An Autonomous Microfluidic Device for Water Quality Monitoring in Continuous Flow

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***Abstract*— Water monitoring in sewage treatment station and rivers is a critical point to ensure human health. A colorimetric autonomous microfluidic device was developed to measure water phosphorous concentration. The device structure consists of a bonded ceramic and glass flow cell, and an apparatus made to position the light source, detector and fluidic tubes. This work evaluate the detection characteristics during continuous flow, aiming to stablish parameters to develop a real-time water quality autonomous system.**

Keywords — Microfluidic, Colorimeter, Absorbance, Water Quality

I. Introduction

The sustainability and preservation of natural resources, especially water, are subject of increasing debate and research. Among several water related topics, chemical analysis of rivers and springs, by real-time remote monitoring systems, has been attracted great interest of the market.

Flow Injection Analysis (FIA) is an analytical chemistry methodology that allows automating manipulation of solutions using inexpensive equipment, easy handling and accuracy results. In addition, the system has advantages such as minimizing the samples and reagents consumption, lowering residues, and reducing or eliminating sample and analyzer contamination [1], when compared with manual methods.

We developed a colorimetric system to monitor phosphorous concentration in water, comparing the income and outcome light intensity interacting with the sample, at a specific wavelength. This is an analytical technique, commonly employed in laboratories due to its relative low cost, easy operation and sensitivity in order of parts per trillion (ppt) [2].

The proposal of this work is the creation of a colorimetric inflow measurement system, aiming to analyze the concentration of chemical elements in water. Standard methods defined by environmental protection agencies, and governmental laws, are used to define the procedures to detect chemical elements in water. We developed an inflow processes to allow real-time colorimetric analysis in sewage and industrial effluents.

Phosphorus is a common constituent of agricultural fertilizers, and organic wastes in effluents. Thought it is an essential element for plant life, at higher concentration in water, it can cause the algal bloom of rivers and lakes. This phenomenon can lead from fish mortality to interruption of cities water supply. Due to the harmful effects of high level of phosphorous in water, there are strict regulations on sewage treatment plants, and industries to monitor phosphorous on their effluents.

The developed colorimetric system will use the standard method of ammonium molybdate. At this method, the higher the phosphorous concentration in water, the bluer the sample becomes.

Commercially we have two options for monitoring of water in sewage treatment station and rivers. The EZ series, which offers several analyzers options for online monitoring fluoride in water; and Fugro Seawatch, a floating equipment capable of integrating real-time data acquisition and on-board processing capabilities to provide reliable, long-range monitoring of freshwater and marine environments with incredible speed and accuracy. However, these equipments are too expensive to monitor ordinary effluents (U$48.000 to EZ Series and U$1.000.000 to Fugro).

This paper presents the development and manufacture of a low cost microfluidic device for phosphorous water analysis and monitoring. This structure allows measurements of absorbance in continuous flow, and has the advantage that can analysis various liquids and gases samples, by selecting the proper light source, and its respective standard method.

II. Materials and methods

Fig. 1 represents the principle of functioning of the system designed and produced in this work. The sample passes through filters to remove particulate matter, and an oxidative digestion method ensures the phosphorous molecules are detectable. A mini-pump brings the sample from digestion to the flow cell.

At the flow cell, light pass through the sample and the color sensor transforms it into a digital value. A microcontroller processes this data and sends it via USB to computer. One can analyze data via serial monitor. Prior to colorimetric detection, mixing sample and all necessary chemicals for phosphorous colorimetric detection is necessary. This entire process occurs in continuous flow of water. After passing through the flow cell, sample goes into a specific container to disposal.

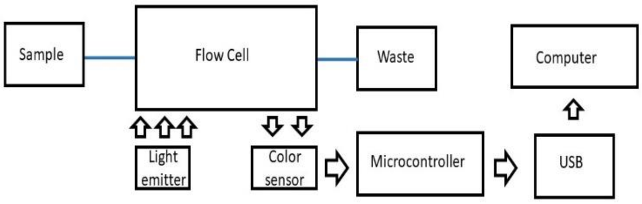

Fig. 1.Principle of functioning of the experimental set up.

