# Capacitance-Based Fluid Flow Measurement

Exploring Non-Intrusive Techniques for Real-Time Fluid Flow Measurement

Personal Project

[#6]

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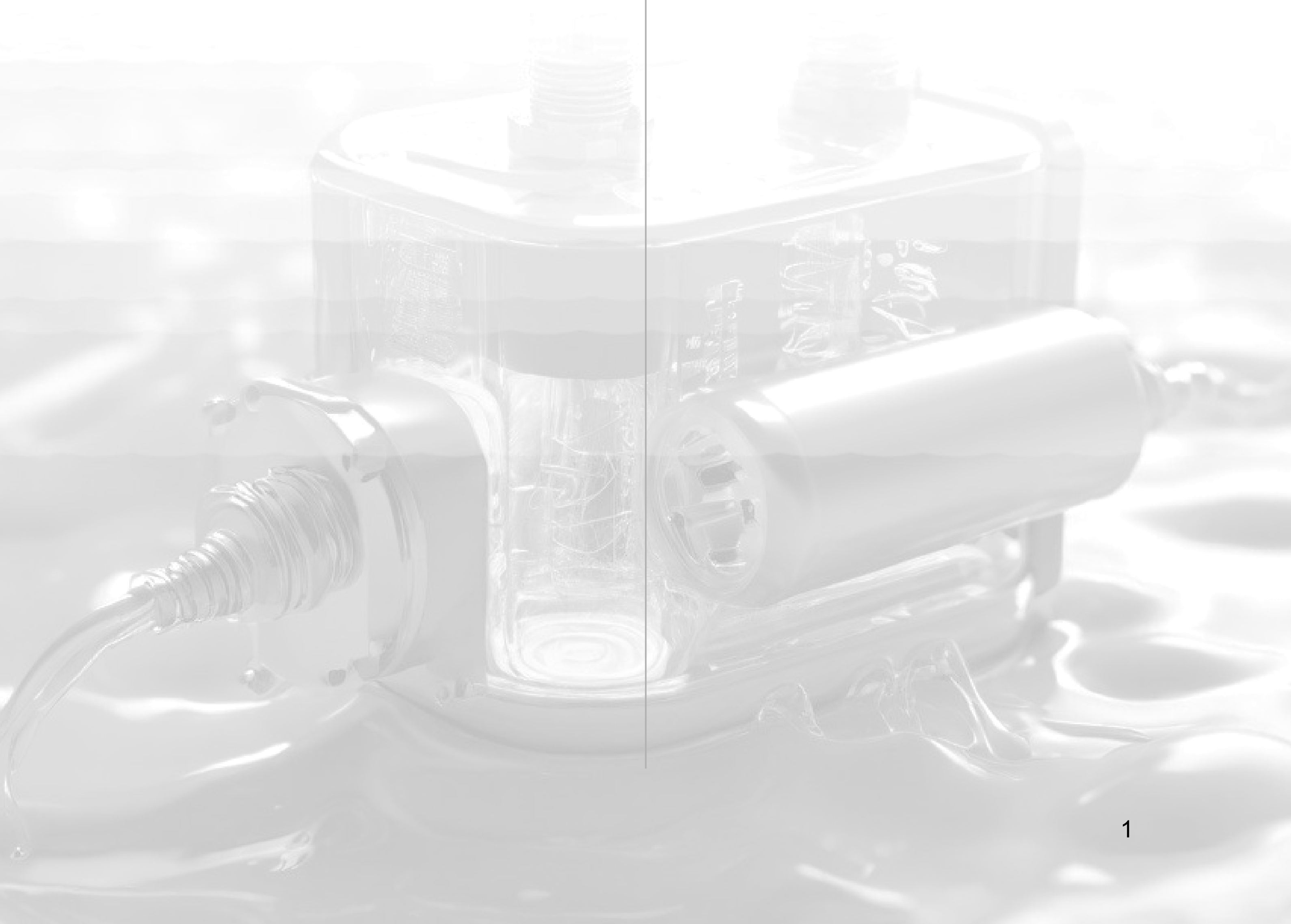


## Abstract

The first approach uses a 555 timer circuit to produce frequency changes proportional to capacitance variations, allowing the detection of flow rates. The second method measures current in a DC setup, where dielectric changes induce minimal yet detectable current shifts. Lastly, the AC circuit approach provides greater control, using impedance adjustments to enhance sensitivity to dielectric variations. Together, these methods establish a foundation for refining capacitance-based flow measurement technology, highlighting its potential as a practical, non-intrusive solution for fluid flow monitoring.

