Development of a Low-Cost Flow Meter for Measuring Subsurface Fluxes

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ABSTRACT

Subsurface flux measurements at the groundwater-surface water interface play a pivotal role in understanding and addressing contemporary environmental challenges. This research presents the development and application of a low-cost flow meter designed to quantify subsurface water fluxes. The instrument leverages a metal-ceramic ring for heating and temperature measurement, accompanied by a robust experimental setup capable of mimicking in-situ conditions, including variations in porosity, thermal conductivity, and water flow.

Through a combination of numerical modelling and experimental trials, this study establishes the effectiveness of the flow meter in quantifying subsurface fluxes. Key findings reveal a strong correlation between power supply and temperature rise, illustrating the instrument's sensitivity to changes in subsurface conditions. Moreover, the impact of flow velocity on temperature variations underscores the instrument's utility in assessing groundwater-surface water interactions.

The research culminates in the conclusion that the low-cost flow meter holds immense promise for revolutionising subsurface flux measurements. The instrument's ability to provide accurate and continuous data in real-time, even within soft sediments, positions it as a valuable tool for long-term deployments and single measurements alike. With discussions on potential solutions, challenges associated with installation methods are addressed, ensuring the instrument's applicability across a spectrum of environmental conditions.

In summary, this research contributes to the sustainable management of vital aquatic ecosystems, offering a cost-effective and versatile solution for quantifying subsurface water fluxes. The low-cost flow meter holds great potential for furthering our understanding of critical environmental processes and supporting informed decision-making in water resource management.

Keywords: Heat Methods, Micro-controller, Numerical Simulation, Design of Experiment

1 INTRODUCTION

Understanding and quantifying subsurface water fluxes at the groundwater-surface water interface is pivotal in unravelling aquatic ecosystems' mysteries and addressing contemporary challenges. This introduction embarks on a journey through the current state of measuring subsurface fluxes, the significance of such measurements, the associated challenges, and how we aim to overcome them with the development of a low-cost flow meter.

The Significance of Subsurface Flux Measurements:.

River-groundwater interactions have emerged as central to addressing numerous critical environmental issues, ranging from ensuring an adequate supply of high-quality drinking water to preserving biodiversity in river ecosystems and managing environmental flow regimes. These interactions involve complex feedback mechanisms between the stream bed's hydraulic, sedimentological, biotic, and chemical processes [2]. The hyporheic zone is particularly interesting and recognised as a biogeochemical hotspot in river ecosystems [3].

Within this hyporheic zone, exchange water fluxes hold the key to understanding the physical and chemical drivers of nitrogen transformations and the attenuation of contaminants. These insights are essential for maintaining the ecological quality of groundwater-fed rivers [1].

Moreover, this unique interface offers conditions for pollutant reactions from both surface water and groundwater, making it a potential hotspot for pollutant mitigation [6].

Existing Methods and Challenges:.

Efforts to measure subsurface fluxes have led to the application of environmental tracers like temperature and radon (222Rn) [1]. These tracers have provided valuable insights into the exchange between rivers and the subsurface. However, the hyporheic zone's complexity and inaccessibility pose significant challenges for experimentation (area).

While essential for various scientific and engineering applications, traditional steady-state methods for determining soil thermal and hydraulic properties have limitations in terms of accuracy and practicality [5]. To overcome these limitations, we draw inspiration from the ”Heat Pulse” method, which allows for accurate and continuous measurements of soil thermal properties. This method is the foundation for our low-cost flow meter, using a metal-ceramic ring heated in sediment and monitored with a thermistor. Observing temperature variations over time and peak temperatures can give us valuable information about flow characteristics.

The Path Forward:.

Our ultimate aim is to develop a cost-effective flow meter that addresses the challenges of subsurface flux measurement, particularly in the soft sediments, which we term Subsurface anemometry. This idea is inspired by Natalie Simon’s work [7]. Using the heat method, we aim to improve our understanding of groundwater-surface water interactions and contribute to the sustainable management of vital aquatic ecosystems. Instrumentation for flow meters involves a systematic approach encompassing three key phases.