The microfluidic prototype developed has the following components:

A. Structure

Due to the prototype being sensitive to the variation of light, it was necessary to design a structure in order to isolate the prototype of the external light. We designed a FR4 structure, due to its low cost, robustness, supports high temperature and resistant against falls. LPKF Protomat s63 machine produced the prototype. After accomplishing the design of the structure, we generated a gerber file. The CircuitPro program made the interface between the generated file and Protomat s63. The device design is compact, lightweight and easy to carry. In the first layer, it has two circular inputs to connect the hoses and another input to make the microcontroller connections with the color light sensor to digital converter sensor TCS32725 and on the back has an input for powering the led. Fig. 2 shows the dimensions of the device (length 100 mm, width 50 mm, height 26 mm).

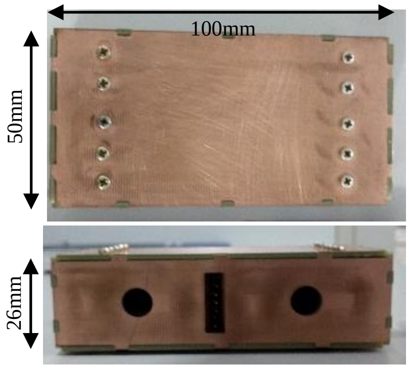

Fig. 2. Prototype structure with dimensions

Internally the structure has three partitions, the first partition we found the color sensor, this sensor is responsible for measuring the incidence of light passing through the sample under analysis. In the second partition there is the Ibidi μ-Slide I luer flow cell. This cell will be the container of the liquid during measurement of the concentration of the substance. It has 75.5 mm length by 25.5 mm width. Its channel has the following characteristics: length of 50 mm, width of 5 mm and thickness of 0.4 mm (Fig. 3). We choose this flow cell due to its small dimensions. The third sector is the light emitter, a SMD LED model WL-SFTW SMD.

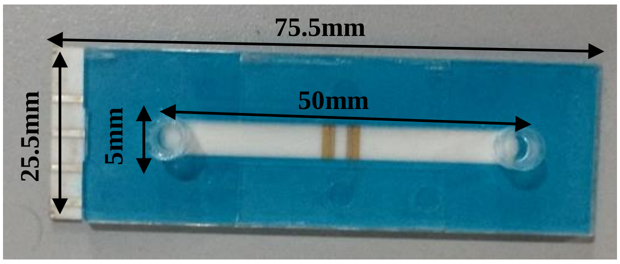

Fig. 3. Flow cell

We used a peristaltic mini pump model RS-360h to pump the sample solution. This pump model is capable of boosting between 1500ml and 2000ml per minute. The pump-reduced size, low cost and power consumption played essential role to choose it. Fig. 4 shows the pump coupled to the developed prototype.

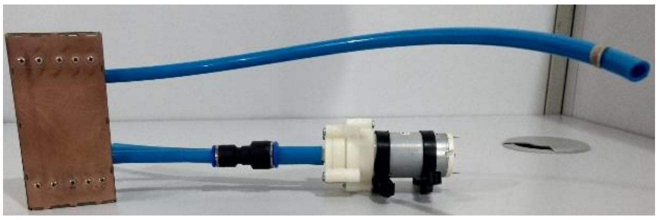

Fig. 4. Mini pump coupled with the device.

B. Light source assembly and detector

The Adafruit TCS34725 sensor module was used (Fig. 5). This sensor is responsible for measuring the amount of light incident on it.

Fig. 5. Color Sensor module TCS34725

We choose this module because it has a great cost benefit, having a reduced size (20.44 x 20.28 mm). This device detects red, green and blue colors, besides detecting the level of clarity. It also has an infrared filter, giving better accuracy in color reading. The input voltage of the board (Vin) ranges from 3.3V to 5V. This makes possible to use the sensor with various platforms.

The color sensor has a light-to-digital converter, containing a 3×4 photodiode array, four analog-to-digital converters (ADC) that integrate the photodiode current, data registers, a state machine, and an I2C interface. The 3×4 photodiode array is composed of red-filtered, green-filtered, blue-filtered, and clear (unfiltered) photodiodes, with a maximum spectral responsivity at 465, 525, 615 nm respectively (Fig. 6). The spectral responsivity plays an important role to determine if the color sensor has the appropriate parameters for the project and to determine the light source used.

