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GROUND WATER

FIELD REPORTS

FLOWMETER ANALYSIS AT RAFT RIVER, IDAHO

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Abstract. A quantitative evaluation of borehole-impeller flowmeter data leads to estimated field hydraulic conductivity. Data were obtained during an injection test of a geothermal well at the Raft River geothermal test site in Idaho. Both stationary and trolling calibrations of the flowmeter were made in the well. Methods were developed to adjust for variations in hole diameter, impeller speed, and trolling speed. These methods were applied to evaluate water losses into the formation as a function of depth. Application of the techniques is restricted to aquifers below the water table. The flowmeter data were digitized and processed by the computer to obtain plots of apparent field hydraulic conductivity versus depth.

Introduction

This study demonstrates a possible approach to the quantitative analysis of borehole-impeller flowmeter data. The flowmeter logs were obtained during an injection test of well 7 in the Raft River geothermal field in Idaho. The well was drilled to a total depth of 3,780 ft (1,134 m) and was cased to a depth of 2,044 ft (613.20 m). The well had an obstruction at about 3,500 ft (1,050 m) when it was logged with the flowmeter. The testing and data analysis were conducted to define zones of relatively large fluid loss and to compute the apparent hydraulic conductivity in the open-hole part of the geothermal well.

The injection test was conducted by pumping geothermal fluids at a temperature of 129°C (Celsius) from well 2 into well 7. The temperature of the formation receiving the fluids was 97°C. The injection rate was maintained at 450 gal/min (gallons per minute) (1,710 L/min); injection pressure was 148 lb/in² (pounds per square inch) (10.41 kg/cm²) and shut-in hydraulic head was zero, measured at ground level, 18 ft (5.40 m) below the KB (Kelly Bushing). The logging was done with a centralized impeller flowmeter. Logging started after the injection had proceeded for approximately 48 hours and had stabilized. Calibration of the flowmeter was done both within and below the casing. Dynamic-calibration data were obtained by varying trolling speeds of the probe, both up and down, in the casing. Static-calibration data were obtained with a stationary probe, both in the casing and in the open hole. Pulses per unit time from the flowmeter and trolling speed were recorded simultaneously on an analog recorder. Analog data, including pulses per second, trolling speed, and hole diameter were subsequently digitized and analyzed by computer.

Theoretical Considerations and Data Analysis

Calibration curves, relating fluid flow velocity in a well to flowmeter response, are readily obtainable at a well site, for a given flowmeter at stabilized injection rates. A similar calibration technique was used earlier in a flowing well at Raft River (Keys and Sullivan, 1978). The impeller for the probe used in this study was vertically asymmetrical, protected by a 4.5-in. basket (11.25 cm), and centered in the well. For a complete calibration response, flowmeter data were obtained for both upward and downward movement of the probe.

The results of the calibration run in the 12.6-in. (31.5 cm) ID (inside diameter) casing are shown in Figure 1. Fluid flow velocity (V_ℓ) inside the casing is computed from the equation:

$$V_\ell = \frac{Q \cdot 231\ \text{in}^3/\text{gal}}{\pi R^2 \cdot 12\ \text{in/ft}} = 6.13\,\frac{Q}{R^2} \qquad (1)$$

where

Q = fluid flow rate, in gal/min; and

R = radius of casing, in inches.

Any other convenient set of units may be used.

A fluid flow velocity in the casing of 69 ft/min (feet per minute) (20.7 m) was calculated from equation (1) for the liquid pumped down the hole at a rate of 450 gal/min (1,710 L/min) in a 12.6-in. (31.5 cm) ID casing. In Figure 1 the flowmeter response is plotted against the trolling speed of the probe inside the casing. Two pulses correspond to one revolution of the impeller. From Figure 1 we obtain:

$$P_u = aP_s + m_u V_{pu}$$

or, for $a = 1.0$ and $m_u = 0.058$ (2)

$$P_u = P_s + 0.058\,V_{pu}$$

where

P_u = number of impeller pulses per second when probe is trolled up;

P_s = number of impeller pulses per second when probe is stationary;

m_u = slope of the plot of impeller pulses per second versus trolling speed when probe is trolled up; and

V_{pu} = probe speed when probe is trolled up.

