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THERMAL FLOWMETER MODIFICATION FOR THE ADDITION OF A PACKER AND PUMP

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ABSTRACT

Measurement accuracy was increased by nearly one order of magnitude by outfitting the thermal-pulse flowmeter (TFM) with an inflatable packer. To accurately measure slow water velocities in boreholes greater than 15 cm diameter, it is necessary to divert borehole fluids through the TFM by inflating a packer. During calibration it was noted that the TFM's accuracy decreased as the borehole diameter increased. With the packer inflated the TFM has a useful flow measurement range of 0.08 to 15 l/min (with flow velocities of 0.24 ± 0.012 cm/min to 45.7 ± 0.61 cm/min, respectively, in 20-cm-diameter pipe), compared to 0.8 to 57 l/min for a packerless TFM. A computer interface was added to the TFM to provide a real-time graphical display of the differential voltage output from the TFM, a running mean and standard deviation of the pulse-response time, and mean flow rate and velocity based on calibration curve fits.

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INTRODUCTION

Measuring water movement in boreholes has achieved greater hydrogeologic importance in recent years. Measurements of borehole flow may be used to identify inflow/outflow zones (areas that may be screened during well completion), to proportion hydraulic parameters from aquifer tests, or to identify intra-aquifer flow in contamination studies. Many borehole flowmeter logging techniques have been developed to identify zones where water may be entering or exiting boreholes. Spinner, trace-injector and oxygen activation logging tools are often used in wells equipped with pumps, and can identify inflow and outflow zones under stressed (pumped) conditions. Most flowmeters can measure flows greater than 180 cm/min, with some specialized spinner flowmeters with stall velocities as low as 14 cm/min (Rehfeldt et al., 1992). However, in many cases the injection or removal of water from a well may not be acceptable. For example, groundwater contamination may prohibit ground-surface discharge of borehole fluids, borehole stability may be of concern in uncased boreholes, and cost may limit the use of a pump.

Under non-stressed conditions, velocities as slow as a few meters per day can be measured with fluid tracer techniques. The radioactive-tracer/gamma-ray detector technique described by Bird and Demsey (1955); the brine-tracer/fluid resistivity detector described by Patten and Bennett (1962); and the deionized water-tracer/fluid conductivity detector described by Pedler et al. (1990) are generally tedious and the density difference between the injected fluid and the formation fluid may cause uncertainties when measuring slow velocities.

Two geophysical logging tools have been developed to measure slow water velocities in boreholes: the thermal-pulse flowmeter (TFM) (Dudgeon et al., 1975), and the electromagnetic flowmeter (Young and Waldrop, 1989). The electromagnetic flowmeter shows great promise for measuring slow water velocity profiles in boreholes; however, this logging tool is still being tested and has only been used in shallow boreholes (less than 30 m).

The TFM used in this study was originally designed by Hess (1982, 1986, 1990) to operate on standard four-conductor logging cable to depths of 3,000 m. The TFM is 6.4 cm in diameter, about 120 cm long, is equipped with centralizing bow-springs, and is designed for stationary measurements. This flowmeter was built by the Desert Research Institute (DRI) and calibrated in a specially designed tank. Calibration curves were developed for several borehole diameters. During calibration, it was determined that the TFM had a useful flow measurement range of 0.8 to 57 l/min in boreholes less than 15 cm in diameter; the accuracy steadily decreased as the borehole diameter increased (Figure 1), due to convection cells and turbulence within the larger diameter pipes. The TFM accuracy is represented by the coefficient of variation in Figure 1. The coefficient of variation is inversely proportional to the TFM accuracy. The standard deviation of repeated measurements at set flow rates increased greatly in boreholes greater than 15 cm diameter. Therefore, it was determined that an inflatable packer would be designed to center the TFM in the borehole, and when inflated would extend radially from the TFM to the borehole wall, diverting water flow through the TFM. This technique has been successfully used by the U.S. Geological Survey (Morin, 1990).

