

Measurement of the Groundwater Flow Velocity Based on Heat Pulse Method

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ABSTRACT

Groundwater flow is characterized by its small Darcy velocity generally in a magnitude of 10^{-6} ~ 10^{-3} m/s. Among the methods of measuring groundwater flow velocity, the heat pulse method, which measures the groundwater flow velocity indirectly by monitoring the temperature response around a heated object, is considered as a simple and economic feasible method. In the previous researches of heat pulse method, the forced heat convection model was widely adopted. However, for a small Darcy velocity, the effect of natural convection may be nonnegligible. To investigate the influence of natural convection in the heat pulse method, a series of experiments were conducted in the laboratory. The measuring equipment consists of a heated hollow copper sphere and 12 thermocouples around the sphere. The fine glass spheres were used as the tested porous medium and filled up in a channel with a square cross profile. The experiments were performed at various heating powers and controlled groundwater velocities. The results show that the temperature response is less obvious with the Darcy velocity decreasing, which means that a larger heating power is needed for measuring a smaller Darcy velocity. The minimum groundwater velocity in an order of 10^{-5} m/s can be measured by using the experimental system. In addition, natural convection occurs when the Darcy velocity is small and the heating power is large, i.e., the buoyancy become significant and comparable with the pressure.

1. INTRODUCTION

Groundwater flow velocity is an essential parameter for groundwater, geotherm and underground contamination migrations. The popular approaches to measure groundwater flow are using tracers, e.g., radioisotopes (Wiebenga, 1967; Drost, 1968; Jennings, 1968), acesulfame (Engelhardt, 2013) and heat (Sisodia and Otto, 1998), to indicate the groundwater flow. Among them, heat is considered as a reliable and economic tracer and has been used in many groundwater flow measurements. Some researchers used nature heat as a tracer to quantify the groundwater flow, which requires that the measuring area has non-equilibrium temperature distribution. Compared with nature heat, induced heat is a more general tracer.

The methods of measuring groundwater flow velocity based on induced heat can be classified into two categories. The first category is the methods based on steady heat transfer model. The heat emitter is heated continuously and the steady temperature distribution is used to quantify the groundwater flow velocity. Generally, it needs a long time, several hours to several days, to become steady, therefore, cannot measure flow velocity fast. An early work of measuring groundwater flow velocity was made by Ballard (Ballard, 1996a). An instrument which relies on a cylindrically shaped heater with 30 thermistors strategically placed on its surface. The instrument is permanently buried in the unconsolidated saturated subsurface. The theoretical fits of steady temperature distribution measured by 30 thermistors are compared with the analytical solutions to determine the velocity magnitude and direction. The technology is able to measure flow velocities in the range of 5×10^{-8} to 1×10^{-5} m/s, depending on the thermal properties of the medium in which it is buried. The probe was tested in an aquifer with flow induced by pumping, and directional flow was successfully measured with a lower detection limit of 0.8 m/day (9.26×10^{-6} m/s) (Ballard S, 1996b).

Another category is based on transient heat transfer model. The artificial heat emitter is heated in a short time and the transient temperature responses measured by the surrounding thermal detectors are used to determine the groundwater flow velocity. Sisodia and Helweg (Sisodia and Otto, 1998) designed a smaller probe with 6 sensors surrounding a heat emitter. It is able to determine flow velocity in laboratory experiments. However, later evaluations of this tool revealed obvious errors (Guaraglia et al., 2006) and the methodology was refined by increasing the number of sensors around the heat pulse emitter (Guaraglia et al., 2007, 2008). Further, a rotary thermal groundwater flowmeter (Guaraglia et al., 2009) was developed to increase the measurement accuracy of flow direction. Simulations showed that the probe would work properly with high flow. Flow direction was estimated with a mean squared error of 1.3° and a standard deviation of 0.9° .

