UNIVERSIDAD DISTRITAL
FRANCISCO JOSÉ DE CALDAS

Tecnura

https://revistas.udistrital.edu.co/ojs/index.php/Tecnura/issue/view/1253
DOI: https://doi.org/10.14483/22487638.20618

RESEARCH

Design and Testing of a Density Sensor for Biological Wastewater Treatment in a Pilot Plant

Diseño y prueba de un sensor de densidad para el tratamiento biológico de aguas residuales en una planta piloto

José Aldemar Muñoz Hernández[1], Helmer Muñoz Muñoz Hernández[2], Kavir Alá Oviedo Prioló[3] and Roberto Carlos Osorio Mass[4],

Fecha de Recepción: 21 de marzo de 2023 **Fecha de Aceptación**: 16 de octubre de 2024

How to cite: Muñoz Hernández J.A., Muñoz Hernández H.M., Oviedo Prioló K.A. and Osorio Mass R.C. (2024). Design and Testing of a Density Sensor for Biological Wastewater Treatment in a Pilot Plant. *Tecnura*, 28(81), 54-66. https://doi.org/10.14483/22487638.20618

Abstract

This paper investigates the design of a density sensor for wastewater treatment. Piezoelectric crystals were chosen for this application, although a vibrating tube element could also be used. The physical implementation, data processing, and sensor's electronic components are presented. The proposed sensor is capable of measuring density and characterizes the density profile inside the clarifier, as density correlates with the amount of flocs and dirt in the water. The entire sensing component of the sensor has been successfully developed and tested, with a preference for piezoelectric crystals. This sensor can differentiate between clean and dirty water, as it presents distinct output signals for both media at varying frequencies. Additionally, the electronic part of the sensor has been developed and tested, yielding satisfactory results.

Keywords: biological, piezoelectric crystal, ultrasonic, sensor.

[1]Petroleum Engineer, Universidad Surcolombiana- USCO Colombia. DSc in Engineering, Universiteit Leuven, Belgium. MSc en Automatic Control, Rijksuniversiteit Te Gent, Bélgica. Lecturer at Universidad del Tolima, Colombia. Email: amunoz@ut.edu.co

[2]Systems Engineer, National Unified Corporation of Higher Education CUN. DSc in Management, Universidad Dr. Rafael Belloso Chacín, Venezuela. MSc in Industrial Control Engineering, Universidad de Ibagué, Colombia. AXON research group leader, Colombia. Email: Helmer_munoz@cun.edu.co

[3]Physicist, Master of Business Administration, Systems Engineering Program Teacher, Member of the AXON Research Group, Category A in Minciencias, Unified Corporation of Higher Education CUN Email: kavir.oviedo@cun.edu.co

[4]Research Professor, Business Administration Program, Corporación Universitaria Remington, Industrial Engineer, MsC in Business Management and Administration. Email: roberto.osorio@uniremington.edu.co

Resumen

Este artículo investiga el diseño de un sensor de densidad para el tratamiento de aguas residuales. Para el estudio, se seleccionaron cristales piezoeléctricos, aunque un elemento de tubo vibratorio también puede ser utilizado. Se presenta la implementación física, el procesamiento de datos y la parte electrónica correspondiente al sensor. El sensor propuesto es capaz de medir la densidad y es utilizado para caracterizar el perfil de densidad dentro del clarificador, ya que la densidad está relacionada con el número de flóculos y suciedad en el agua. Se ha realizado y probado toda la parte de detección del sensor, dando preferencia al uso de cristales piezoeléctricos. Se demostró que este sensor tiene la capacidad de distinguir entre agua limpia y sucia, pues generó señales de salida distintas para ambos tipos de agua a diferentes frecuencias. Además, la parte electrónica del sensor ha sido desarrollada y probada, obteniendo resultados satisfactorios.

Palabras clave: biológico, cristales piezoeléctricos, ultrasonido, sensor.

Introduction

The plant consists of two tanks. In the first one, microorganisms degrade waste primarily into carbon dioxide, which can escape from the tank. In the second tank, microorganisms form flocs that undergo sedimentation. As a result of this process, clean water can be drawn from the top of the reactor. Figure **1a** shows a schematic of the plant. This biological aerobic method for water treatment, known as the activated sludge process, can operate continuously or semi-continuously, with microbial growth controlled within the reactor to regulate the process.