Figure 1. TFM accuracy as a function of borehole diameter. The coefficient of variation is inversely proportional to accuracy (as borehole diameter increases, TFM accuracy decreases).

During this study, several tasks were accomplished: 1) a small-diameter submersible pump was developed which uses borehole fluid to inflate a packer; 2) the TFM was modified to send voltage to the pump; 3) the TFM was outfitted with various sizes of commercially available flow diverters (packers); and 4) the TFM was interfaced with a computer to more efficiently measure the TFM response. These combined modifications increased the measurement resolution of the TFM by nearly one order of magnitude, and increased the usefulness of the TFM in wellbores larger than 15 cm in diameter. During the calibration of the TFM, under ultra-slow water velocities (less than 3 cm/min), modifications were made to the calibration techniques specified by Hess (1990). A constant head tank was used to maintain stable and constant flow rates during calibration, and a computer interfaced with the TFM surface module was used to compute statistics related to the TFM accuracy and resolution at various flow rates. With the packer inflated, the TFM had a useful flow measurement range of 0.08 to 15 l/min.

BASIC FLOWMETER DESIGN AND THEORY

The TFM directly measures the rate of fluid flowing through the TFM's flow-through cell, which equals the flow rate in the borehole. The TFM cannot measure the velocity of the water moving in the borehole directly; however, knowing the flow rate and borehole area, the fluid velocity can be computed using the equations:

$$V = \frac{Q}{A}$$

where V = velocity, Q = flow rate, and A = borehole cross-sectional area. The area may be computed from the borehole diameter:

$$A = \pi r^2 = \frac{1}{4}\pi D^2$$

where r = borehole radius, and D = borehole diameter. By combining the previous two equations and performing units conversion, the fluid velocity can be computed from the flow rate and borehole diameter, using the equation:

$$V = 1273.24 \frac{Q}{D^2}$$

where V = velocity (cm/min), Q = flow rate (l/min), and D = well diameter (cm).

At flow rates of 0.08 to 15 l/min, the respective velocities computed for 20-cm-diameter pipe range from 0.25 ± 0.012 to 47.7 ± 0.61 cm/min. However, boreholes up to 60 cm can be evaluated with DRI's largest packer, which would yield a velocity of 0.03 cm/min at a flow rate of 0.08 l/min.

The basic TFM, without the packer and pump assembly, is 6.4 cm in diameter, about 120 cm long, and weighs approximately 4.5 Kg. Electronic circuitry is housed in the top of the logging tool and a flow-through cell is located near the bottom of the tool (Figure 2). The down-hole electronics (circuitry within the logging tool) receive electricity and signals from the TFM surface module (located in a mobile logging vehicle) via a multi-conductor electric logging cable. The down-hole electronics control the charge/discharge of capacitors used to emit pulses of energy that heat the water flowing through the TFM's flow-through cell, and to measure the heat propagation at thermistors positioned near the top and bottom of the flow-through cell; the heat-pulse response time is sent to the surface module as a 1 to 35 kilo-Hertz frequency. The signal is transmitted as a frequency rather than an analog voltage to eliminate errors associated with long cable lengths. The surface module converts this frequency into a voltage, which is sent to a plotter, datalogger, and/or computer.

Discharge of the capacitors is controlled via the surface module. When the capacitors are discharged, 100 VDC (volts direct current) is sent to a heat-grid made of NiCr (nickle chromium) wire which has a nominal resistance of about 10 Ω (ohms); 90 percent of the capacitors' energy is sent to the heat-grid in approximately 1 millisecond, nearly instantaneously. The heat-grid is

Figure 2. Generalized schematic of thermal-pulse flowmeter.