Initially, a lab or proof of concept stage is undertaken to test the feasibility and accuracy of the selected flow meter technology in controlled conditions. Subsequently, during the in-situ application phase, the flow meter is deployed in its intended operating environment to gather real-world data. This phase allows for the assessment of the meter’s performance in practical scenarios. Finally, it is essential to identify any mechanical design issues that may arise during in-situ application and make necessary modifications to ensure optimal functionality. These iterative steps are crucial for ensuring the reliability and precision of flow meter instrumentation

In the subsequent sections of this research paper, we will delve into the intricate aspects of our innovative low-cost flow meter, elaborating on its design, methodology, and rigorous validation process. Our objective is to showcase how this technology has the potential to revolutionise our approach to subsurface flux measurements, shedding light on critical environmental processes that impact aquatic ecosystems and beyond. Furthermore, we will explore the mechanical design of the flow meter to provide a comprehensive view of its functionality and reliability.

2 METHODOLOGY

The methodology employed in this study leverages the principles of heat transport within a metal-ceramic ring when subjected to controlled heating. The temperature differential observed between the heated ring and the surrounding media serves as a crucial indicator of subsurface conditions, including thermal conductivity and groundwater flow patterns, both in boreholes and sedimentary environments.

The intensity of groundwater flow plays a pivotal role in influencing temperature variations and stabilisation within the system. Consequently, higher temperature differentials (T) may correspond to lower flux values, contingent upon a given thermal conductivity parameter. This fundamental concept finds support in Natalie Simon’s research, as demonstrated in her work titled ”Numerical and Experimental Validation of the Applicability of Active-DTS Experiments.” [7]

The heat transport phenomena occurring within saturated porous media, involving both conduction and advection, are mathematically described by the following heat transport equation:

$$\frac{\partial T}{\partial t} = D_t \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) - q \left(\frac{\rho_w c_w}{\rho c} \right) \frac{\partial T}{\partial x} \tag{1}$$

Equation 1 corresponds to the 2D advection-diffusion equation for a homogeneous, isotropic porous medium with a uniform, constant fluid flux q in the x direction. In this equation, T is the temperature (K), q the groundwater flux (or specific discharge) (m/s), ρc the volumetric heat capacity of the rock–fluid matrix (J/m^3/K), and $\rho_w c_w$ the volumetric heat capacity of water (J/m^3/K).

D_t is the thermal diffusivity coefficient (m^2/s) and depends on λ, the bulk thermal conductivity (W/m/K):

$$D_t = \frac{\lambda}{\rho c} \tag{2}$$

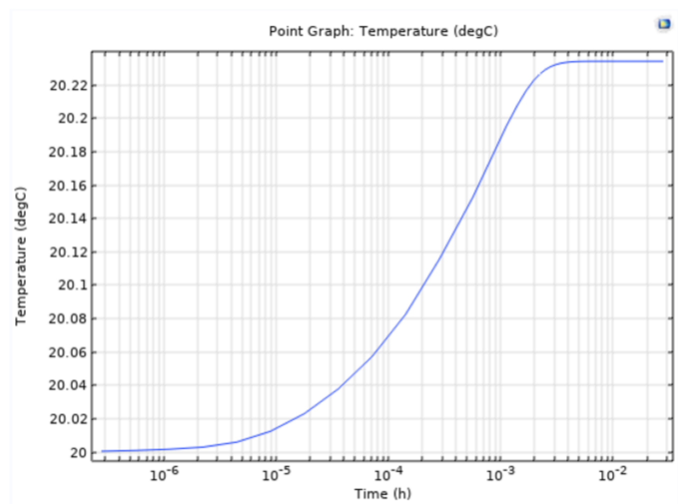

Fig. 1. Variation of Temperature with time from COMSOL Simulation

The temperature variation over time for the metal-ceramic ring is depicted in accordance with the numerical model. The stabilisation temperature observed in this context is contingent upon several key factors, including the power input to the ring, the subsurface flux, and the thermal conductivity of the surrounding medium.

A comparable temperature-time profile is also observed for the Fiber Optic (FO) Cable, exhibiting similar characteristics.

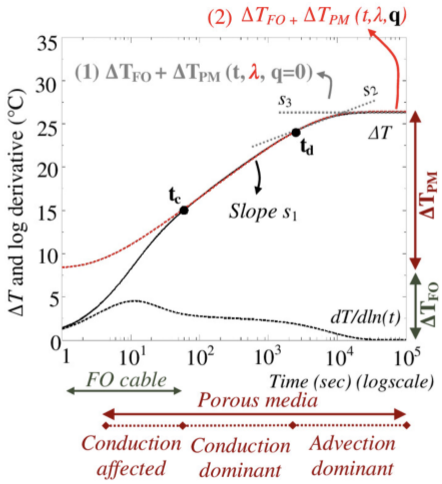

Fig. 2. Active-DTS Temperature Time Variation from Nataline's Work

3 EXPERIMENTAL SETUP

Design of Experiment: Overview

In our quest to replicate in-situ conditions, we meticulously designed our experimental setup with a keen focus on simulating key environmental factors, including porosity, thermal conductivity, and the manipulation of water flow within the medium. The following sections provide a detailed overview of the components and apparatus used in our experimental setup, as illustrated below. The primary components include the Metal-Ceramic Ring, Cylindrical Channel, Circuitry, and a Peristaltic Pump.