The factor, a, allows for an experimental correction factor, if needed. Note that both up and down calibrations in Figure 1 can be fitted with straight lines for the trolling speeds tested. A break in slope occurs between up and down trolling even though the impeller is turning in the same direction. A straight-line extrapolation of either slope does not intersect the zero pulses per second line at the theoretical fluid velocity of 69 ft/min (20.7 m). No explanation is offered for this experimental result pending further experimentation. However, for the evaluation of the flowmeter logging data in this hole, no use was made of the calibration. The calibration shows, however, that for upward trolling the calibration in the casing is consistent with that obtained in the open hole. Because there was no apparent fluid loss from the well in the upper part of the open hole below the casing, an opportunity was presented to obtain stationary calibrations for different borehole sizes obtained from the caliper log. The results of the stationary

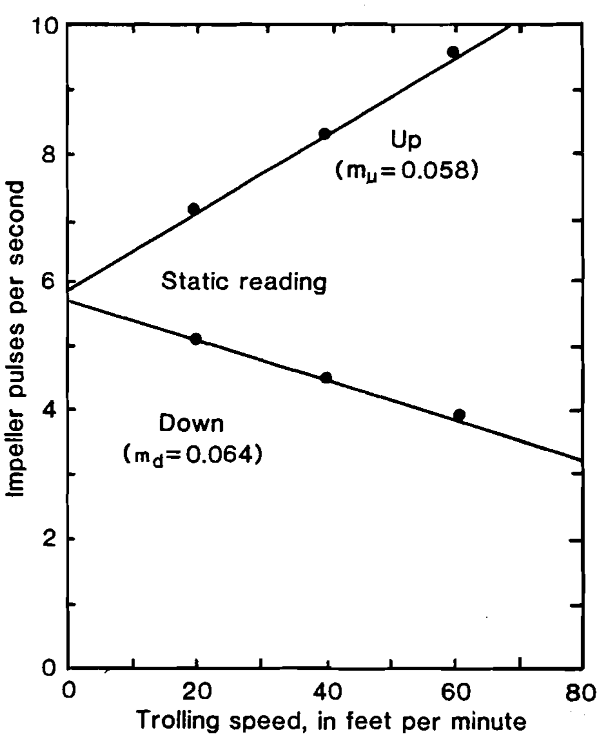

Fig. 1. Impeller flowmeter calibration inside casing for V_ℓ = 69 ft/min (20.7 m/min).

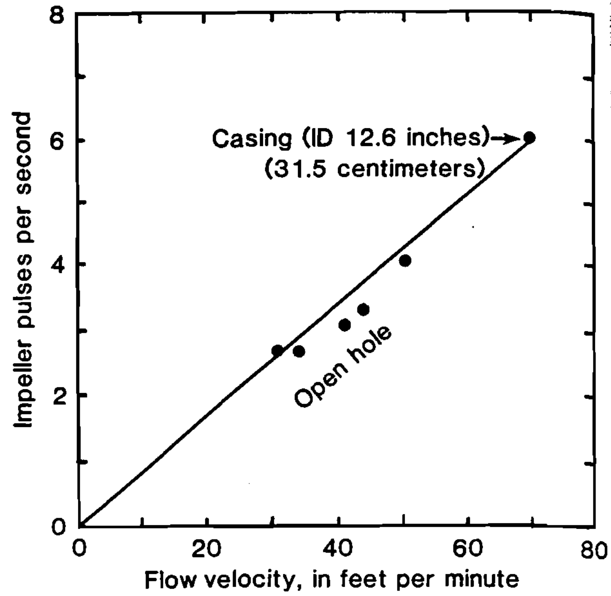

Fig. 2. Static calibration for various hole diameters; fluid flow velocities were calculated for a flow of 450 gal/min (1,710 L/min) using borehole diameters from the caliper log.

calibration in both the casing and the open hole are shown in Figure 2. From Figure 2 one obtains:

$$P_s = m_s V_\ell$$

or

$$P_s = 0.087\ V_\ell \qquad (3)$$

where

m_s = slope for stationary calibration;

V_ℓ = liquid velocity; and

P_s = number of impeller pulses per second for stationary probe.