designed to heat a sheet of water within the flow-through cell as uniformly as possible. Glass-bead thermistors are positioned about 2 cm above and below the heat-grid (the precise location of the thermistors with respect to the heat-grid is not required because each TFM is individually calibrated); the thermistors have a response-time of about 0.5 seconds and have a resolution of 0.001 °C, according to Fenwal Electronic, Inc., the manufacturer of the thermistors. The heat plume radiates uniformly upward and downward; under no-flow conditions, the heat-pulse is received by the top thermistor first, due to buoyancy effects (approximately 60 sec), then it is received by the bottom thermistor (approximately 90 sec). Under vertical flow conditions, the heat-pulse is received by the thermistors in 0.5 to 40 seconds. The data are shown as differential temperature (millivolts) between the two thermistors on the y-axis and as heat-pulse response-time (seconds) on the x-axis (Figure 3). If a peak (sharply increasing positive values) is received first, then the water is flowing upward through the flow cell; conversely, if a trough is received first, then the flow direction is downward. After the TFM is calibrated, the flow rate can be computed from the TFM heat-pulse response time (described in the calibration section).

THERMAL FLOWMETER MODIFICATIONS

The basic TFM design (Hess, 1990) included some of the machining modifications required to power the submersible pump, but did not include modifications to the electronics. In consultation with Hess (1990–1992), simple modifications were made to free-up one of the wireline conductors to be used for the pump (refer to Hess (1990) for a more complete description of the TFM electrical schematics). Conductor 3 was modified to control the pump operation. To accomplish this, the AC (alternating current) signal normally sent down conductor 3 is superimposed on the DC (direct current) signal on conductor 2. In the surface module, “signal pulse input” conductor 3 was connected to the 24 VDC supply and a 10 μ H (micro-Henry) choke was inserted between the 24 VDC supply and the combined AC and DC signal on conductor 2 (Figure 4). In the logging tool, a similar 10 μ H choke was installed between conductor 2 and 24 VDC, to trap the AC on the line, and a 20 nF (nano-Farad) capacitor was added between conductor 2 and the signal wire (S orange), to trap the DC on the line (Figure 5). Conductor 3 was wired straight through the logging tool to the unused high-pressure electrical feed-through specified by Hess (1990).

A single conductor male bottom-sub was added to the bottom of the TFM to support the submersible pump, and the “bottom cover” specified by Hess (1990) was modified to accept a second high-pressure electrical feed-through (Figure 6). Power for the pump is supplied by a separate 100 VDC power supply. The pump voltage is supplied through conductor 3 and the steel armor of the wireline; by simply reversing the polarity, the pump can be switched from inflation to deflation mode. Voltage and amperage are monitored during packer inflation; when the packer seats against the side of the well, an amperage increase can be detected on the 100 VDC power supply.

PACKER AND PUMP DESIGN

An adaptor was designed to attach a commercially available packer to the flow-through cell of the TFM (Figure 7). This adaptor was constructed of 2 1/2-inch brass pipe, a 2 1/2-inch brass pipe coupling, and two machined brass washers. The packers are available in several styles and sizes, and

Figure 3. Typical heat-pulse responses: upward flow is indicated by a peak-type response, downward flow is indicated by a trough-type response.

Figure 4. Modification to electronic circuitry in the TFM surface module (modified after Hess, 1990).

Figure 5. Modification to electronic circuitry in the TFM down-hole components (modified after Hess, 1990).

Figure 6. Machining modifications to TFM down-hole components.

are marketed as inflatable flow diverters by Plug-it Products, Inc., of Lodi, California. Flow diverters are generally used to fix broken sewer pipes, storm drains, etc. (two flow diverters are usually linked together with a section of steel pipe, the flow diverter assembly is then placed in the pipeline being repaired, the flow diverters straddle the broken section of the pipeline and are then inflated, diverting the fluid through the steel pipe, bypassing the broken pipeline). These packers are made of butal rubber, are vulcanized to aluminum pipe, and can be inflated with air or water. Most packers require 275 kN/m^2 (40 PSI) to achieve maximum inflation and can hold back 207 kN/m^2 (30 PSI) of water pressure; however, since fluid can readily flow through the TFM, the differential pressure above and below the packer is generally insignificant. The TFM-to-packer

Figure 7. Schematic of adaptor used to connect packer to TFM.

adaptor is designed to accept 3-inch NPT (national pipe thread) fittings, which can easily couple with the packers. Different-sized packers have been fitted to the TFM used in this study (Table 1).