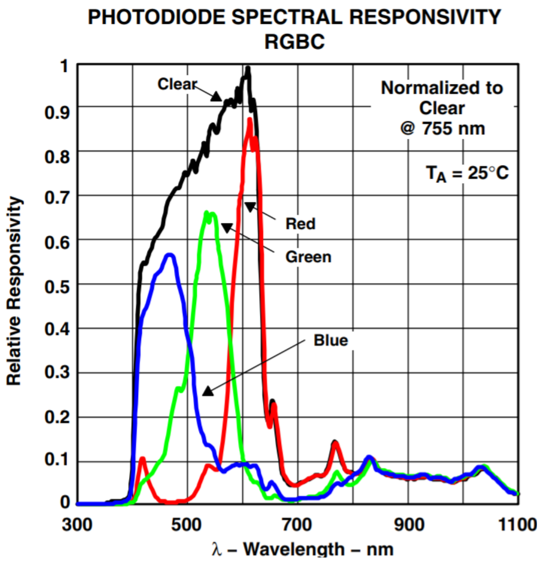

Fig. 6. Spectral responsivity of TCS34725 color sensor.

As source of light emission, we used an RGB LED SMD model WL-SFTW, due to its RGB wavelengths, 625 nm for red color, 520 nm for green color and 470 nm for blue color. Fig. 7 shows the relationship between relative intensity and wavelength. Note that the wavelengths emitted by the led have values very close to the spectral responsibility peaks of the sensor, this allowed the color sensor to read all the maximum peaks of light sent by the chosen led.

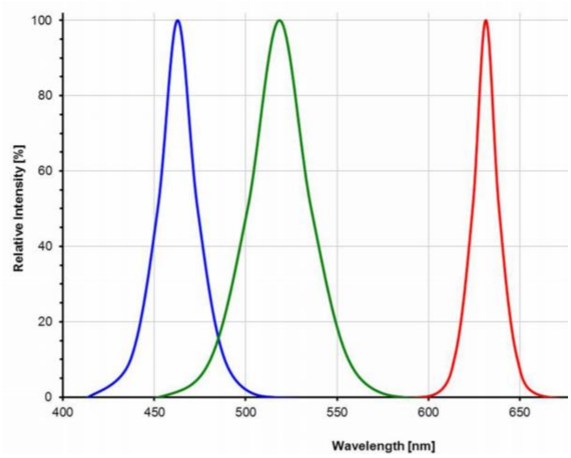

Fig. 7. Relative intensity of WL-SFTW

The I2C protocol sends the color sensor data to the microcontroller (Arduino Nano), which uses the Atmega328. The Arduino Nano module has a dimension of 45 x 18 mm, operating voltage of 5V, 14 digital and 8 analogue ports and clock speed of 16MHz. For the experiments, we use only red color, due to better interaction with blue sample. The process of data collect is show in Fig. 8.

The operation of the I2C protocol is based on the interaction between elements following the master and slave hierarchy. When we have several devices communicating according to this premise, at least one of them must act as master and the others will be slaves. The function of the master is to perform the coordination of all communication, since it has the ability to send and request information structure.

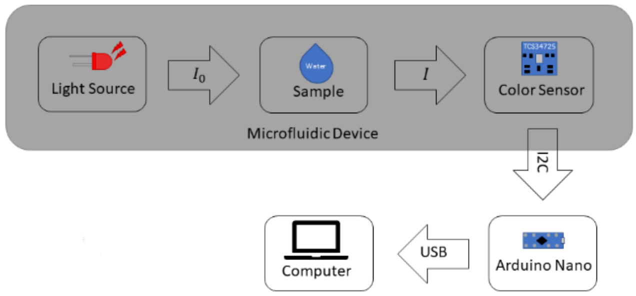

Fig. 8. Data Collect process.

