Infrared Turbidimeter for Nephelometric, Turbidimetric and Ratio Control and Monitoring of Water during Treatment

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***Abstract*— Clarity, finess and quality characteristic of water or any other aqueous suspension depends on the magnitude of the concentration of particles / suspended matter. This paper presents the design and implementation of a light, simple, cheap and reliable infrared turbidimeter, that can easily be used to preform nephelometric, turbidimetric and ratio turbidity measurements during water treatment. It's operating principle is based on the fact that light intensities scattered and transmitted by a given suspension are respectively proportional and inversely proportional to the concentration of particles /suspended matter. The device allows one to explore and compare in a single operation, the three optical techniques used for turbidity measurements. An experimental evaluation of the prototype was obtained for two types of synthetic aqueous suspension, with different particle sizes and material refractive indices and the results obtained were compared to those of a standard tungsten lamp turbidimeter designed according the US.EPA standard. In nephelometric mode, a wider range of linear measurements as well as good information on Turbidity / concentration are obtained with our device. Measurements on the standard commercial turbidimeter used for comparison are affected by particle size. The modulation of the power supply of the infrared emitting diode is an excellent factor for the accuracy of measurement. The performance of turbidimetric measurements varies depending on whether or not the Beer-Lambert law is applied to the signals transmitted through the samples. In the ratio mode, the response profile is identical to that obtained by the nephelometric method.**

***Keywords*— Turbidity , water, turbidimeter, nephelometry , turbidimetry , infrared light scattering and absorption**

I. INTRODUCTION

The issue of detection and quantification of particles / suspended matter in a liquid is of a great concern for producers of drinking water and beverage drinks. The presence of particles in water is governed by quality and clarity standards owing to their potential adverse health effects (WHO., 1996; APHA, AWWA, WEF, 1998; CFPT., 2002). Water clarity is ascertained by turbidity measurements. Turbidity is an expression of the optical property of a medium in which a beam of incident light is either scattered or absorbed by the particles in suspension in the medium rather than passing straight through (APHA, AWWA, WEF, 1998). It is defined by the International Standards Organization (ISO) as the reduction in transparency of a liquid by the presence of insoluble matter. In natural surface water it is caused by various particulate or colloidal substances consisting of silt, clay, organic or inorganic compounds as well as plankton and other microorganisms. Sources of particulate matter can be natural (humic acids, particulates from the decay of plant material or from soil erosion) or anthropogenic such as industrial, agricultural and urban discharges (US EPA, 1999). Turbidity is measured using turbidimeters designed according to nephelometric or turbidimetric principles and techniques and is expressed in arbitrary units: the nephelometric turbidity unit (NTU).

Turbidimetry and nephelometry are two basic conventional techniques used in the determination of turbidity. These two techniques have led to the implementation of a third turbidity measurement technique: the Ratio technique. Consequently, three types of turbidimeter are generally in use: 1) the absorption or attenuation turbidimeters which measure the intensity of the attenuated light beam which has passed through the sample. An optical sensor is positioned at 180° relative to the incident source and directly converts the luminous flux transmitted into an electrical signal; 2) Nephelometric turbidimeters measure the intensity of light scattered by the sample, usually at 90° with respect to the incident source. In this case, the optical sensor is placed at 90° relative to the incident source and converts the luminous flux scattered by the sample to an electrical signal; 3) Ratio turbidimeters operate by the simultaneous measurement of transmitted and scattered light intensities; two identical optical sensors are respectively placed at 90° and 180° with respect to the incident source and directly convert the scattered and transmitted light flux into electrical signals of magnitudes $V_{90°}$ and $V_{180°}$ respectively. The turbidity ratio measurement is expressed by the relation $V_R = V_{90°} / (V_{90°} + V_{180°})$. In each of the above three cases, the light source may be white visible light emitted by a tungsten lamp (400 - 600nm), for those conformable to the USEPA standard or the Infrared light of 860 nm for those built according the EN 7027 standard, or laser light according to the EPA 10133 standard or, finally, simple white or colored LEDs, light emitting diodes (US EPA standard, 1998). Turbidimeters equipped with Tungsten lamps and those with colored LEDs are optically complex to design, heavy, bulky and expensive because they use complicated collimating devices such as optical wavelength filters, lenses and mirrors.