More recently, a tool using the heat pulse methodology was developed for the measurement of three-dimensional groundwater flow velocities and directions (Lewandowski et al., 2011). The temperature increases obtained by the surrounding PT1000 temperature sensors are fitted by using software and then the flow velocity can be determined. The instrument was validated in laboratory experiments and then applied to measure the flow velocity in shallow sediments. Angermann et al. (Angermann et al., 2012a) developed a 3D algorithm for the inversion of flow velocity magnitude and direction from temperature breakthrough curves. The analysis is based on the analytical solution of heat transport in porous media. The heat pulse sensor was tested in the laboratory at absolute flow velocities range from 0.7×10^{-4} to 7.8×10^{-4} m/s and field measurements with velocities less than 0.3×10^{-4} m/s. The tool was also applied to (Angermann et al., 2012b) quantify the shallow hyporheic flow in a lowland river. The lowest average flow velocity given by the tool is 1.6×10^{-5} m/s.

The heat pulse methods mentioned above are based on forced convection heat transfer model with the local equilibrium assumption. However, a large heat pulse will create a high temperature increase in the area near the heat source. For example, for a heat pulse of

12 W and 60 s, the temperature increase of the heater is 21.7 K (Lewandowski et al., 2011). When the groundwater velocity is small and the temperature increase is large, the buoyance may be nonnegligible and nature convection may appear. The aim of the paper is to investigate the influence of nature convection in the heat pulse method.

2. MEASUREMENT THEORY

Generally, the heat pulse method is based on forced convection heat transfer model. The governing equation can be given as

$$\rho c \frac{\partial T}{\partial t} = -\nabla \cdot (\rho_w c_w \mathbf{u}_s T) + \nabla \cdot (k_{eff} \nabla T) + Q \quad (1)$$

where \mathbf{u}_s is the Darcy velocity, i.e., surface-averaged velocity, t is time, Q is the source term, ρ_w and c_w are the density and specific heat capacity of water, k_{eff} , ρ and c are the effective heat conductivity, density and specific heat capacity of the porous medium, respectively. For a uniform initial temperature distribution $T(\mathbf{x}, t=0)=T_0$, the solution of Eq. (1) can be written as the following scheme:

$$T(\mathbf{x}, t) = T_0 + \Delta T(\mathbf{x}, t) \quad (2)$$

where T_0 and ΔT are the initial temperature and temperature increase, respectively, \mathbf{x} denotes position.

According to the definition of specific heat capacity, the specific heat capacity of the porous medium can be determined by

$$\rho c = \rho_w c_w \theta + \rho_s c_s (1 - \theta) \quad (3)$$

The effective thermal conductivity k_{eff} is a very important parameter for heat transport, and many empirical models have been proposed to calculate it. For instance, Woodside and Messmer (Woodside and Messmer, 1961) suggested a simple model for a two-phase medium with a random distribution, e.g., water and sand or soil, which can be given as

$$k_{eff} = k_w^n k_s^{1-n} \quad (4)$$

where k_w and k_s are the heat conductivities of water and solid, respectively, n is the porosity.

Under the assumption of negligible natural convection, the flow field can be determined by Darcy's law:

$$\mathbf{u}_s = -K \nabla h \quad (5)$$

where K and h are the hydraulic conductivity and water head, respectively. When the water heads of the two water tanks are fixed (i.e., the boundary conditions of Eq. (5) are fixed) and the heat source Q is amplified to γQ , the velocity field has no change according to the assumption. Thus, for the same uniform initial temperature distribution $T(\mathbf{x}, t=0)=T_0$, the solution of Eq. (1) can be given as

$$T(\mathbf{x}, t) = T_0 + \gamma \Delta T(\mathbf{x}, t) \quad (6)$$

It means that the temperature increase ΔT is proportional to the heat source Q .

When natural convection is nonnegligible, amplifying the heat source Q will significantly change the velocity field near the heated sphere owing to nonnegligible buoyance. As a result, the temperature increase ΔT is no longer linearly proportional to the heat source Q . Therefore, in the experiments, for a fixed water head difference, the temperature increases at 12 nodes under different heating powers were monitored. The influence of natural convection can be identified by analyzing the relation between ΔT and heating power ΔT .