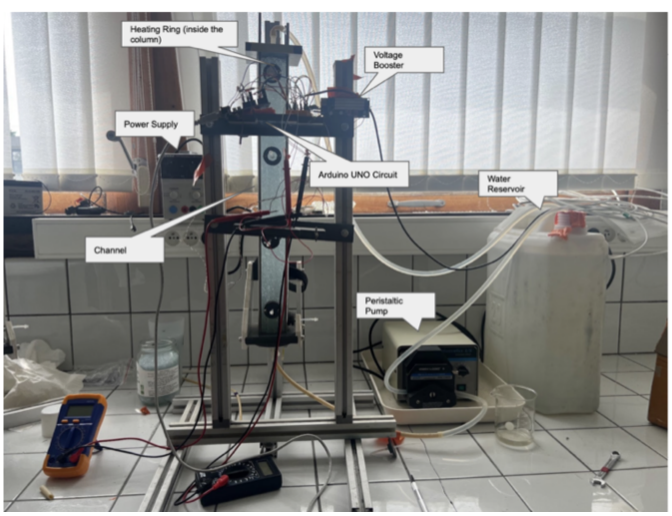

Fig. 3. This represents the experiment setup used for mimicking subsurface

Heating Element:

For the purpose of heating and temperature measurement within our experimental setup, a Metal-Ceramic Ring is employed. This heating element has a power rating of 10 watts when supplied with 24 volts of electrical power. The dimensions of the ring are as follows:

- Outer Diameter: 24.9 mm
- Inner Diameter: 20.0 mm
- Thickness: 1 mm

This Metal-Ceramic Ring serves as the primary heat source in our setup, enabling precise control over the temperature of the surrounding medium. It plays a crucial role in facilitating the heat pulse method, allowing us to obtain accurate and continuous temperature measurements.

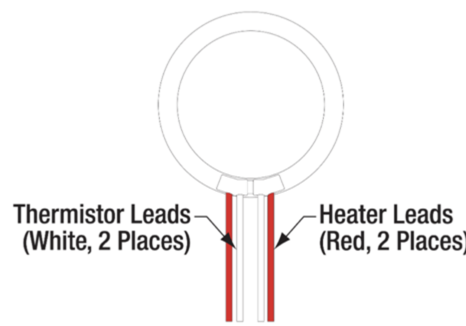

Fig. 4. Heating Element- Metal Ceramic Ring

Thermistor:

Within the Metal-Ceramic Ring assembly, we have incorporated a Negative Temperature Coefficient (NTC) thermistor. This thermistor exhibits a negative thermal coefficient, meaning its resistance decreases as temperature increases. The thermistor is characterised by a resistance (R) of 10,000 ohms (10k ohms) at a reference temperature.

The thermistor is strategically positioned between both thermistor leads, enabling us to monitor temperature changes within the Metal-Ceramic Ring and, consequently, the surrounding medium. The resistance variation of the thermistor in response to temperature fluctuations is a critical parameter used in our temperature measurement and data acquisition process.

By combining the Metal-Ceramic Ring as a heating element with the NTC thermistor for temperature sensing, we have established a robust and accurate system for precisely controlling and measuring temperature variations within our experimental setup. This arrangement plays a central role in implementing the heat pulse method, which is fundamental to our subsurface flux measurement approach.

Cylindrical Channel:

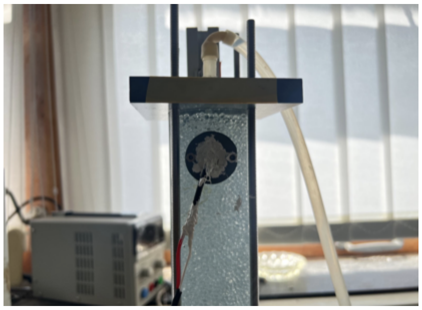

Fig. 5. Cylindrical Channel

The channel we used in the experiment consists of 2 porosities, one created using small glass beads and the other using sand. The characteristics are stated below.