While currently a work in progress, this initial setup opens avenues for expanded testing and optimization to improve accuracy and applicability in various environments.

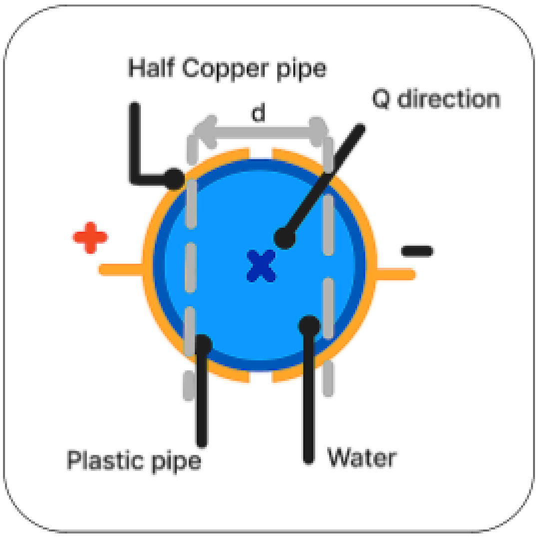




*Figure 1. Illustration*

*Figure 2. Prototype*

# 1. Objective

The primary objective is to measure water flow by detecting capacitance changes in a capacitor with a variable dielectric. The capacitor's dielectric constant changes with the flow rate of water, influencing the measured capacitance, which then serves as an indicator of flow rate.

# 2. Methodology

The project is divided into three main experiments:

1. **555 Timer-based Frequency Measurement**: A 555 timer generates a square wave, with the output frequency inversely proportional to the capacitance. The frequency shifts with water flow, indicating variations in dielectric properties.

2. **DC Current Measurement**: A DC voltage is applied, and the capacitor is charged. Current changes, induced by fluctuations in the dielectric due to water flow, are detected.

3. **AC Current Measurement**: An AC signal is applied, allowing impedance and frequency adjustments to detect changes in capacitance. This setup provides control and adaptability but may present challenges in different environments.

Each method is designed to capture the effect of water flow on capacitance, offering flexibility and insight into how capacitance-based flow measurement can be applied in real-world conditions.

# 3. Theory

## 3.1 Capacitance

$$C = \frac{Q}{\Delta V} = \frac{\epsilon_r \epsilon_0 A}{d}$$

*(1)*

$$I = Q f$$

*(2)*

Rewriting left side of equation 1 and utilising equation 2 we get that the current through the capacitor follows the equation below

$$I = f\, C\, \Delta V$$

*(3)*

The insulating material within the plates of the capacitor when supplied by a constant voltage will induce a current during the charge time of the capacitor, when fully charged, ideally no current will pass through. Lets prove the relationship between this current and the flow rate that will be the insulation material of the capacitor.

Electrical field E exposing a volume of fluid leads to an absorbent of some energy which is given by:

$$E = \frac{V}{d}$$

*(4)*

$$W = \iiint_v \frac{1}{2}\epsilon E^2 dv$$

*(5)*

This will exert power when in motion and therefore this power is the time derivative of energy W.

$$P = I\, V = \frac{dW}{dt}$$

*(6)*

Right side of equation 6 becomes:

$$\frac{1}{2}\epsilon E^2 \frac{dv}{dt}$$

*(7)*

Now we observe that the change of volume over time is flow rate: Q = dv/dt and we can therefore find the relationship between current and flow rate when combining this with equation 6 & 7 to;

$$I\, V = \frac{1}{2}\epsilon E^2 Q$$

*(8)*

The electric field can be replaced with equation 5 and we find the final relationship with the help of ohm's law:

$$I = \frac{1}{2}\epsilon \frac{V}{d^2} Q = \frac{V}{R}$$

*(9)*

In summary, when a constant voltage is applied to a capacitor with a fluid as the insulating medium, the current I will linearly depend on the flow rate. With no flow, resistance R converges to infinity, and the capacitor fully charges. During the charge time, the voltage V changes, inducing current. Once fully charged (constant V), current can only be induced by a change in the insulating medium's properties ($\epsilon$), plate distance (d), (both regarded as constant in this experiment) or the flow itself, which is the focus of this project.

## 3.2 555 Timer and its Capacitance dependency

The 555 timer is an integrated circuit (IC) widely used in pulse generation, timers, and oscillators. It operates in three primary modes where we will utilise the Astable Mode, which generates a continuous square wave signal.