TABLE 1. Packers used with the Thermal-pulse Flowmeter.

Packer	minimum diameter (cm)	maximum diameter (cm)
400-610-3	13.3	26.7
400-1016-4	21.6	40.6
400-1824-3	40.6	61.0

No submersible pumps were commercially available that could operate at 100 VDC and withstand 1,000 m of head, the design depth requirements for the pump. Therefore, the TFM pump was designed and fabricated by DRI. A commercially available magnetically coupled (non-submersible) gear pump was purchased from Tuthill Corporation of Concord, California, based on its pump characteristics, physical size, power requirements, magnetic coupling between the pump-head and motor, and cost. The pump motor is generally run with 24 VDC and 3 amps to develop the required 275 kN/m^2 to completely inflate the packer; in our application we are starving the motor for current and supplying extra voltage to achieve the same goal (0.9 amps and 100 VDC, respectively). Our design also includes a check valve which keeps the packer inflated after the pump is turned off, and an electric solenoid valve which allows packer fluid to bypass the check-valve when the pump motor polarity is reversed during packer deflation. The pump housing is fabricated of 10-cm-diameter stainless steel, is about 30 cm long, and weighs approximately 11 Kg (Figure 8). A stainless steel cup is welded to the middle plate, which accommodates the ring magnet attached to the motor and the disk magnet attached to the pump-head. An axial inlet port was machined in the top of the pump for the electric solenoid valve, which is only opened during packer deflation (a diode is connected to the solenoid valve so that it is activated only when the DC polarity to the pump is reversed, + (pos) connected to the armor and - (neg) connected to conductor 3). A ball check-valve is connected to the original outlet port and the original inlet port is open to the inside of the pump housing. Fine-mesh brass screen covers the fluid inlets at the top of the pump housing. The bottom of the pump housing is filled with kerosene and a bellows is attached to the middle plate to pressure compensate the kerosene-filled motor housing to wellbore pressure-head (this stops the deformation of the stainless steel cup between the magnets, due to high differential pressures between the motor housing and the wellbore). The motor housing is watertight with o-ring seals, thereby minimizing the possibility of kerosene leakage into the wellbore.

CALIBRATION

Only one size of pipe is required during TFM calibration with the packer inflated, as compared to non-packer calibration where many different-sized pipes are required to simulate the wide variety of borehole dimensions that may be encountered. The calibration tank used in this study can be fitted with a large variety of pipe sizes, and was set up with an 20-cm-diameter PVC pipe during this calibration. The calibration tank consists of a 750-liter nalgene tank, a 20-cm-diameter by 1.8-m-tall PVC simulated well, a 75 l/min submersible pump, three flowmeters (0 to 3.8 l/min, 0 to 19 l/min, and 0 to 75 l/min), a constant head tank, and miscellaneous valves, PVC pipe and fittings (Figure

Figure 8. Submersible pump schematic.

9). The valves are used to control the volume of water flowing through the 20-cm pipe, and can direct the water in upward or downward directions. The appropriate flowmeter is used to measure the flow rate through the pipe, but a graduated cylinder and stopwatch are used for ultra-low flow rates (0.4

Figure 9. Calibration tank (water tank, simulated wellbore, flowmeters, and miscellaneous control valves).

to 0.08 l/min). To insure that flow rates are constant, they are recorded at the beginning and end of each suite of calibration measurements.