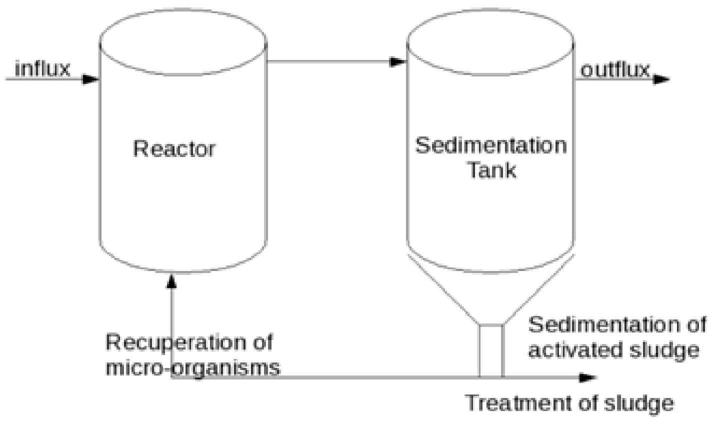

Figure 1a. Schematic diagram of the Pilot Wastewater Treatment Plant

Activated sludge is based on the aeration of wastewater with flocculating biological growth, followed by the separation of treated wastewater from this growth. A portion of the biomass is discarded, while the remainder is returned to the system (bioreactor), consisting of a mixed community of microorganisms that metabolize and transform organic and inorganic substances into environmentally acceptable forms. The microbiology of activated sludge typically consists of approximately 95 % bacteria and 5 % higher organisms (protozoa, rotifers, and higher forms of invertebrates). This mixture of microorganisms contacts and digests biodegradable materials (=food) from wastewater. Thus, activated sludge is a biological process that can be regulated by properly controlling the growth of the microorganisms (biomass concentration). The separation of the growth from the treated wastewater is usually performed by settling, but it may also be done by flotation or other methods. The particles suspended in surface water range in size from 10^{-1} to 10^{-7} mm in diameter. Very small particles, those smaller than 10^{-4} mm in diameter, are treated by dissolution. Wastewater containing particulate matter flows slowly through the settler tank (sedimentation tank) and is retained for an extended period (typically 3 hours in tanks 3 to 5 meters deep) to allow larger particles to settle at the bottom—due to their high density—before the clarified water exits the tank (outflux). The settled particles are removed manually or mechanically using scrapers.

Methods

Generalities

A general figure of the plant is shown in Figure **1b**.

SCHEMATIC DIAGRAM OF THE EXPERIMENTAL WASTEWATER TREATMENT PLANT

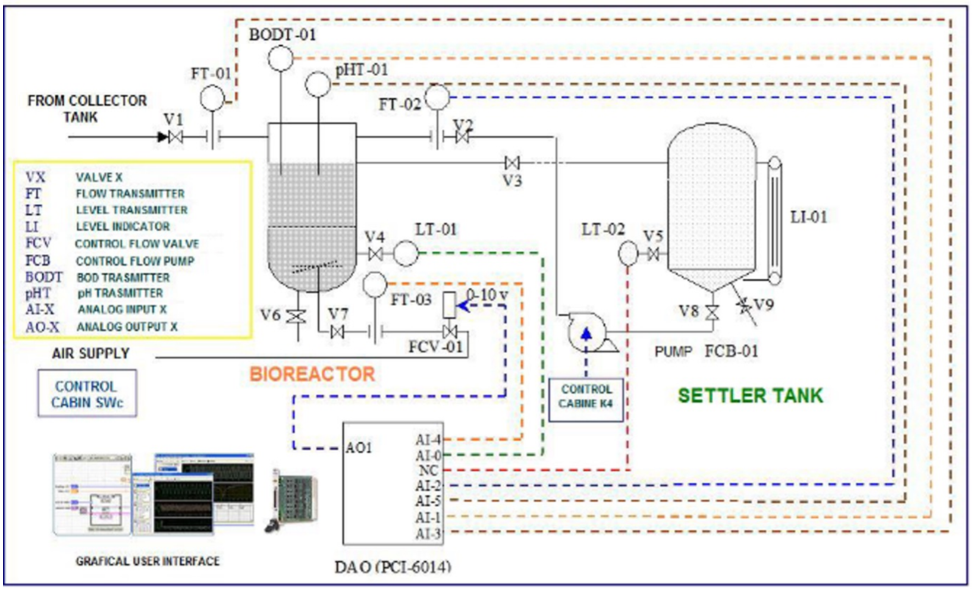

Figure 1b. Schematic diagram of the Pilot Wastewater Treatment Plant

Sedimentation occurs in the second tank, therefore, the clean water will be in the upper part of the tank. It would be highly beneficial to determine the height at which the water is clean enough to be tapped from the tank. This can be achieved using a density sensor, as density correlates with the number of flocs and dirt in the water. By controlling sludge concentration in the settler tank, it treated sewage can be effectively purified in a wastewater treatment plant using the activated sludge process. Therefore, measurement instruments enabling continuous and accurate monitoring of sludge are required.