The generated square wave is created by the timer continuously switching between its high and low states, the key to this operation is the timing capacitor C and resistors R1 connected to the discharge pin and R2 connected to the threshold pin.

The frequency of the oscillations and the duty cycle (D) of the square wave are determined by C, R1, and R2, and follows the equations:

$$f = \frac{1}{T} = \frac{1.44}{(R_1 + 2R_2) \cdot C}$$

*(10)*

$$D = \frac{T_{on}}{T_{on} + T_{off}} = \frac{R_1 + R_2}{(R_1 + 2R_2)} \%$$

*(11)*

Equation 10 shows the linear relationship between the frequency and the capacitance which we will utilise to find the fluid flow through the capacitor.

## 3.3 Capacitor in an AC circuit

In an AC circuit, a capacitor reacts to the changing voltage by storing and releasing energy, causing a phase shift between the voltage and the current. The relationship between the current I, the capacitance C, the voltage V, and the angular frequency ω of the AC signal is given by equations 1 and 2. For a sinusoidal signal the voltage and current is described by:

$$V(t) = A\, sin(2\pi f \cdot t + \phi)$$

*(11)*

$$I(t) = C \cdot A \cdot 2\pi f \cdot cos(2\pi f \cdot t + \phi + \frac{\pi}{2})$$

*(12)*

The impedance Z of a capacitor in an AC circuit is:

$$Z_c = \frac{1}{j\omega C}$$

*(13)*

Since we are primarily concerned with the amplitude of the measured current in this experiment, we use the magnitude of the impedance, which represents the "resistance" in an AC circuit. This can then be applied in conjunction with Ohm's law to establish the relationship:

$$V_{rms} = (R_{tot} + |Z_c|) \cdot I = (R_{tot} + \frac{1}{2\pi f \cdot C}) \cdot I_{rms}$$

*(14)*

This equation demonstrates that the measured current is linearly proportional to the total impedance of the circuit and the applied voltage, with the capacitance C directly affecting the impedance.

We have now three ways of directly measuring fluid flow.

# 4. Results and Discussion

## 4.1 Component values

Choosing component values is crucial to know that we are operating within boundaries such as bandwidth and noise tolerances.

### 4.1.1 DC circuit

The capacitor in this experiment is constructed by splitting a 35cm long, ⌀28 mm copper pipe lengthwise and clamping the halves around an ⌀26 mm diameter plastic pipe, which acts as the dielectric layer. The separation distance d (shown in Figure 1) represents the average distance between the copper electrodes. To approximate the dielectric constant, we use an effective layered dielectric method: the dielectric constant $\epsilon_r$ combines contributions from both the plastic pipe and the water within it.

The relative permittivity $\epsilon_r$ of the PVC plastic is approximately 2 – 4, while for water at room temperature, it's around 80. Using the formula for dielectrics in series, we can approximate the effective dielectric constant $\epsilon_{r,eff}$

$$\frac{1}{\epsilon_{r,eff}} = \frac{d_{plastic}}{\epsilon_{r,plastic}} + \frac{d_{water}}{\epsilon_{r,water}} \tag{15}$$

This yields an effective relative dielectric constant of approximately 1250. The Area is calculated using:

$$A = l \cdot h = l \cdot \frac{\pi\,(\varnothing - 2 \cdot thickness)}{2} \tag{16}$$

,where h represents the half-circumference of the pipe's inner surface (the concave side). This accounts for the thickness of the copper layers, as the effective area of the capacitor is based on the inside surface of the copper split pipe.

Calculating C from Equation 1 gives approximately 6.59 nF when the pipe is filled with water. and 0.053nF empty.

Using Equation 9 with a flow rate of about 0.2 L/s (typical for household systems), a voltage of 12V, and the same pipe diameter, the estimated current I would be around 23nA. Since the Current I is inversely proportional to the square of the distance between the plates this setup would be suitable for smaller fluids. The sensitivity can be calculated:

$$S = \frac{\Delta I}{\Delta Q} = \frac{1}{2}\epsilon\frac{V}{d^2} = 115\mu A/m^3 \tag{17}$$

This range is relatively large, making precise measurements challenging. However, it would be more suitable for measuring smaller fluids or very high flow rates.