The effects of hole-radius variation on flow rate [see equation (1)] have been plotted in Figure 3 for the range of radius changes in well 7. To illustrate the effects of different injection rates, curves for a 50-gal/min (190 L/min) and a 450-gal/min (1,710 L/min) rate were calculated for comparison.

Another plot was constructed from flowmeter readings obtained in the well when the probe was stationary (static) versus the readings obtained at the same location when the probe was in motion (dynamic) (Figure 4). Trolling speed was about 55 ft/min (16.5 m/min) for trolling up, and 50 ft/min (15 m/min) for trolling down. The results from Figure 4, using equation (2), can be expressed as:

$$P_u = aP_s + 0.058\ V_{pu} \qquad (4a)$$

Similarly

$$-P_d = bP_s - 0.064\ V_{pd} \qquad (4b)$$

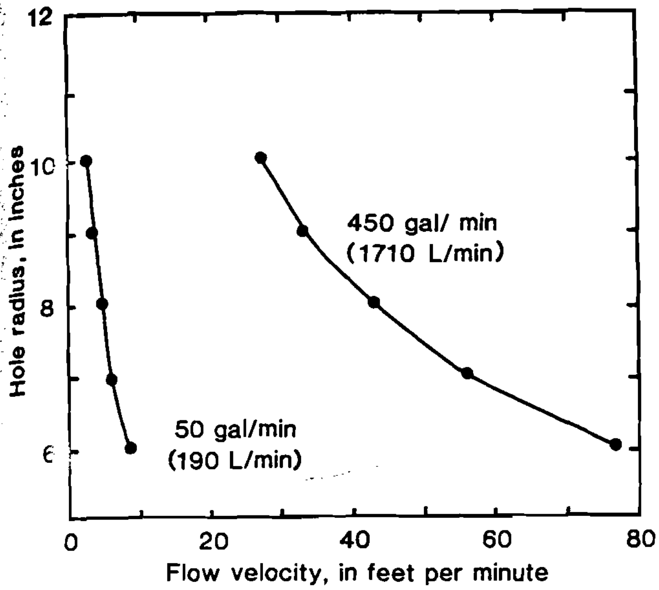

Fig. 3. Theoretical effects of hole radius variation at different flow rates.

where

b = 0.80; and

P_d = number of pulses when the probe is going down.

Both a and b are correction factors obtained from Figure 4 at the location where the lines cross the ordinate.

Equations (4a) and (4b) can be used to calibrate flowmeter logs. However, if equations (4a) and (4b) are combined, one obtains:

Let $\Delta P = P_u - P_d$, then

$$P_u - P_d = \Delta P = (a + b)\, P_s - m_d\, V_{pd} + m_u\, V_{pu} \quad (5)$$

or $$\Delta P = (a + b)\, m_s\, V_\ell - m_d\, V_{pd} + m_u\, V_{pu}$$

where

ΔP = the differences in pulses per second while trolling up and down, at the same depth in the hole.

From equation (5):

$$V_\ell = \frac{1}{m_s\,(a + b)} (\Delta P + m_d\, V_{pd}\, V_{pu}) \quad (6)$$

From equation (1):

$$V_\ell = \frac{6.13\, Q}{R^2} \quad (7)$$

Combining equations (6) and (7):

$$Q(\text{gal/min}) = \frac{R^2}{6.13(a+b)m_s} (\Delta P + m_d\, V_{pd} - m_u\, V_{pu}) \quad \ldots\ldots (8)$$

From Figures 1 and 4:

$$m_d = 0.064$$

$$m_u = 0.058$$

$$V_{pu} = 55$$

$$V_{pd} = 50$$

From Figure 2 and equation (4):

$$m_s = 0.087$$

From equation (2):

$$a = 1.0$$

From equation (4a):

$$b = 0.80$$

$$Q\,(\text{gal/min}) = 1.04\, R^2\, (\Delta P + 0.01) \quad (9)$$

Or $$Q\,(\text{gal/min}) \simeq R^2\, \Delta P \quad (10)$$

Equation (10) will be used to calculate vertical flow rates at various depths in the hole.

