Thermal dilution test: a new method for the determination of fracture positions, flow zones and ground water velocities in aquifers, using temperature as a tracer in single wells

Richard Ayuk II Akoachere[1], Gerrit Van Tonder,[2]

[1]*Department of Geology and Environmental Sciences, University of Buea, South West Region Cameroon*
E-mail: rakoachere_ayuk@yahoo.com, Tel: +2379 624 6613, Fax: (237) 332 22 72 / (237) 343 25 08
[2]*Institute for Groundwater StudiesUniversity of the Free State Bloemfontein, 9300, South Africa*

Abstract Thermal dilution test determines position, depth, number and groundwater velocity of fractures in single wells in fractured rock aquifers, using temperature as tracer. With trigger-tube apparatus, cold water is introduced into well. Groundwater flow rate is measured as temperature change in wells and used to determine flow zones, position, depths and Darcy velocity of fractures. This method was used in well UO5 to determine fractures at 14m to 27.5m below surface. Darcy velocities ranged from 1.54m/day to 4.17m/day with largest fracture at 21m, confirmed by pump tests, acoustic scan and borehole camera images.

Key Words Temperature as tracer, single well injection test, fracture depth, Darcy velocity determination

Introduction

In wells drilled in fractured rock aquifers, the position, number of fractures present, flow zones and relative flow contributions of the fractures is important for characterization of these aquifers. Acoustic scanners, callipers and down-hole cameras can determine position and number of fractures in a well. These are very expensive equipment not within the reach of every investigator. Their use takes time and a level of technical know-how. These methods cannot tell you which and to what extent the fractures present contribute to the flow of ground water in the aquifer.

Pump-tests, Tracer tests, point dilution tests and single well injection withdrawal tests are used to determine aquifer and fracture hydraulic characteristics. However in most situations where fractures are so closely-spaced that packers and other grouting techniques used to isolate fractures for characterization are difficult to use, it becomes extremely difficult to tell which fracture has what characteristic flow properties. Thus, the use of terms such as; test segments, test sections, test zones, etc., to denote bulk properties of a number of inseparable fractures. The use of packers and grouting techniques to isolate fractures for tests, is complicated and equipment intensive. There was need therefore for a new technique to determine the groundwater velocity, flow zones and fracture depths in fractured rock aquifers, named Thermal Dilution Test (TDT). The geology of the Campus Test Site, University of the Free State, South Africa is in Botha et al (1998)

Aims

Develop technique to determine zones with flow, fracture position, depth, and groundwater velocity without fore knowledge of aquifer's effective porosity in a single well test.

Methods

We can consider the test segment of a well with a radius r, a vertical cross-sectional area through its centre. If the initial temperature of the water was T_0, the temperature after a period of time t is T and the volume of the cylindrical segment is V.

The change in temperature of the water with time in the segment is given by;

$$\frac{dT}{dt} = A\bar{v}\frac{T}{V} \quad (1)$$

The cross-sectional area A = 2 r h, and the volume of the segment $V = \pi r^2 h$ and $\bar{v}$ is the velocity of flow. Replacing (A) and (V) in equation (1) gives

$$\frac{dT}{dt} = 2\bar{v}\frac{T}{r} \quad (2)$$

Integrating (2), gives

$$\frac{r}{2}\ \ln(T) + B = \bar{v}\ t \tag{3}$$

At time 0, $t = 0$, $\bar{v}\ t = 0$ and $T = T_o$

$$\frac{r}{2}\ \ln(T_o) = -B \tag{4}$$

Replacing the (B) in (3) in (4)

$$q\alpha = \bar{v} = \frac{r}{2t}\ \ln\left(\frac{T}{T_o}\right) \tag{5}$$

q is the Darcy velocity which is equal to when α =1(parallel plate model for fracture has porosity as 1 at the fracture in the borehole using Thermal dilution test (TDT).

Also, considering the segment of well above, with known initial temperature and volume, we can calculate how much volume of water will be necessary to change the temperature from an initial temperature to the final temperature from thermodynamics, using the specific heat capacity of water within 5 -20 degrees centigrade as C_v = 4.184 (constant volumes).