The flocs will then settle, forming a density profile along the tank, which must be identified to obtain the point at which clean water can be extracted from the plant. Cho *et al.* (1996) presented modeling and control of the sludge settling characteristics and the conditions of sludge thickening or clarification in the settler tank, showing the importance of designing sensors to measure density profile inside these tanks. A good design for measuring the density is presented in Chen *et al.* (1996) and Muñoz (2013), where it is shown that settling characteristics for sludge are important in determining the performance of the settler, as well as for the efficiency of the wastewater treatment plant.

The Vibrating Tube Element design is one of the most widely accepted methods for density measurements (Bentley, 2005). It employs a vibrating element because the displacements produced by the coils are minimal. Due to the large temperature variations inside the water clearance reactor, this design requires compensation for temperature effects using a temperature element.

A transverse force is applied to the clamped tube using a drive coil connected to a maintaining amplifier in a resonator circuit. This force induces a transverse deflection at the tube's center, which is detected by a pick-up coil and fed back to the amplifier.

The sensor's accuracy depends on the mass—if the mass is too large, accuracy decreases. The tube can be held to a transverse oscillation at the fundamental frequency by properly selecting the gain of the operational amplifier and the phase characteristics.

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{1}$$

$$\rho = \frac{A}{f_n^2} + \frac{B}{f_n} + C \tag{2}$$

f_n: fundamental frequency, Hz
ρ: Fluid density, kg/m^3
m: sensor mass, kg.
A, B, and C: experimentally values.

Puttmer *et al*. (2000) proposed a design using piezoelectric crystals to overcome the accuracy limitations of the resonant tube. Muñoz (2013), in turn, implemented a piezoelectric design by positioning both crystals with their sensitive axes aligned to maximize output at the sensor's receiver. A gap was created in the plastic board between the crystals, allowing fluid to enter and enabling fluid analysis.

Since the sensor operates in an aqueous environment, its conductive components had to be isolated. For this primary design, a transparent nail polish was used which was able to give some satisfying results.

Physical implementation

The transmitting part of the sensor was connected to a function generator to characterize the entire circuit at different frequencies. However, challenges arose due to a high capacitive coupling between the input and output, as described later.

The receiving part of the sensor was connected to a filter circuit, which is essential for analyzing the fluid under investigation. Various filtering circuit designs are presented in the following subsections.

Ultrasonic waves

The transmitting piezoelectric crystal emits ultrasonic waves with a frequency above 20 kHz into the fluid whose density is to be measured. Before reaching the receiving piezoelectric crystal, these waves partially reflect at the interfaces between different materials. Understanding how ultrasonic (US) waves propagate through various media and interact at these interfaces is crucial for maximizing energy transfer from the input to the output.

However, direct calculation of the energy transfer was problematic due to the lack of datasheets for the medical ultrasound sensor. As a result, the piezoelectric crystals had to be characterized first. For this characterization, test data were compared with the computed data in MATLAB.

To maximize energy transfer, a backing and buffer layer were also incorporated. Cellulose acetate (nail polish) was chosen for the buffer layer due to its wide availability and suitability as an isolator. For the backing layer, a material with a significantly different acoustic impedance (ZL) was required to reflect as much energy as possible towards the fluid under investigation. To ensure effective and thick isolation—reducing capacitive coupling—and achieve a high ZL, anisotropic silicones were used.

Materials

The characteristics of the various materials used are provided in Tables 1-4. This data enabled the calculation of variations in the output-to-input signal ratio as a function of the applied frequency. This information can be useful for identifying the type of piezoelectric material by comparing it with experimental data. Clean water was selected as the measuring medium for this experiment.