It should be pointed out that in trolling down the well, different slopes were obtained for the open hole and the casing. The slope was computed from Figure 4 for trolling down in the open hole.

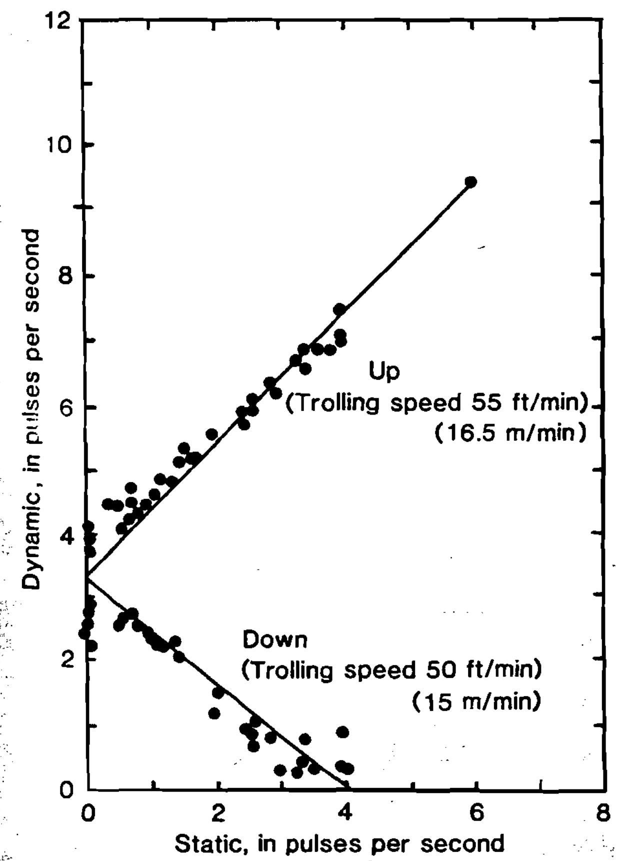

Fig. 4. Static versus dynamic impeller readings taken at the same depth for the same well diameter.

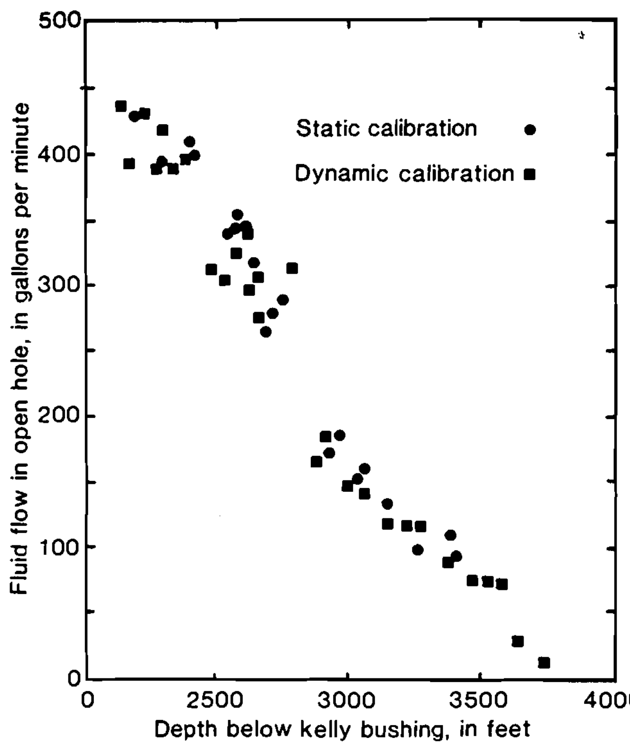

Fig. 5. Comparison of fluid flow rates calculated for both stationary and moving flowmeter measurements at selected depths.