Thus,

$$T_1V_1 / T_2V_2 = C_V \tag{6}$$

$$q = V_2 / At \tag{7}$$

Area of a section across centre of well segment, $A = 2rh$; $T_1 = T_i$; $T_2 = T_f$; $V_1 = \pi r^2 h$

Replacing V_2 in (2) by V_2 in (1),

$$q = \frac{\pi}{2t} r * \frac{nT_i}{C_v T_f} \tag{8}$$

C_v = Heat capacity of water (at constant volumes), C_v = 4.184(5—20°C), n = Flow dimension. (Parallel plate model fracture flow, n = 2.), q = Darcy velocity, r = Radius of borehole, h = Length of borehole segment, t = Time elapsed after introduction of cold water by trigger tube to get from, T_i to T_f, T_i = Initial temperature at start of test, T_f = Final Temperature at end of test after time t.

During the test, the water level in the borehole is constant. The volume of water is constant since inflow = outflow across the centre of the borehole in the direction of flow. Change in temperature due to advection, is proportional to rate of change of inflowing volume of ground water in the well. Heat exchange between the water in the well and the formation is negligible since the ground water causing the change in temperature is at same temperature as the formation. The two systems A (Groundwater) and B (Formation) are in thermal equilibrium with one another. The temperature retardation factor and the thermal diffusion coefficient are important. Both parameters may vary in time, but are uniform (and temperature independent) over the flow domain here since the cold water cannot lose heat to the formation or groundwater.

Test procedure and apparatus was that for the trigger tube apparatus. (Akoachere and Van Tonder, 2008). Cold water at 2 °C instantaneously mixed with borehole water at 19.45 °C to 9.98 °C by trigger tube apparatus. Change in temperature, T, recorded during the test as difference between initial temperature T_o and final temperature T_f (Table1, Figure1), normalized by subtracting least value of T from all other T values, to account for time lag created by dropdown lift temperature measurement method. Normalized values were plotted to get thermal profile (Figure2), for various flow regimes in the fractures.

Results

Thermal profile and Fracture Positions

The resultant temperature profile from table1, fig.2, shows spikes at 14.0m, 15.0m, 16.8m, 18.2m, 19.8m, 21m, 22.4m, 24.0m, 26.1m and 27.4m. The largest spike corresponded to a depth of 21m which is where the major fracture is found. This shows that the thermal dilution test detects fractures in which ground water flows and the relative size of the spikes show the relative contribution to flow in the borehole of each fracture. The fractures which did not have corresponding thermal spikes were those in which there was very little or no ground water flow, and therefore no signatures.

Darcy velocity (q)

From the field test data at 21m, T_o = 13.9 °C. T = 19.4 °C. t = 0.01 days r = 0.08 m. ln (T/ T_o) = 0.38. using equation (5), q = 4.23 m/day. Also, Using equation (8), q = 4.77 m/day. These values tally with other estimates of Darcy velocity on UO5. Botha et al (1998) q = 4.86 m/day; Van Tonder et al, (2001) q = 4.67 m/day and natural gradient tests by Akoachere Van Tonder (2008) q = 4.06 m/day. Similarly, Darcy velocities for borehole UO5 were calculated (figure 3).

Discussions

Comparing the spikes, to the acoustic scan and lithological section of borehole UO5, with depth (Botha et al 1998) shows that, the spikes correspond to some of the fractures. These same fractures were identified by the packer tests by Botha et al (1998) as those contributing to the flow of ground water in this aquifer. The major fracture determined by acoustic scan borehole calliper, and borehole camera imagery, is that found at the depth of twenty-one meters. It has been confirmed as the major contributor to the ground water flow in the aquifer at the test site, by pump-tests using packers (Botha et al, 1998), Van Tonder et al, (2001) and this thermal dilution test.

A number of workers have carried out work on wells using temperature, notably, Devlin (2002), Grace et al (2005) who used heating probes to heat sections of the water in wells and the flow around in-situ heat based flow sensors by inverting thermistor temperature evolutions and using numerical simulations to obtain estimates of ground water flow velocity. Also, Tsang et al,

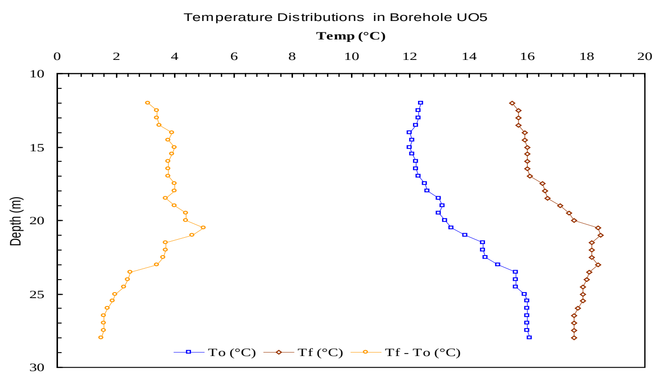

Figure 1 *Temperature distributions for the thermal dilution test carried out in borehole UO5. T_o represents the initial temperature measurements, T_f represents the final temperature measurements and $\Delta T = T_f - T_o$ represents the normalized change in temperature during the test*