- Channel Diameter 5 cm
- Height of column 51.5 cm
- Volume of channel 1010 ml
- Porosity of Glass Beads 0.33
- Porosity of Sand Column 0.4

Pumping Source:

A variable flow rate is achieved in the channel using a peristaltic pump. The speed range of the pump is 0.5 cm/s to 4 cm/s in the channel. A split distribution flow setting is also used to achieve more lower flow rates. The lowest volume rate we achieved is 0.0031 L/min with the split distribution. In contrast, the lowest flow rate with the pump is 0.025 L/min.

Fig. 6. Cylindrical Channel

Circuitry:

The electronic circuit design involves:

Supplying constant power to the ring

Sensing the temperature through an NTC thermistor

A microcontroller for plotting and storing data in real-time

A brief schematic of the connections is mentioned. A detailed description will be discussed in the later sections.

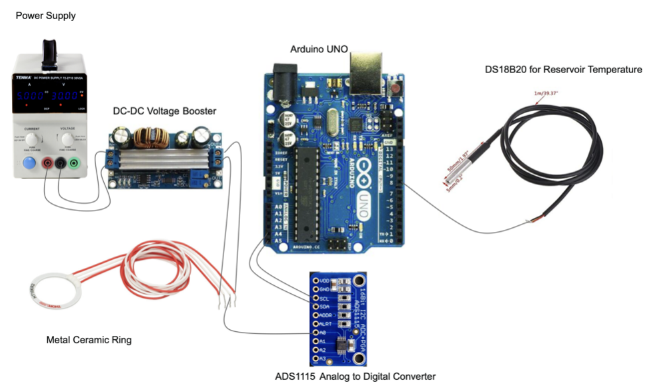

Fig. 7. Brief Schematic of circuit

DC-DC Voltage Booster:

A DC-DC Voltage Booster is used in the circuit so as to provide constant power to the metal-ceramic ring heater. This is to ensure a regularised output irrespective of varying inputs to the voltage booster. The calibration of the output power is done as mentioned below. Output Voltage can be adjusted by turning the CV potentiometer without connecting to the load. Then, without disturbing the CV potentiometer, the load is connected, and the output current is monitored.

DS18B20 Temperature Sensor:

A one-wire digital temperature sensor is used to measure the temperature of the reservoir, which plays an important role in the calculation of temperature rise because of heating.

Analog to Digital Converter:

All microcontrollers already consist of ADC pins, but they lack high precision. So, ADS1115 is used, which has a high precision with 16 bits.

4 SIMULATION

Figure shows that the numerical model considers a simple 2D domain within which heat transfer occurs with steady-state fluid flow in porous media. Simulations were done using the Conjugate Heat Transfer module of COMSOL Multiphysics. Mesh size ranges from 4.85 * 106 to 2.68 * 10 2 m with the finest meshes around the heating source.

There are some assumptions taken into consideration while modelling on COMSOL, Even though the experiment describes a finite domain, the in-situ case is infinite. A larger domain than the heating element size is considered for the same. The exact geometry of the heating element (i.e., a ring) is replaced by a small disc of the same size for easier computation. However, the power supplied to the disc remains the same.

Considering the mesh size of the model as a characteristic length (COMSOL Multiphysics), the Courant number ranges between and 0.62, and the Peclet number ranges from to 0.91; such values lower than 1 ensure numerical stability.

5 RESULTS

Both experiments and simulations were performed on various conditions. Those include the effect of power supplied and the Orientation of the Ring with respect to the flow. The numerical results are discussed below.

Numerical Simulation Results

The numerical model mentioned above is used to obtain the Delta T vs Time variation. These results perfectly synchronise with the variation of results in Natalie Simon's work, Numerical and Experimental Validation of the Applicability of Active-DTS Experiments.

Though there is a similarity with the FO-cable experiment's results, the time required to reach peak temperature in this case is not more than 100 seconds, making it perfectly suitable for in-situ utilisation.

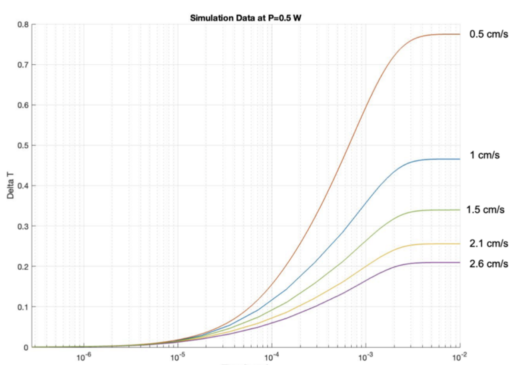

Fig. 8. Results obtained from Numerical Simulation

This plot described how increasing flow velocity will decrease the peak temperature reached.