III. Measurement and Results

In order to measure the phosphorus concentration in the sample, first we mix a solution of stannous chloride with ammonia mobilidate and water sample. Once mixed, the solution will turn into blue, with a maximum absorption at 700 nm ($\lambda_{máx}$). The phosphorous concentration is obtained according to Lambert-Beer's law, as defined bellow:

$$A = \log\left(\frac{I_0}{I}\right) = c \cdot \varepsilon \cdot l \qquad (1)$$

Where I_0 is then income light intensity in Wm^{-2}, I is the outcome light intensity (after absorbed by the sample), c is molar concentration of the analyte (in mol dm^{-3}), ε is the molar absorptivity (in $cm^{-1}mol^{-1}$) and l is the length of the absorption cell (in cm). When ε and l are constant, then optical absorbance (A) has to be proportional to concentration of the analyte. In our case the intensity I_0 was related to the signal measured for distilled water.

In order to validate our setup, seven solutions were prepared consisting of distilled water and food blue dye (table I), the objective was to verify how the sensor behaves by changing the color tonality. We choose the blue color because it is the same color of the phosphorus after reaction with the solution composed of stannous chloride and ammonium molybdate, which we wish to detect in a future process. Therefore in order to test the functionality of the detection set up already built (Fig. 8), these solutions help in understanding the system.

TABLE I. CONCENTRATION OF FOOD BLUE DYE

Samples	1	2	3	4	5	6	7
Concentration (g/L)	0.30	0.35	0.44	0.64	0.77	1.04	1.24

For the preparation of the solutions, a semi-micro precision microwave scale AUW220D from Marte was used, the weight of the becker was measured and afterwards, drops of the food color used were added.

We connected the light source and color light detector in the same axes. We used a red light source, since the literature reports it presents a higher sensibility [3]. The flowing medium partially absorbs the income light. The color sensor detects the unabsorbed. The output signal data goes to Arduino Nano by I2C protocol and after passed thought to the computer by USB.

We analyzed the data by equation 1. The Lambert-Beer's law states that the ratio between absorbance and concentration should be linear. To know if the behavior of the readings of the device is correct the value of ε, molar absorptivity, must be equal or very close comparing all samples.

Fig. 9 shows the concentration of blue food dye in function of the measured absorbance. It shows that the microfluidic device was able to obtain identify different concentration of dye in water. The test was repeated three times and we obtained similar results.

These results show that the prototype has great potential to measure phosphorous in water.

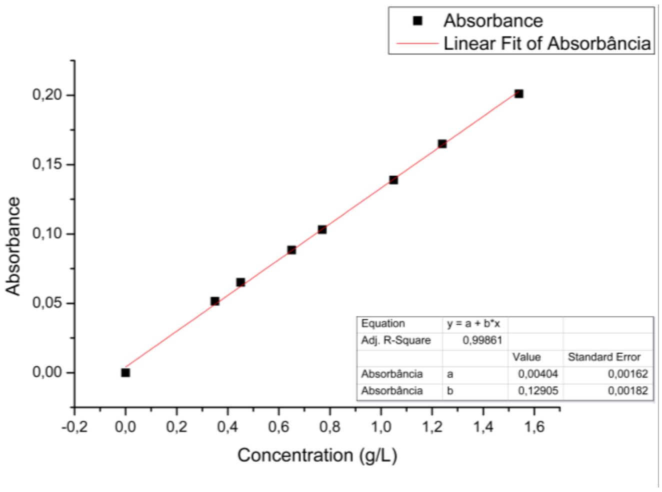

Fig. 9. Concentration x Absorbance

Conclusion

The microfluidic device for absorbance measurements was successfully tested with a blue food dye

We designed, developed and built an inexpensive photometric device with very accessible materials. Originally the device was built to measure the phosphorus concentration in the water thought absorbance. Due to the light source and sensor used, the device has great potential to be used to detect other elements than phosphorous.

The preliminary tests have shown linear detection in the range 0 – 1,24 g/L of blue food dye in distilled water. Performed experiments have proven usability of the low-cost, miniature optoelectronic devices for absorbance measurements. Obtained output signal for the microfluidic sensor was proportional to concentration of the applied test solution. The device enables easy integration of fluidic structures, electronic and optoelectronic components in one a compact structure.

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