Table 1. Characteristics of possible piezo crystals

Material	VL[m=s]	ρ[kg=m^3]	ZL[Rayl]	Np=m
PVDF	2.3×10^3	1.79×10^3	4.2×10^6	1×10^2
Quartz - X-cut	5.75×10^3	2.65×10^3	15.3×10^6	1×10^2
PZT	4.72×10^3	7.95×10^3	37.5×10^6	1×10^2

Table 2. Buffer layer characteristics

Material	VL [m=s]	ρ [kg=m^3]	ZL [Rayl]	α [Np=m]
cellulose acetate	2.45×10^3	1.3×10^3	3.18×10^6	21.9×10^2

Table 3. Backing layer characteristics

Material	VL [m=s]	ρ [kg=m^3]	ZL [Rayl]	α [Np=m]
Epoxy	2.70×10^3	1.21×10^3	3.25×10^6	4.5×10^2
Silicone	8.43×10^3	2.34×10^3	19.7×10^6	3.8×10^2

Table 4. Measured layer characteristics

Material	VL [m=s]	ρ [kg=m^3]	ZL [Rayl]	α [Np=m]
Water	1.48×10^3	1.0×10^3	1.48×10^6	$23\times10^2/(20\log_{10}e)$
Air	0.34×10^3	1.293	0.42×10^6	1

Data Processing and Electronics

The signal received from the piezoelectric crystal has a small amplitude and contains significant noise. Thus, it is necessary to amplify and filter the signal. The receiver circuit is composed of several components to achieve this.

Part 1: High Pass Filter: To eliminate low-frequency noise, particularly the 60 Hz frequency, a high-pass filter is required. There are several methods to achieve this. A few of them were tested and are described below.

Sallen-Key Topology (Thomas, 2008): The Sallen-Key filter is an active filter that makes use of an OPAMP, as shown in Figure **2**.

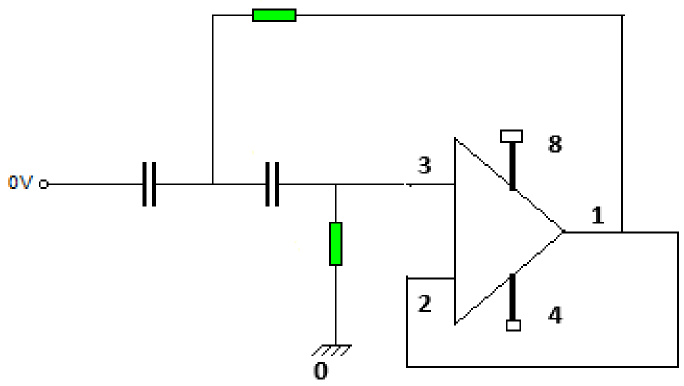

Figure 2. Unity-Gain Sallen-Key High-Pass Filter

Note: Adapted from Thomas (2008).

At low frequencies, the capacitors behave like open circuits, meaning that low frequencies will not pass through to the output. The OPAMP should be a high-frequency OPAMP to ensure that the high-frequency signal is not attenuated.

The transfer function of this filter is given by:

$$A(s) = \frac{1}{1 + \frac{a_1}{s} + \frac{b_1}{s^2}} = \frac{s^2}{s^2 + a_1 s + b_1} \tag{3}$$

Con,

$$a_1 = \frac{2}{w_c RC} \tag{4}$$

$$b_1 = \frac{1}{w_c^2 R^2 C^2} \tag{5}$$

Since it is a second-order filter, the transfer function can also be expressed as:

$$A(s) = \frac{s^2}{(s+c)^2} = \frac{s^2}{s^2 + 2cs + cs^2} \tag{6}$$

where $c = 2\pi 1000$, with 1000 Hz as the cut-off frequency.

By comparing Equation (3) and Equation (6), it can be determined that resistors of 25,300 Ω and capacitors of 1pF are required.

Second-Order Passive High Pass Filter: This design (see Figure **3**) consists of two simple first-order RC high-pass filters connected in series, with an OPAMP used as a buffer in between. The OPAMP prevents loading effects and should be a high-frequency OPAMP. To set the cut-off frequency at 1000 Hz, capacitors of 0.1μF and resistors of 1500 Ω are used.