The tank is filled with hot tap-water the night before calibrations are to start to deoxygenate the water as much as possible; oxygen bubbles collecting on the heat-grid and thermistors adversely affect the TFM response. Water in the tank is homogenized prior to the start of calibration by pumping water through the 20-cm pipe and overflowing back into the tank. Water in the tank also

acts as insulation around the 20-cm pipe, greatly decreasing the thermal convection within the pipe. Once the water is homogenized, the valves are adjusted to their proper positions to achieve the proper flow rate and direction.

The differential temperature response measured by the TFM is plotted in real-time on the computer monitor. Software was developed to control the triggering of the TFM by depressing a function key (F1) on the computer's keyboard. The computer monitors the differential temperature and measures the heat-pulse response-time measured by the TFM. After monitoring the real-time graphical response on the computer monitor, the operator saves the measured response times by depressing another function key (F3). By depressing the F3 key, the running mean and standard deviation are computed and displayed on the computer monitor. The operator then depresses the F1 key to trigger another heat-pulse from the TFM; however, the operator must wait until the previous heat pulse has completely dissipated and the capacitors are fully charged (greater than 95 VDC). The amount of time between measurements depends on the flow rate through the tool. Typically, the operator should allow five times the flow response time or 10 minutes, whichever comes first (Hess, 1990). The operator may take several measurements while waiting for the TFM to stabilize. To zero-out the statistics, the operator depresses the F4 key; this also records the final mean and standard deviation to a data file. Although the measurements are saved by the computer, the operator should hand copy all measurements with pen and paper. A mean and standard deviation are computed from a minimum of ten measurements at each flow rate. In many cases, during laboratory conditions, the standard deviation is two orders of magnitude lower than the mean. This produces extremely well-defined calibration curves.

Once the calibration measurements are complete, two calibration graphs are plotted: one for upward flow and one for downward flow. For upward flow, the heat-pulse response times (seconds) are plotted on the x-axis and the flow rates (liters per minute) are plotted on the y-axis (Figure 10). Polynomial regression is performed on the data; coefficients from this regression are entered in the computer program previously mentioned. Then, during future TFM surveys, the operator can monitor borehole flow rates in the field without laboring over tedious post-processing. By entering the borehole diameter the computer program can also compute borehole velocities. Data for downward flow directions are presented the same as for upward directions, except the flow rates in downward directions are recorded as negative flow rate and heat-pulse response times are recorded as negative time (Figure 10). This notation is simply for bookkeeping purposes and has no computational significance.

FIELD TESTS

The TFM equipped with the packer and pump have been used in cased wells and uncased boreholes to measure flow rates at discrete depths. Generally, other logs are used to identify intervals where the TFM should be positioned, including: temperature, differential temperature, electrical conductivity, pH, caliper, fracture, acoustic televiewer, and video. Depending on the borehole diameter and flow rate to be measured, it may take up to 20 minutes to inflate the packer, 10 minutes to equilibrate, 10 to 60 minutes to take measurements, and 15 minutes to deflate the packer.

Figure 10. Flow direction calibration curves (negative values denote downward flow directions).

Measurements at 10 depths commonly takes 12 to 14 hours; therefore, it is important to use any information from other borehole logs that may help identify potential inflow/outflow zones. The following are examples of TFM results from two wells located in south-central Nevada.

WELL UE-10J

Well UE-10j is cased with 32-cm-inside-diameter casing from 0.30 m above land surface to 670 m below land surface, with the bottom 126.5 m uncased in carbonate rocks. The casing was cemented from land surface to the bottom of the casing (670 m).

On March 18, 1993, a temperature and electrical conductivity (EC) log was conducted in UE-10j and TFM measurements were made at seven discrete depths (Figure 11). A fluid level of 658.3 m and a total depth of 766.2 m were measured at that time (Table 2).

TABLE 2. Temperature and EC Logging Results for Well UE-10j.