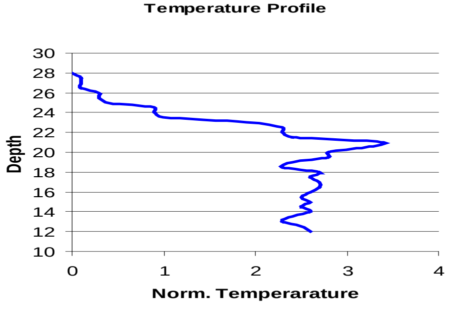

Figure 2 *Normalized temperature profile denoting, major fractures and their depths, note the distinct spiked peaks at 21m*

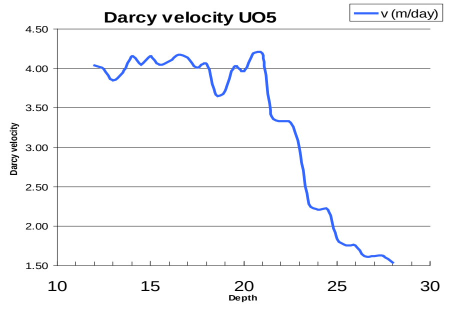

Figure 3 *Darcy velocity profile of fractures in UO5 determined using the thermal dilution test method, showing groundwater flow velocities and contributions.*

(1990) replaced well bore water with de-ionized water and then profiling the well's electrical conductivity through time in his hydro-physical method. The results were then used in numerical simulations to estimate fracture parameters.

These methods however are different from the new method developed here which replaces well-bore water with ice cold water and then the heat/influx of the formation water is used to determine directly, the fracture depth, fracture positions, number of fractures and the Darcy velocity of the fractures.

Conclusion

The need for a technique that can be used to determine fracture positions down hole and flow zones in fractured rock aquifers, together with the groundwater velocity (Darcy velocity) abounds. The thermal dilution test accurately determines the position and relative flow contribution of these fractures in fractured rock aquifers using a single borehole. Of importance also is the fact that, the determination of the Darcy velocity does not require a pre-knowledge of the aquifer porosity or effective porosity. The thermal dilution test therefore is an important tool added to the field investigators kit for the characterization of fractured rock aquifers.

Advantages

- No need for a pre-knowledge of effective porosity. – Detects fracture with flow.
- No specialized pump (Peristaltic etc)
- No isolation of test section or use of packers.
- Better control of water temperature (predetermined).
- Whole length of well tested at once to give hydraulic characteristics from single well test
- This test method uses few instruments and as such is quick to set up and carry out.

Disadvantages

- Values are for areas within the reach of the single well. Point values (small scale cm).
- Does not determine characteristics of vertical fractures in vertical boreholes.
- Does not detect fracture with no flow.

However, if the fractures are not parallel to the vertical borehole and many of such tests are carried out in a reasoned manner over an area, such data could become a powerful tool for the modelling of fractured rock aquifers.

Recommendations

Future research should focus on the development of a wire line multi-parameter/temperature probe for the thermal dilution test

References

Akoachere RA and Van Tonder, GJ (2008a) The trigger tube; a new apparatus for mixing solutes for injection tests in boreholes. (Unpublished).

Botha JF, Verwey JP, Van der Voort I, Vivier JJP, Colliston WP and Loock JC (1998) Karoo Aquifers. Their Geology, Geometry and Physical Behavior WRC Report No 487/1/98. Water Research Commission, P.O. Box 824, Pretoria 0001

Grace WS, Barry MF, Curtis MO, Preston DJ and Daley PF (2005) Interpreting velocities from heat based flow sensors by numerical simulations, Groundwater 44; 3. 386—393

Tsang CF, Hufschmied P and Hale FV (1990) Determination of fracture inflow parameters with a borehole fluid conductivity logging method. Water Resources Research 26(4):561–578.

Van Tonder GJ, Botha JF, Chiang WH, Kunstmann H and Xu Y (2001) Estimation of the Sustainable Yields of Boreholes in Fractured Rock Formations, Journal of Hydrology.241,70—90