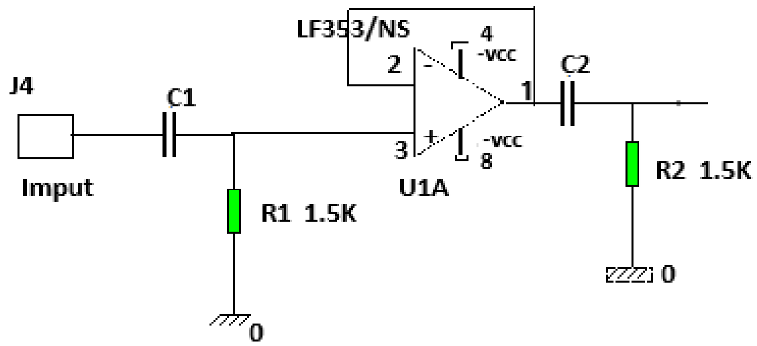

Figure 3. Second-Order Passive High Pass Filter

Part 2: Non-Inverting Amplifier: To amplify the received signal, a non-inverting amplifier is used, as shown in Figure **4**.

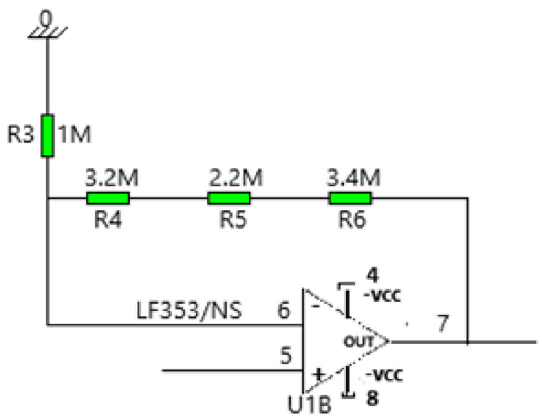

Figure 4. Non-Inverting Amplifier

Part 3: Rectifier: To obtain a DC value from the signal, it is necessary to rectify it. The main challenge in this process is handling the high-frequency signal. Initially, a rectifier bridge was considered. An alternative approach is the circuit shown in Figure **5**.

In this configuration, when the input is positive, the output follows the input. However, when the input is negative, the output becomes zero because the negative supply is connected to ground.

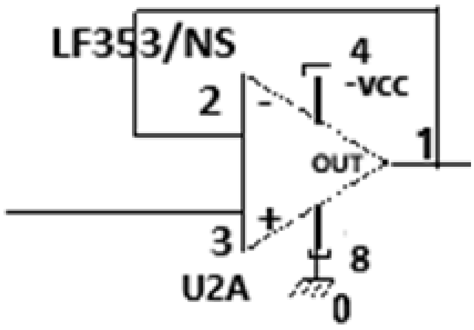

Figure 5. Rectifier using an OPAMP

Unfortunately, this approach is ineffective for high frequencies, likely due to the limited slew rate of OPAMP. To mitigate interference, an OPAMP configured as a buffer is placed before the diode, as shown in Figure **6**.

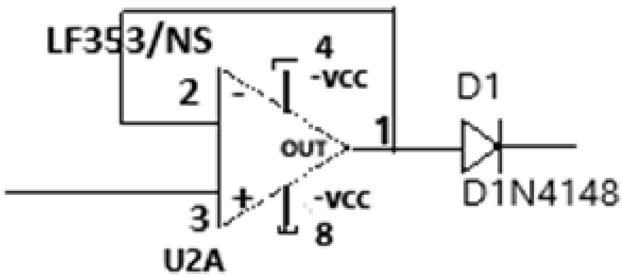

Figure 6. Rectifier using a high frequency diode

Part 4. Low Pass Filter: To obtain a DC signal from the rectified signal, a low-pass filter with a 1 Hz cutoff frequency is used. For this, a resistor of 3MΩ and a capacitor of 0.1μF are employed, as shown in Figure **7**.

The different components and configurations were simulated using OrcadP Spice®, and based on these simulations, all components and options appeared to function as expected. After testing, the second-order passive high-pass filter outperformed the Sallen-Key topology for Part 1, so the second option was chosen.

Processing circuit

The signal that is received from the piezo Cristal has only a small amplitude and contains a lot of noise. Therefore, it is necessary to amplify and filter the signal. The receiver circuit consists of multiple parts, as shown in Figure **8**.