A plot of the calculated fluid flow rate at various depths in the open hole portion of the well, for both static and dynamic flowmeter measurements, is shown in Figure 5. Fluid loss from the open hole into the surrounding rocks, as evidenced by gradual decrease in vertical fluid flow rate with increasing depth, can be calculated for given intervals within the well. Depths are referenced from the KB. Breaks in slope on Figure 5 indicate changes in the rate of water loss. Generally a flatter slope corresponds to a smaller apparent hydraulic conductivity. The scatter in the data points indicates that errors in fluid flow velocity of about 20 percent are not uncommon, and occasionally errors may exceed 40 percent when hole diameters are poorly defined by the caliper log.

The method described in this paper depends on accurate calibration procedures. For best results, one needs to avoid approaching the impeller stall speed of 3-5 ft/min (0.9-1.5 m/min) while trolling either up or down. Appropriate trolling speed can be calculated from the caliper log (see also Figure 3). It is, of course, not necessary to obtain data from up and down trolling; stationary measurements can be used. Equation (4a) can be used for upward trolling, and equation (4b) for downward trolling. Using the difference between upward- and downward-trolling readings with equation (8) tends to average out measurement errors and is believed to result in better over-all estimates of fluid flow velocity.

Calculation of Hydraulic Conductivity of a Horizontal Layer Surrounding a Borehole

Apparent hydraulic conductivity, obtained from pump-in tests, can be calculated from equation (11) (Zanger, 1953). In addition, the reader is referred to Designation E-18, in a report by the U.S. Department of Interior (1974), where on page 576:

$$K = \frac{Q_r \ln (2H/d)}{2 \pi H \Delta S} \quad \text{where } H \geqslant 5d \qquad (11)$$

where

Q_r = rate of radial fluid flow;

K = hydraulic conductivity;

H = layer thickness;

d = borehole diameter; and

ΔS = differential head of water.

Any consistent set of units may be used. Equation (11) (Zanger, 1953) was developed for conditions of steady radial flow into a confined aquifer. Because the physical constraints used in the derivation of the above mathematical relationship are not precisely met under actual conditions in the borehole, equation (11) represents an apparent, or calculated, hydraulic conductivity designed to aid in the interpretation of flowmeter logs (Figure 6).

The difference between fluid flow rates Q_i and Q_{i+1} in the borehole can be thought of as radial flow into layer H. Hence, this loss represents the radial flow, Q, in equation (11). The differential head of water (ΔS), is the gravity head plus the applied pressure head expressed in feet at the midpoint of the layer H. Additional details can be found in the Department of Interior publication

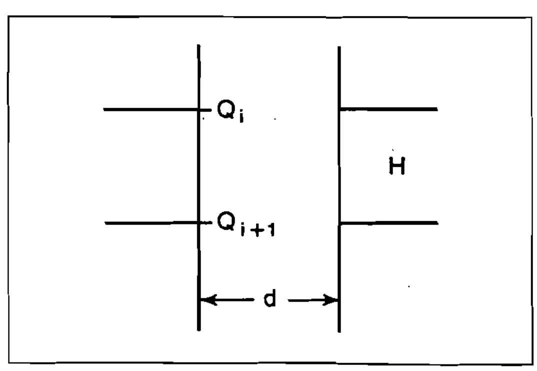

Fig. 6. Model used for calculating apparent hydraulic conductivity.

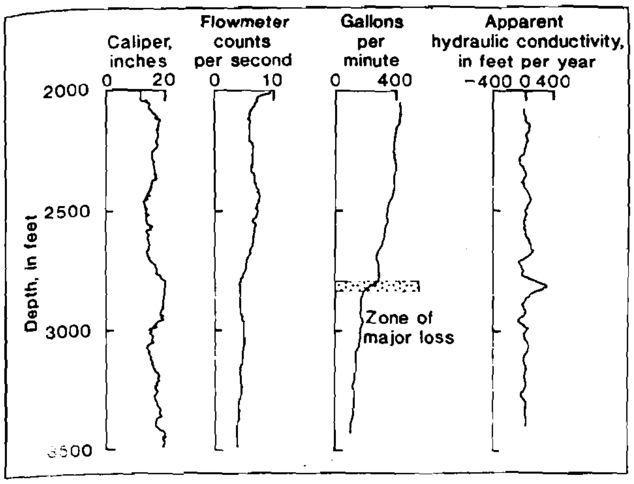

Fig. 7. Results of flowmeter interpretation in geothermal well Raft River 7 using only the calibration obtained for trolling up.