	Depth (m)	Temperature (°C)	EC ($\mu\text{S}/\text{cm}$ @25 (°C))
minimum	659.9	32.3	596.3
maximum	766.2	33.8	854.0
range	107.5	1.5	257.7

The temperature gradient increased slightly with depth from the water table to 768 m (1.4°C per 100 m) (Figure 10). The EC increased approximately $100\ \mu\text{S}$ from the water table to 727 m, then increased approximately $75\ \mu\text{S}$ in a short 5-m interval from 727 to 732 m, and then steadily increased an additional $50\ \mu\text{S}$ from 732 to 765 m. No distinct inflow/outflow zones could be identified based solely on these logs.

Eight TFM surveys were conducted at seven discrete depths in UE-10j (Table 3). Slow downward flow was observed within the cased portion of the well. This is not believed to be significant because the TFM may not have equilibrated to the water and the reading may have been influenced by the immersion of the tool in the borehole; shallow measurements are commonly influenced by air bubbles on the TFM heat-grid and thermistors, which are dissipated at greater depths. Three flow regimes were identified from the TFM survey: 1) aside from one measurement at 730 m, gradually increasing upward flow was observed from the bottom of the borehole to approximately 716 m below land surface; 2) greatly increased vertical upward flow was observed at 705 m; and 3) little or no vertical flow was observed between the bottom of the casing and 695 m. Based on the TFM survey results: 1) relatively uniform inflow to the borehole is occurring from the bottom of the borehole to approximately 716 m (the slight decrease in flow at 731 m is not believed to be significant, and may be the result of a partial packer seat); 2) a fracture identified in the Acoustic Televiewer Log between 705 and 716 m is believed to be the source of inflow into the borehole, which corresponds to the increased vertical flow observed at 705 m; and 3) an area

Figure 11. Generalized well schematic, temperature/EC log and TFM results for well UE-10j.

between 695 and 705 m was identified as a zone of potentially fractured rock from the Acoustic Televiewer and Caliper Logs, and is believed to be the dominant outflow zone from the well.

TABLE 3. Thermal-pulse Flowmeter Survey Results for Well UE-10j.

Depth (m)	Bore Diameter (cm)	Response Time (sec)	Flow Rate (l/min)	Velocity (cm/min)
667.8	32.00	-5.50 ± 2.120	-0.15 ± 0.058	-0.187 ± 0.072
694.9	31.11	10.20 ± 11.960	0.37 ± 0.432	0.484 ± 0.568
694.9	31.11	-6.92 ± 1.468	-0.11 ± 0.023	-0.143 ± 0.030
704.7	31.11	1.71 ± 0.112	3.84 ± 0.252	5.053 ± 0.331
716.2	31.11	4.38 ± 1.906	1.12 ± 0.186	1.470 ± 0.640
730.0	31.11	7.43 ± 1.276	0.56 ± 0.096	0.734 ± 0.126
734.5	31.11	4.78 ± 0.502	1.00 ± 0.105	1.310 ± 0.138
743.4	31.11	5.37 ± 0.540	0.86 ± 0.086	1.125 ± 0.113
762.0	31.11	6.53 ± 1.838	0.66 ± 0.186	0.870 ± 0.245

Negative values indicate downward flow.
Positive values indicate upward flow.

WELL UE-1Q

Well UE-1q was drilled as an exploration hole in 1980 and was deepened and recompleted. The original hole was drilled to a total depth of 742.8 m and was deepened to a total depth of 798.2 m. UE-1q is cased with 17.5-cm-inside-diameter casing from 0.46 m above land surface to 749.5 m below land surface, with the bottom 57.6 m uncased in carbonate rocks. The casing was cemented from land-surface to the bottom of the casing (749.5 m).

On March 17, 1993, a temperature and EC log was conducted in UE-1q and TFM measurements were made at six discrete depths (Figure 12). The fluid depth was 504.7 m and the total depth was 793.6 m at that time (Table 4).