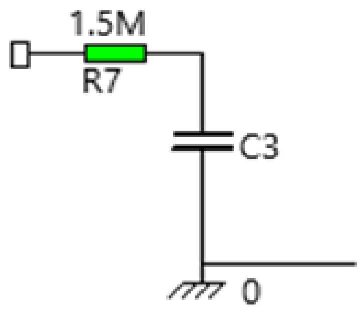

Figure 7. Low Pass Filter

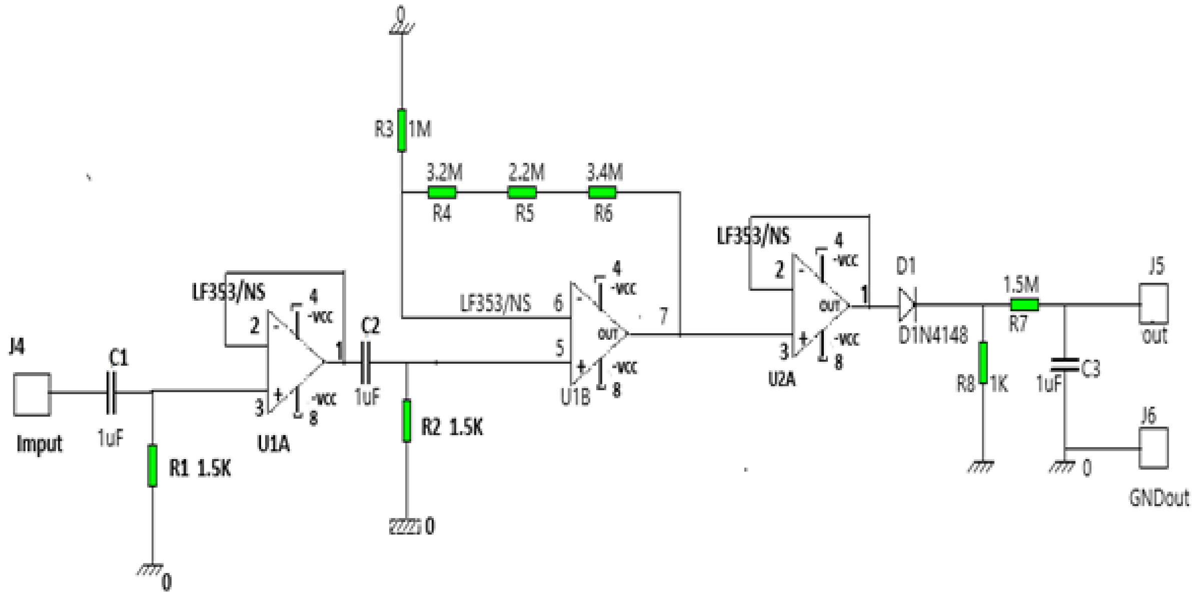

Figure 8. The final signal processing circuit

Mechanical part

After assembling the sensor and integrating its electronics onto a PCB, the entire system must be mounted on a mechanical lifting device. This device should allow the sensor to move in a vertical direction to measure the height of the cleaned water. Since this height is influenced by the water′s composition (density), the device should be designed to minimize any disturbance to its composition.

Results

To test the viability of the sensor, several experiments were conducted. Figure **9** presents the frequency response of the sensor in both air and dirty water.

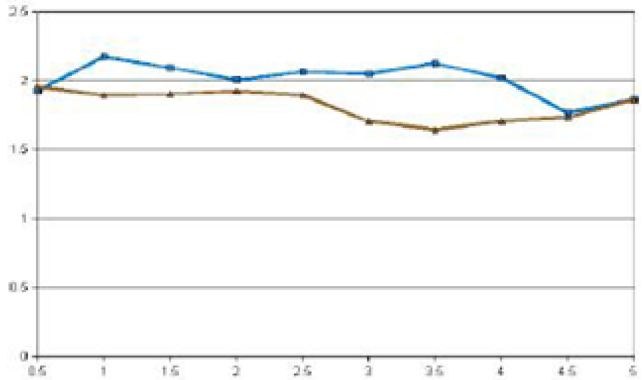

Figure 9. Frequency response of the sensor in clean and dirty water, in the x-axis the Frequency MHz) and in the y-axis the output voltage (V)

In the initial design of the sensor, some issues were encountered with the isolation of the conducting parts. As expected from our previous calculations, the output signal of the receiver part changed when the space between the two crystals was filled with water. However, as the sensor was further submerged, the output signal also increased. This phenomenon can be attributed to the capacitive coupling between the sender and receiver. Since the sender received a signal of approximately 10V, while the receiver detected only 1V, the capacitive coupling increased as the aqueous (conducting) environment filled the space between the varnished conducting parts.