3. EXPERIMENTAL SYSTEM

The experimental system of Darcy flow through a porous channel was designed according to the experiments of Lewandowski (Lewandowski et al., 2011), which is photographed as shown in Fig. 1. The main parts of the experimental system consist of the data collector, flow channel and two water tanks to keep water heads. The channel filled with glass spheres of size in diameter range 0.8mm~1mm is used as a porous medium, which refers to the size of general sand sedimentation less than 2mm. The size of the test porous section is 1.1m×0.3m×0.3m. The flow velocity in the porous medium can be adjusted in a Darcy velocity range from 3.32×10^{-5} to 2.7×10^{-4} m/s by changing the water levels of the two water tanks. The measurement equipment is buried into the porous medium in the channel middle.

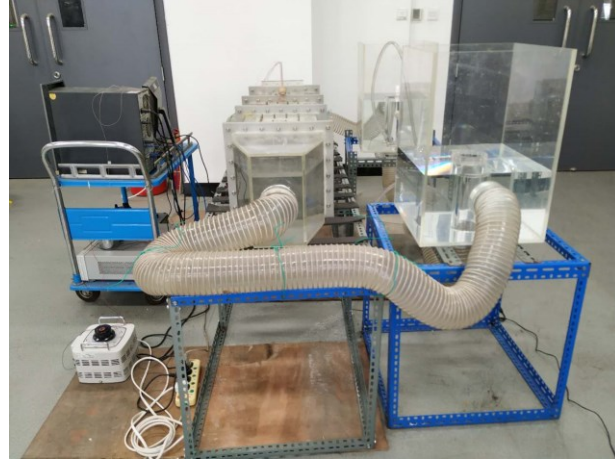


Figure 1: The experimental system, the main parts are data collector, flow channel and two water tanks

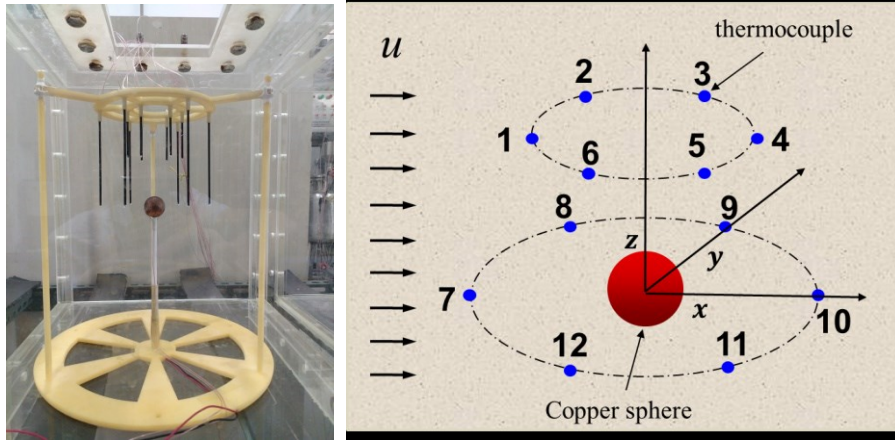


Figure 2: The measurement equipment (left) and its schematic (right)

The detailed geometric structure of the measurement equipment can be seen in Fig. 2. The heater is a hollow copper sphere of outside diameter 20mm and inside diameter 12mm. The electric heating wire is buried inside the sphere to generate heat pulse. Twelve T-type thermocouples, which are fixed by slender irons, are symmetrically distributed around the copper sphere. The accuracy of the T-type thermocouple is $\pm 0.1^\circ\text{C}$. The numbered thermocouples are shown in Fig. 2. The positions of these thermocouples can be illustrated using the XYZ coordinates as

$$\begin{aligned} x &= 50 \cos\left(i \frac{\pi}{3} - \frac{4\pi}{3}\right), y = 50 \sin\left(i \frac{\pi}{3} - \frac{4\pi}{3}\right) \\ z &= \begin{cases} 0 & i = 1, 2, 3, 4, 5, 6 \\ 25\sqrt{3} & i = 7, 8, 9, 10, 11, 12 \end{cases} \end{aligned} \quad (7)$$

where i is the serial number of thermocouples. The sphere center is located at the origin and the flow direction is the positive direction of X-axis. The frame of equipment was made by 3D printing technic of accuracy $\pm 0.5 \text{ mm}$. Considering the possible shift deviation in installing, the position deviations of the sphere and thermocouples are assumed to be $\pm 1.5 \text{ mm}$, which are not considered in data analysis. The data collector 34980A was applied to record all the temperature data of the 12 thermocouples and copper sphere surface, and voltage and electric current data of the electric heating wire inside the heating sphere. The sampling interval is 2 seconds.

