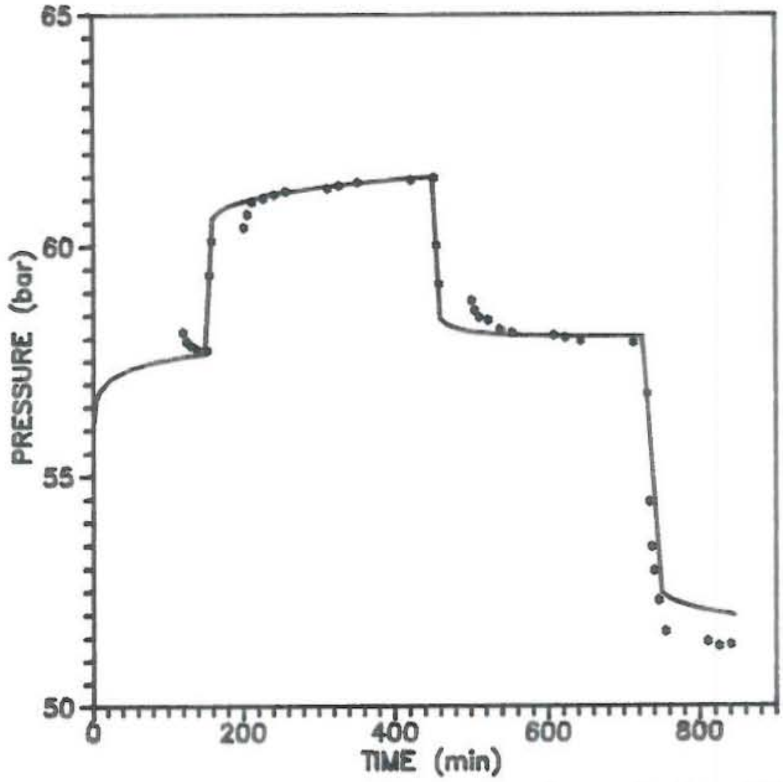


Fig.4.21 Calculated pressure in well KJ–13 by Varflow

## *APPENDIX A: Examples of input and output files for Varflow*

```
*** Input file for well KMJ-42 ***
==============================================================
PROBLEM DESCRIPTION
--------------------------------------------
Number of observation wells              : 1
Number of production wells               : 1
Input unit flag (0 = SI units)           : 1
Number of times for pressure calculations      : 47
==============================================================
CONVERSION FACTORS
--------------------------------------------
Pressure unit per Pa                 : 9.8 E+4
Flowrate unit per m3/s                 : 1.67 E-5
Time unit per s                    : 60
Length per m                       : 1.0
Viscosity per Pa*s                  : 1.0
Permeability per m2                  : 9.862E-13
==============================================================
PARAMETER VALUES
--------------------------------------------
X-axis transmissivity                : 1.7E+4
Y-axis transmissivity                : 1.7E+4
Storativity                       : 1.0e-4
Boundary angle (clockwise from pos. y-axis)    : 0
Distance to the boundary from the origin       : 0
Type of boundary (BARRIER,LEAKY,' '=No boundary) :
==============================================================
OBSERVATION WELLS
 Name   X-coord.  Y-coord.  Initial   Well number if   Skin value if
                            pressure  also prod. well  also prod. well
---------.---------.---------.---------.---------------.--------------
obs 1    0.0      0.0       35.5      1                -2.5
==============================================================
PRODUCTION WELLS
 Name   X-coord.  Y-coord.  Number of flow   Time   Flow rate
                            rate points
---------.---------.---------.---------------.---------.--------------
prod 1   0.1      0.1       11          0      0
                                   0    - 600
                                 250    - 600
                                 255    - 880
                                 280    - 880
                                 285    -1320
                                 306    -1320
                                 306    -1617
                                 376    -1617
                                 376        0
                                 550        0
==============================================================
TIMES AT WHICH PRESSURES ARE TO BE CALCULATED
--------------------------------------------
1., 5., 10., 25., 50., 75., 100., 125., 150., 175., 200., 240., 245., 250.,
255., 260., 265., 270., 275.,280., 285., 290., 295., 300., 305., 310., 315.,
320., 325., 340., 345., 360.,370., 374., 377., 380., 385., 390., 396., 400.,
409., 435., 455., 470., 490., 505., 550.
```

****** An example of output file from Varflow ******

```
NUMBER OF OBSERVATION WELLS      1
NUMBER OF PRODUCTION WELLS       1
NUMBER OF TIMES AT WHICH PRESSURES WILL BE CALCULATED      47

        CONVERSION FACTORS
        ==================
   PRESSURE UNIT PER PASCAL                    0.9800E+05
   FLOWRATE UNIT PER CUBIC METER PER SECOND    0.1670E-04
   TIME UNIT PER SECOND                        60.00
   LENGTH PER METER                            1.00
   VISCOSITY PER PASCAL-SECOND                 0.1000E+01
   PERMEABILITY PER SQUARE METER               0.9862E-12

PARAMETER VALUES
================
 X-AXIS TRANSMISSIVITY =0.1700E+05
 Y-AXIS TRANSMISSIVITY =0.1700E+05
 STORATIVITY           =0.1000E-03

OBSERVATION WELL NUMBER   1
 WELL obs 1    COORDINATES (    0.00,     0.00)
 INITIAL PRESS=0.3550E+02
 THIS OBSERVATION WELL IS ALSO PRODUCTION WELL NUMBER      1
 IT HAS A SKIN VALUE OF    -2.50

PRODUCTION WELL NUMBER   1
 WELL prod 1    COORDINATES (    0.10,     0.10)
 NUMBER OF FLOWRATE POINTS=   11

          TIME        FLOWRATE
        0.0000E+00   0.0000E+00
        0.0000E+00   -.6000E+03
        0.2500E+03   -.6000E+03
        0.2550E+03   -.8800E+03
        0.2800E+03   -.8800E+03
        0.2850E+03   -.1320E+04
        0.3060E+03   -.1320E+04
        0.3060E+03   -.1617E+04
        0.3760E+03   -.1617E+04
        0.3760E+03   0.0000E+00
        0.5500E+03   0.0000E+00

DISTANCES BETWEEN OBSERVATION WELLS AND PRODUCTION WELLS

      obs 1
prod 1      0.14

   TIME     obs 1
0.1000E+01 0.3871E+02
0.5000E+01 0.3949E+02
0.1000E+02 0.3983E+02
0.2500E+02 0.4027E+02
0.5000E+02 0.4061E+02
0.7500E+02 0.4081E+02
0.1000E+03 0.4095E+02
0.1250E+03 0.4105E+02
.
.
.
.
```