A potential solution to this problem involves using a thicker isolation material that prevents water from entering the space between the conducting parts. This would ensure that only the space between the two crystals remains free for the fluid to occupy. To address this, a thicker isolation material, specifically anisotropic silicones, was used, as mentioned in the subsection about ultrasonic waves.

The sensor demonstrated optimal performance at 3.5 MHz, where the greatest difference in amplitude was observed between measurements in dirty and clean water.

Thus, there is a need for a highly sensitive, self-calibrating, online sensor to characterize the liquid in the settler during the settling process. Bamberger and Greenwood (2004) demonstrate the use of measurements of the reflections at the fluid-sensor interface, sound speed, and ultrasound attenuation to determine fluid density and solids concentration.

The state of technology of the ultrasonic sensor systems is shown in Henning and Rautenberg (2006), where the advantages and limitations of ultrasonic sensors are discussed.

Conclusions

It became evident that the piezoelectric material used must be Lead Zirconium Titanate (PZT). Additionally, due to the significant temperature variations inside the water clearance reactor, this design requires temperature compensation using a temperature element.

The sensor can be applied to measure sludge levels in settling basins or tanks by detecting the interface layer between two or more phases. It can also be used to measure density profiles and thereby picture the heights of the different product layers inside a vessel. To enhance the sensor's performance, some extra improvements must be considered:

- Calibration of the sensor needs to be performed and compared with other industrial sensors.
- Linearity and some other static characteristics of the sensor must be evaluated.
- Further signal processing is needed to meet industrial standards.

Acknowledgements

The authors express their gratitude to the Universities of Tolima and CUN for providing the time and opportunity to contribute to the development of these projects related to the implementation of measurement technologies.

References

Bamberger, J. A. & Greenwood, M. S. (2004). Non-invasive characterization of fluid foodstuffs based on ultrasonic measurements. *Food research international, 37*(6), 621-625.

Bentley, J. P. (2005). *Principles of measurement systems*. Prentice Hall.

Cheeke, J. D. (2012). *Fundamentals and applications of ultrasonic waves.* CRC Press.

Chen, G. W., Chang, I. L., Hung, W. T., & Lee, D. J. (1996). Regimes for zone settling of waste activated sludges. *Water Research, 30*(8), 1844-1850.

Cho, S. H., Chang, H. N., & Prost, C. (1996). Steady state analysis of the coupling aerator and secondary settling tank in activated sludge process. *Water Research, 30*(11), 2601-2608.

Density – the key to product consistency. (2001). *Sensor Review, 21*(4). http://dx.doi.org/10.1108/sr.2001.08721dad.007

Farach-Colton, M. & Mosteiro, M. (2014). Initializing Sensor Networks of Non-Uniform Density in the Weak Sensor Model. *Algorithmica, 73*(1), 87-114. http://dx.doi.org/10.1007/s00453-014-9905-5

Henning, B. & Rautenberg, J. (2006). Process monitoring using ultrasonic sensor systems. *Ultrasonics, 44*, e1395-e1399.

Muñoz, J.A. (2013). Design of a density sensor based on piezoelectric crystals for the identification of the density profile in a wastewater treatment plant settler. IFAC proceedings volumes (*IFAC-Papers Online), 4*, 288–292.

Puttmer, A., Hauptmann, P., & Henning, B. (2000). Ultrasonic density sensor for liquids. Ultrasonics, Ferroelectrics and Frequency Control. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 47*(1), 85-92.

Shang, Y. & Shi, H. (2007). Flexible Energy Efficient Density Control on Wireless Sensor Networks. *International Journal of Distributed Sensor Networks, 3*(1), 5-21. http://dx.doi.org/10.1080/15501320601066727

Kugelstadt, T. (2008). Active filter design techniques. In R. Mancini (Ed.), *Op Amps for Everyone* (pp. 16.1–16.60). Newness.

Wang, X. (2009). Movement-assisted deployment for irregular sensor density in wireless sensor networks. *JCIT, 4*(2). http://dx.doi.org/10.4156/jcit.vol4.issue2.wang

Weiss, B., Heinisch, M., Reichel, E., & Jakoby, B. (2013). Driving modes and material stability of a double membrane rheometer and density sensor. *Journal of Sensors and Sensor Systems, 2*(1), 19-26. http://dx.doi.org/10.5194/jsss-2-19-2013