The experimental procedures are given as follows:

- (a) Adjust the water head difference between the two water tanks.
- (b) When the flow is stable, start recording data.
- (c) After 2 minutes, start heating the sphere with a constant power P .
- (d) After 1 minute, stop heating the sphere.
- (e) When the temperatures of all the thermocouples are stable, stop recording data.
- (f) Change the heating power and repeat the procedures (b) to (e).

(g) Change the water head difference of the two water tanks and repeat the procedures (a) to (f).

Note that the initial time $t=0$ used in data analysis is the time to start heating the sphere. For every water head difference, the mass flux was measured three times by weighting the outflow water. Thus, the flow velocity across the sphere can be determined and all the relative errors are in the range of $\pm 3\%$. The corresponding water level at the channel middle was measured as well.

The experiments contain two parts. One part is measuring the temperature responses for seven different flow velocities (from 3.32×10^{-5} to 2.70×10^{-4} m/s) at three heat pulses (5.92W, 11.75W and 17.79W for 1 minute). The other part is measuring the temperature responses for different heating powers at a fixed small velocity 3.32×10^{-5} m/s.

4. EXPERIMENTAL RESULTS AND DISCUSSIONS

Firstly, the temperature responses for different flow velocities at three heating powers (5.92W, 11.75W and 17.79W for 1 minute) were investigated. After analyzing the temperature data of the 12 thermocouples, it was found that only thermocouple 10 in the downstream has an obvious temperature response. The temperature response curves of thermocouple 10 at different flow velocities and heating powers are shown in Fig. 3. It can be seen that with velocity increasing, the maximum temperature increase ΔT_{\max} of thermocouple 10 increases as well and the corresponding time of the maximum temperature (t_{\max}) decreases. The regularities are almost the same for the three different heating powers. It is noticed that the vertical axes in Fig. 3 have different scale in accordance with the heating power.

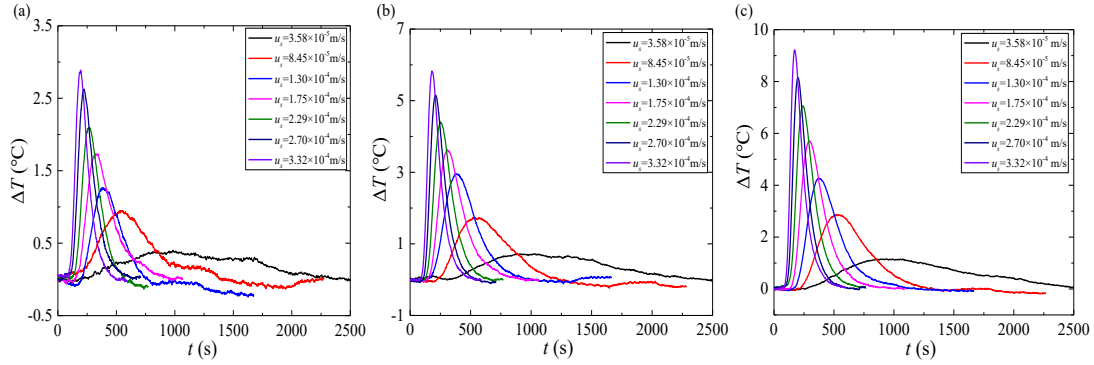


Figure 3: $\Delta T_{\max}/P$ and t_{\max} of thermocouple 10 against u_s at heating powers 5.92W (a), 11.75W (b) and 17.79W (c)

Furthermore, to show the relation between the temperature response and the heating power in quantity, $\Delta T_{\max}/P$ and t_{\max} at different velocities for three heating powers are summarized in Fig. 4.