### 4.1.2 AC circuit

The AC circuit setup is similar to the DC circuit, but here the measured current depends on the frequency of the applied signal. The current is affected by the impedance of the capacitor, which changes as the capacitance varies, as shown in equation 13. This variation is also linked to the flow rate.

To determine the current range for the applied signal, we first need to choose an appropriate ADC to measure the current. The ESP32 features a 12-bit ADC with a range of 0V to 3.3V, giving a voltage step of 0.8mV per step (calculated as $3.3V / 2^{12}$)

Next, we convert the current into a measurable voltage across a known resistor using Ohm's Law. This is where Rtot from equation 14 comes into play. Keep in mind that the ESP32 GPIO pins are rated for a maximum current of 40mA. Assuming a $V_{rms}$ of 10V, the maximum circuit impedance can be calculated as 250Ω. This means that $R_{tot}$ + |Z_C| = 250Ω, where $R_{tot}$ is set to 220Ω, leaving |Z_C| = 30Ω for the maximum.

Given the expected maximum capacitance of 100nF, the frequency becomes the key variable in the following equation:

$$f = \frac{1}{2\pi\cdot 100nF\cdot 30\Omega} = 53kHz \tag{18}$$

To ensure that the GPIO pin current remains within safe limits (40mA), a frequency of 50kHz is chosen as a safe operating point.

Taken all this into account we can observe that the current through the circuit would be ranging from ~ 3mA — 40mA given by:

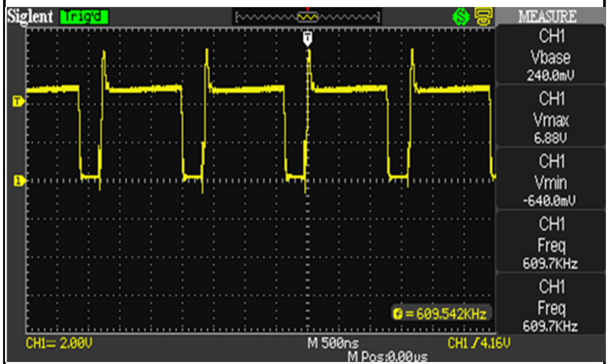
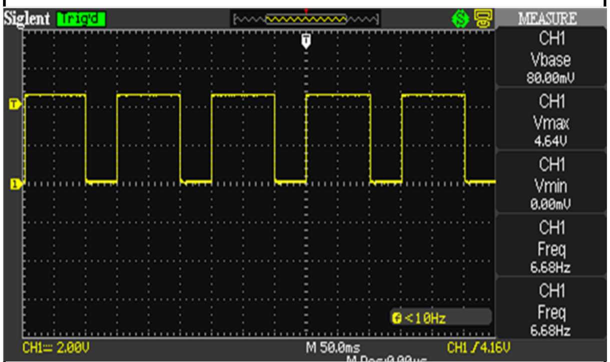
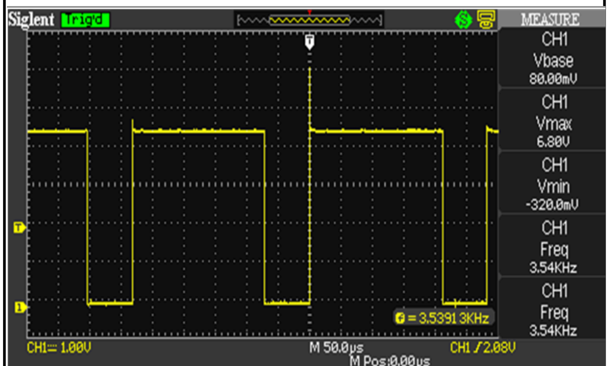
$$\frac{10}{220+\frac{1}{2\pi\cdot 50kHz\cdot 1nF}} \le I \le \frac{10}{220+\frac{1}{2\pi\cdot 50kHz\cdot 100nF}} \tag{19}$$

### 4.1.3 555 Timer

To ensure accurate measurements, a 50% duty cycle is ideal, but since this isn't achievable, we settle on $R_1 = R_2$ for a 66% duty cycle. The theoretical capacitance ranges from 0.053nF when empty to 6.59nF when filled with water. Assuming the capacitance can reach up to 100nF, we aim for a step size of 1nF = 1kHz for precise measurements. Given the uncertainty in how the flow will affect capacitance, we focus on a maximum capacitance of 100nF. Using equations 10 and 11, $R_1 = R_2 = 36k\Omega$) provides a broad measurement spectrum while maintaining an appropriate resolution.