(1974). The apparent hydraulic conductivity is that calculated for in-hole conditions of temperature, viscosity, and density.

Discussion of Results

The application of the mathematical formulas presented earlier leads to the computer plots displayed in Figure 7. Frictional losses in the well casing and open hole are negligible in the present instance. To comply with the mathematical stipulations and yet retain reasonable resolution, a 40-ft (12-m) interval average (see Zanger, 1953) was chosen, and calculated for 1-ft (30-cm) increments on the log. The caliper and flowmeter logs are reproduced to show the input data. Total drilled depth could not be logged with the flowmeter, owing to an obstruction in the hole. The vertical flow measured in the drillhole is shown in gallons per minute. A zone of major loss is indicated between approximate depths of 2,780 to 2,830 ft (834 to 849 m). The apparent hydraulic conductivity log is "noisy" and can be used only in a relative sense. At a depth of approximately 2,667 to 2,671 ft (800.1 to 801.3 m), vugular solution openings were detectable on the televiewer logs. The largest apparent hydraulic conductivity, at a depth of about 2,820 ft (846 m), corresponds to a zone of larger than average borehole diameter. The average hydraulic conductivity under on-site conditions of temperature and viscosity for the drillhole to a depth indicated in Figure 7 is 31 ft/yr (feet per year) (9.3 m/yr) with a maximum indicated hydraulic conductivity of 370 ft/yr (111 m/yr) at about 2,820 ft (846 m). Again, this should not be considered a precise value, but it is a result of the mathematical assumptions presented earlier. Apparent negative hydraulic conductivities are most likely due to "noise." Theoretically, the apparent negative hydraulic conductivities would indicate zones of flow into the hole rather than loss from the hole. Relogging the hole under shut-in conditions might identify zones of natural inflow and outflow.

Increased accuracy and resolution is most likely attainable by a more judicious choice of impeller size, trolling speed, and injection pump rate. The apparent hydraulic conductivities computed from the data are not closely related to the conventional concept of permeabilities measured on cores. The apparent hydraulic conductivities need to be considered related to fractures and vugular openings in a rock matrix of relatively small permeability. The computed hydraulic conductivity values represent averages over a given rock interval due to perhaps one or several conductive openings. The method presented here, however, serves to adequately delineate broad zones of increased fluid loss from the well and thus greater hydraulic conductivity.

Acknowledgments

The author wishes to express his gratitude for the cooperation received from the staff of both Edgarton Germantown Greer (EG&G) and the U.S. Department of Energy in coordinating the obtaining of the data.

References Cited

Keys, W. S. and L. M. MacCary. 1971. Application of borehole geophysics to water-resources investigations. U.S. Geol. Survey Techniques of Water Res. Inv. book 2, chap. E1.

Keys, W. S. and J. K. Sullivan. 1978. Role of borehole geophysics in defining the physical characteristics of the Raft River geothermal reservoir, Idaho. Geophysics. v. 44, no. 6, pp. 1116-1141.

U.S. Dept. of Interior, Bur. of Reclamation. 1974. A Water Res. tech. pub. in Earth Manual. U.S. Water and Power Res. Ser. 810 pp.

U.S. Dept. of Interior, Bur. of Reclamation. 1977. A Water Res. tech. pub. in Ground Water Manual. U.S. Water and Power Res. Ser. 810 pp.

Zanger, C. N. 1953. Theory and problems of water percolation. U.S. Bur. of Rec., Eng. Monographs no. 8.

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