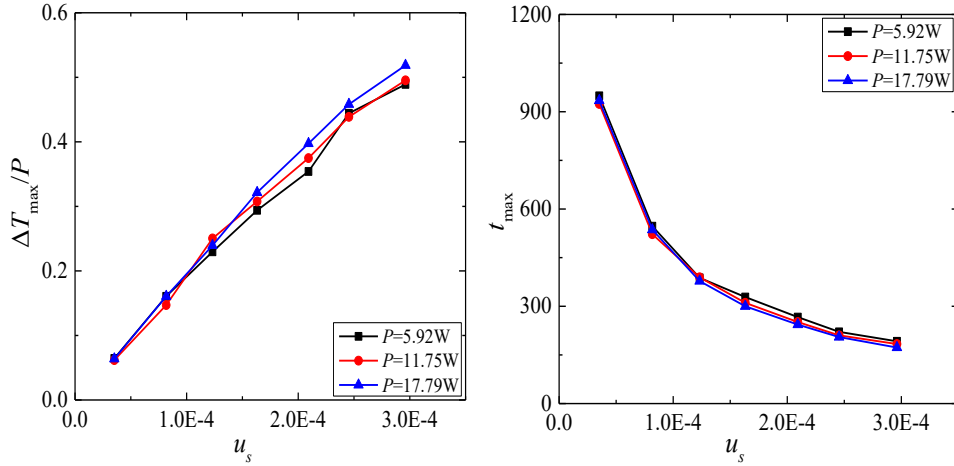


Figure 4: $\Delta T_{\max}/P$ and t_{\max} of thermocouple 10 against u_s at three different heating powers

It can be seen that the curves of $\Delta T_{\max}/P$ and t_{\max} against u_s at three different heating powers are much identical, which indicates that the velocity field is not perturbed obviously, i.e., the natural convection effect can be neglected. It can also be seen that with velocity decreasing, the value of $\Delta T_{\max}/P$ becomes smaller and smaller, i.e., the temperature response is less obvious. Even though t_{\max} is sensitive to small velocity, the exact t_{\max} is hard to obtain since the temperature response curve is much wide and flat in this case. It indicates that a stronger heat pulse is necessary to detect a smaller velocity. However, a stronger heat pulse may induce obvious natural convection.

According to the results, the empirical formulations of $\Delta T_{\max}/P$ and t_{\max} of thermocouple 10 can be given as follows:

$$\begin{cases} \Delta T_{\max}/P = -1.713 \times 10^6 u_s^2 + 2261.18 u_s - 0.01511 \\ t_{\max} = 1260 \times \exp(-u_s/432300) + 418.4 - 782700 u_s \end{cases} \quad 3.58 \times 10^{-5} \leq u_s \leq 2.70 \times 10^{-4} \quad (8)$$

Once $\Delta T_{\max}/P$ and t_{\max} of thermocouple 10 are obtained through experiments, the surface-averaged velocity can be determined. The theoretical accuracy of measurement is related to the heating power and velocity. For instance, for $P=12\text{W}$, real velocity $u_s=10^{-4}\text{ m/s}$, Eq. (8) gives $\partial \Delta T_{\max}/\partial u_s = 23021$. Assuming that the accuracy of ΔT_{\max} is the accuracy of T-type thermocouple ($\pm 0.1^\circ\text{C}$), we can obtain the error of u_s is $E(u_s) = E(\Delta T_{\max}) \times \partial u_s / \partial \Delta T_{\max} = \pm 4.34 \times 10^{-6}\text{ m/s}$. Here, the flow direction measurement is not considered.

To investigate the influence of natural convection for small velocity and strong heat pulse, the temperature responses for 6 different heating powers at a fixed small velocity $3.32 \times 10^{-5}\text{ m/s}$ were investigated. In this group of experiments, thermocouples 4 and 10 show obvious temperature responses. As shown in Fig. 5a, for thermocouple 10, the value of $\Delta T_{\max}/P$ has no obvious variation for P less than 18 W, while slightly decreases with increasing P when P is larger than 18 W. For thermocouple 4, $\Delta T_{\max}/P$ has obvious increase with increasing P . On the other hand, Fig. 5b shows that t_{\max} of the thermocouple 10 has no obvious variation with increasing P . However, t_{\max} of the thermocouple 4 placed at the top right of the sphere has an obvious decrease with increasing P . These results indicate that with increasing P , a vertical upflow occurs owing to the appearance of natural convection. As a result, the heat transfer in vertical direction was enhanced, and heat transfer in horizontal direction decreased relatively. It can be concluded that natural convection takes into the role for $P \geq 12\text{ W}$.