The circuit was designed shown in figure 3, and output screenshots from the 555 timer were captured using various capacitors. All values were calculated and verified using equation 10.

*Table 1*

| No capacitor, pure noise |
|---|
| f = 609kHz → C = 23.4pF |
| <br> |
| Test with 2.2µF capacitor |
| f = 6.68Hz → C = 2.136µF |
| <br> |
| Test with 5nF capacitor |
| f = 3.54kHz → C = 4.135nF |
| <br> |

## 5. Future Work

Further experimentation is needed to optimize the sensitivity and reliability of each measurement approach. Future work should focus on improving the linearity of the 555 timer circuit's response to small changes in capacitance, which would help in achieving higher precision in flow measurement.

In addition to refining the existing setups, it would be beneficial to introduce a new measurement technique by building an oscillator circuit that sweeps across frequencies to identify the resonant frequency. This frequency would directly relate to the capacitance, offering another way to monitor flow-induced capacitance changes. This approach allows for high sensitivity to small capacitance variations, making it well-suited for dynamic conditions or applications requiring high precision. However, there are potential drawbacks: the complexity of the circuit increases, requiring additional components and potentially more advanced signal processing. Environmental interference could also affect the oscillator's accuracy, requiring additional shielding in high-noise areas.

Finally, integrating data logging and analysis with the ESP32 could enable real-time monitoring, allowing for more dynamic tracking of flow changes
sources. Refining the capacitor design or experimenting with alternative materials for the dielectric layer could also enhance measurement accuracy.

## 6. Key Takeaways

**DC vs. AC Measurements**: The DC setup was found to be insufficient for fluid flow measurements due to limitations in sensitivity at larger plate distances. T he AC circuit proved more adaptable, enabling finer tuning of parameters like frequency to respond to dielectric changes.

**Linearity and Sensitivity**: For optimal accuracy, the linearity of the 555 timer circuit's frequency response to changes in capacitance should be checked and calibrated. Ensuring a close-to-linear response would significantly improve the reliability of capacitance-based flow measurements.

**Practicality of Capacitance-Based Flow Measurement**: This project demonstrated that capacitance variations can effectively measure fluid flow in a non-intrusive manner. With further development, this technique has potential applications in various fields, especially where traditional flow meters that is installed inside pipes are unsuitable due to physical constraints or the need for minimal intervention.

These findings provide a strong theoretical foundation for the possibility of developing a capacitance-based flow measurement system, with clear paths for improvements and practical adjustments in future implementations.

# Appendix

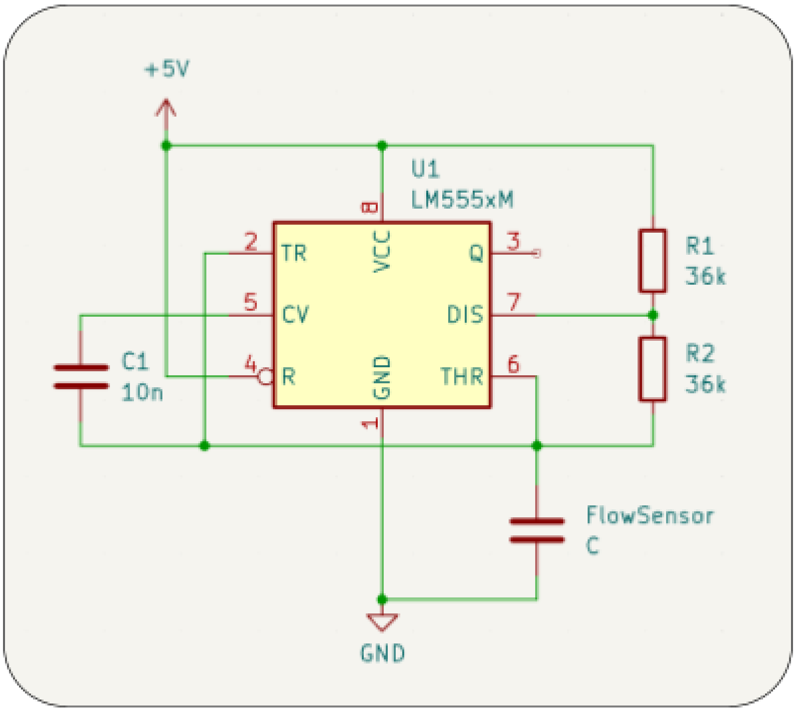



*Figure 3. 555 timer circuit in KiCad 7*