TABLE 4. Temperature and EC Logging Results from Well UE-1q.

	Depth (m)	Temperature (°C)	EC ($\mu\text{S}/\text{cm}$ @25 (°C))
minimum	716.3	26.6	330
maximum	793.1	27.1	590
range	78.8	0.5	260

Figure 12. Generalized well schematic, temperature/EC log and TFM results for well UE-1q.

The fluid temperatures in the borehole are slightly cooler (0.3°C) than the fluid in the casing, which may be a residual effect of the cement used around the casing. The temperature gradient remained relatively constant from 755 to 775 m, then increased slightly with depth from 775 to the bottom of the hole (793 m). The EC remained relatively constant within the casing (about 350 μ S), increased approximately 250 μ S from the bottom of the casing (740 m) to 755 m, then decreased about 150 μ S from 755 to the bottom of the hole (793 m).

Nine TFM surveys were conducted at six discrete depths in UE-1q (Table 5). The first five measurements yielded questionable results, with measurements at the same depths changing from upward to downward flow. Review of these data suggested that the TFM packer was not fully inflated; the packer inflation time was increased for the four final measurements. Little or no downward flow was observed near the bottom of the casing. Slight downward flow was observed from 761 m to the bottom of the hole. Based on the TFM survey and the temperature/EC log, inflow is believed to be entering the well between 750 and 760 m, and may be near 753 m. Approximately half of the water flows out of the borehole between 780 and 790 m, the remainder flows out between 790 and 793 m.

TABLE 5. Thermal-pulse Flowmeter Results from Well UE-1q.

Depth (m)	Bore Diameter (cm)	Response Time (sec)	Flow Rate (l/min)	Velocity (cm/min)
731.5	17.53	999.9 $\pm$ 0.00*	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00
765.0	17.15	999.9 $\pm$ 0.00*	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00
791.8	17.15	10.4 $\pm$ 7.72	0.36 $\pm$ 0.267	1.55 $\pm$ 1.15
777.8	17.15	13.8 $\pm$ 3.74	0.25 $\pm$ 0.067	1.07 $\pm$ 0.29
765.0	17.15	999.9 $\pm$ 0.00*	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00
761.4	17.15	-4.27 $\pm$ 2.46	-0.22 $\pm$ 0.124	-0.93 $\pm$ 0.54
777.8	17.15	-4.32 $\pm$ 1.94	-0.21 $\pm$ 0.095	-0.92 $\pm$ 0.41
791.8	17.15	-7.60 $\pm$ 4.22	-0.10 $\pm$ 0.053	-0.41 $\pm$ 0.23
746.7	17.15	-38.1 $\pm$ 26.4	-0.01 $\pm$ 0.007	-0.04 $\pm$ 0.03

NOTE: depths are listed in the order that they were recorded

Negative values indicate downward flow.

Positive values indicate upward flow.

* = measurement was below calibration limits; 40 seconds

SUMMARY

To accurately measure water flow in boreholes greater than 15 cm in diameter, the TFM must be equipped with an inflatable packer; TFM accuracy decreases rapidly with increasing borehole diameter, unless equipped with a packer. By outfitting the TFM with an inflatable packer and small

submersible pump, and by interfacing the TFM with a computer, measurement accuracy was increased by nearly one order of magnitude, and statistical measurements of the error can be made. Conversely, by concentrating flow through the TFM with a packer, the maximum measurable flow rate is reduced by nearly an order of magnitude; at flow rates > 15 l/min the packer must be removed to quantify flows up to 57 l/min. With the packer inflated, the TFM has a useful flow measurement range of 0.08 to 15 l/min (with computed fluid velocities of 0.24 ± 0.012 cm/min to 45.7 ± 0.61 cm/min, respectively, in the 20-cm-diameter pipe used during calibration), compared to 0.8 to 57 l/min for the TFM without a packer.

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