Experimental Results

The experimental results absolutely match with the results obtained from a numerical model. The only point of concern with respect to these results is the smoothness of the curve. The Arduino UNO being used in the data collection cannot collect temperature data at a higher frequency because of the heating caused to the thermistor while measuring temperature.

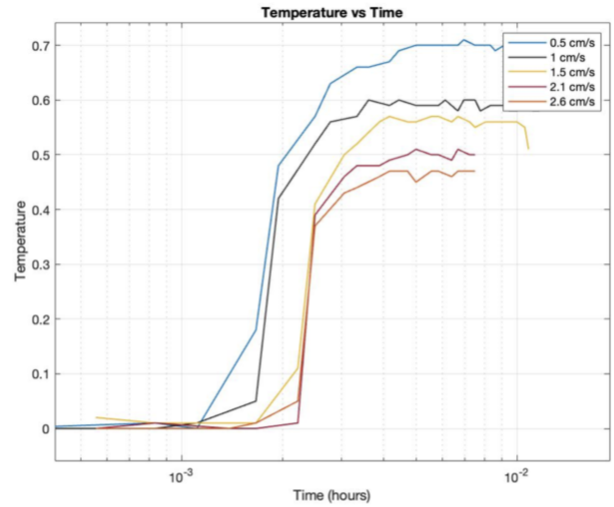

Fig. 9. Results obtained from Experiment

The variation of the peak temperature with power supplied to the ring is also considered. There is a linear variation of temperature with respect to the power, which is provided by following experimental results.

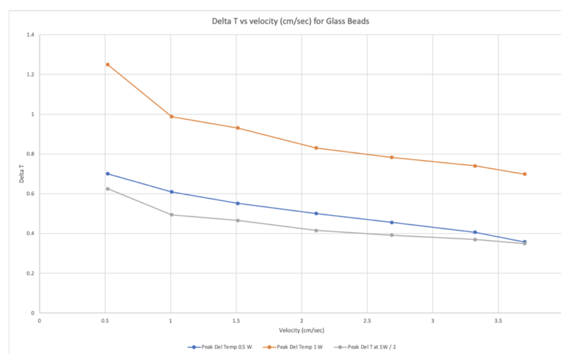

Fig. 10. Effect of velocity on Peak Temperature obtained

Through experiments it was evident that the peak temperature was independent of the orientation of the ring.

6 MECHANICAL DESIGN

Even though there is a strong theoretical basis for the total mechanism, the problem arises when installing the flowmeter. Field trials have yet to be conducted, but there are several installation methods that might be envisaged. In suitably soft sediments, the probe might be pushed directly into the substrate on the end of a spear, which could then be withdrawn to leave the probe in place for long-term deployment or withdrawn with the probe attached for single measurements. In more consolidated sediments or those containing larger grains, it would be possible to use a 'lost-point' technique. This method is discussed in detail in "A heat perturbation flow meter for application in soft sediments"[4].

Also, there is a soil compactness disturbed when installing and is normalised as flowing sediment evens it out.

7 CONCLUSION

In our pursuit of understanding and quantifying subsurface water fluxes at the groundwater-surface water interface, this research has yielded significant insights and advancements. The development and application of a low-cost flow meter featuring a metal-ceramic ring for heating and temperature measurement have been demonstrated as a promising approach.

Through rigorous experimental trials and numerical modelling, we have established the instrument's effectiveness in quantifying subsurface fluxes. The correlation between power supply and temperature rise showcases its sensitivity to changing environmental conditions. Furthermore, the influence of flow velocity on temperature variations highlights its utility in assessing groundwater-surface water interactions.

We have outlined potential solutions to the challenge of installation methods, enabling the flow meter's deployment in diverse environmental settings, from soft sediments to consolidated substrates.

This research represents a significant step forward in our ability to monitor and comprehend critical environmental processes, contributing to the sustainable management of aquatic ecosystems. The low-cost flow meter offers an affordable and versatile tool for researchers and practitioners, paving the way for more informed decision-making in water resource management and ecological preservation. As we look ahead, the potential for this instrument to revolutionise subsurface flux measurements is both promising and exciting.

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