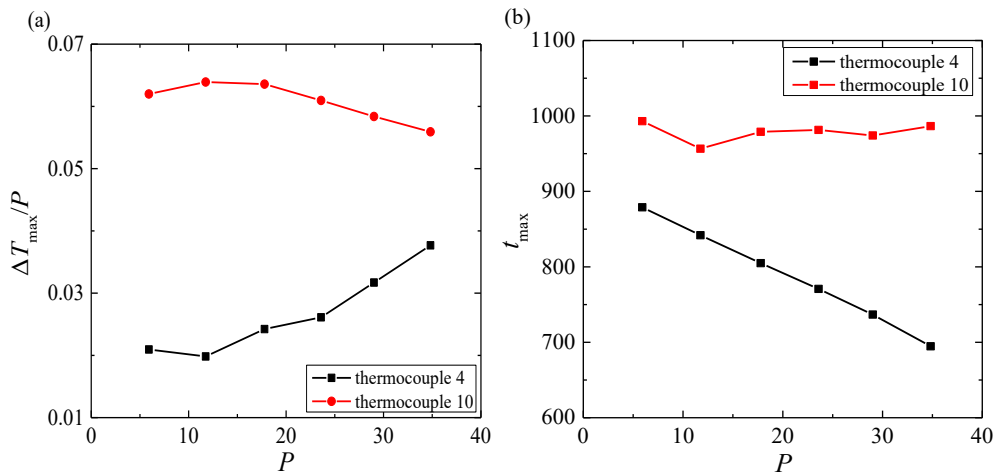


Figure 5: $\Delta T_{\max}/P$ and t_{\max} of thermocouples 4 and 10 at different heating powers

A reasonable parameter to quantify the relative strength between nature convection and forced convection is the ratio of pressure and maximum buoyance, i.e., $\nabla p/(\rho\beta g\Delta T_{\max,s})$. In the experiments, natural convection was observed at $u_s = 3.32 \times 10^{-5}\text{ m/s}$ and $P \geq 12\text{ W}$, the corresponding initial background temperature T_0 and maximum temperature increase of copper sphere surface $\Delta T_{\max,s}$ are 25.4°C and 20.5°C , respectively, the water head difference of 7 mm corresponds to a pressure gradient of $\nabla p = 64.24\text{ N/m}^3$. Choosing the volumetric thermal expansion coefficient β at $T_0 + \Delta T_{\max,s}/2$, the critical value of $\nabla p/(\rho\beta g\Delta T_{\max,s})$ is 0.9173. Therefore, the critical value is approximated as 1. Note that the critical value is also related to the heating duration and thermophysical properties of the solid phase. The critical value only fits to the present heat pulse method with heating duration of 1 minute for measuring groundwater in sand sedimentation (thermophysical properties are similar to the glass).

5. CONCLUSIONS

As a conclusion, the experiments prove that for heat pulse method with a heating power 12W for 1 minute, natural convection can be neglected in the flow velocity range from 3.58×10^{-5} to $2.70 \times 10^{-4}\text{ m/s}$. With velocity decreasing, the temperature response is less obvious. To measure a smaller velocity, a stronger heat pulse is needed. In addition, the experiments for investigating the temperature responses for 6 different heating powers at a fixed small velocity $3.32 \times 10^{-5}\text{ m/s}$ were performed, the results indicate that natural convection is obvious for a heating power larger than 12W. The ratio of pressure and maximum buoyance, i.e., $\nabla p/(\rho\beta g\Delta T_{\max,s})$ is applied to quantify the relative strength between nature convection and forced convection. The reference critical value of the present experiments is about 1. When the ratio is less than the reference value, the influence of natural convection is nonnegligible. Since the critical value is also related to the heating duration and thermophysical properties of the solid phase, the present critical value is only applicable to the present heat pulse method with heating duration of 1 minute for measuring groundwater in sand sedimentation.

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