In drinking water treatment plants turbidimeters are used to assess the effectiveness of operations of coagulation /

flocculation and filtration, and to check that the treated water complies with the standards in force (CFPT., 2002). The turbidimeters can be used in static mode, or online to determine in real time the optimum clarification point (Huang et al., 1996; Liu et al., 2008). Marketed turbidimeters are relatively expensive and do not always take account of the requirements of the field and the work environment of the users, especially as regards South countries. They can perform only a single type of measurement (either nephelometry or turbidimetry or ratio) on the working sample whereas it remains true that the result of measurement of turbidity depends on the measurement technique used (disposition of sensors and transmitters), the type of light source, particle size, concentration and colour of suspended particulate matter (Lawler, 1995). Altogether these factors raise, on one hand, the need to reduce errors likely to occur in the measurement and on the other hand, the curiosity to explore and appreciate simultaneously the contributions of each of the measurement techniques and types of light source in the turbidity measurements. The second option is that which best fits our research approach. Many investigators have developed appropriate systems, usually based on simple electronic sensors and light sources (Bedidi *et al*., 1993; Lawler 1995; Papadopoulou *et al*., 1998; Bizi, 2006; Greswell *et al.,* 2010). Nowadays there is an excellent range of online testers, portable field nephelometers such as those manufactured by HACH, HANNA and HF Scientific Inc. (USA) but they are all limited to a single type of measurement technique and do not allow comparison between them. This work presents the design and implementation of a prototype simple Infrared turbidimeter to use in industrial and laboratory applications. The device allows one to explore, evaluate and compare in a single test and simultaneously the three basic optical techniques applied in turbidity measurements. Direct and indirect assessment of the experimental device was made using synthetic aqueous suspensions.

II. THEORETICAL: PHYSICAL PRINCIPLE

When a mono or polychromatic beam of light passes through a measuring cell containing the sample to be analyzed, it is absorbed and/or scattered by the particles in suspension. The intensity of the transmitted beam at 180° after the sample is traversed is related to the incident beam intensity by the Beer Lambert law:

$$I(\lambda, \mathrm{L}) = I_0(\lambda)\cdot e^{(-\alpha LC)}$$

- I_0 the intensity of the incident light of wavelength,
- I the intensity of the light exiting from the cell,
- α is a constant called the absorption coefficient ($m^2\cdot mol^{-1}$ or $m^3\cdot mol^{-1}\cdot cm^{-1}$)
- L the optical path length (cm or m) traversed,
- C the concentration of the absorbing species in the medium ($mol\cdot m^{-3}$).

In the case of synthetic suspensions or solutions of chemical compounds, the Beer-Lambert law involves concentrations in a linear form as follows.

$$\mathbf{A = -\log(I_0/I) = \alpha LC}$$

Where, A is the absorbance or optical density

The absorbance A (λ) is a constant characteristic of the material in suspension and depends on its refractive index. It is proportional to the concentration, C of the dissolved or suspended materials.

The phenomenon of light scattering by particles in a suspension is best explained by theories of Mie and Rayleigh (Greswell *et al*., 2010). Indeed, the beam of light passing through a fluid containing particles is scattered in various directions by the solid particles present in suspension; scattering effect is similar to that of the emission lobes of an antenna. As in the case of absorption, the diffusion coefficient is a constant characteristic of the material in suspension and depends on the wavelength of the light. In the case of simple scattering (as opposed to multiple broadcasts/ scattering) the scattering coefficient is proportional to the concentration of the particles in suspension.

III. MATERIALS AND METHODS

A. *Infrared (IR) Transmitter and Receiver*

The IR transmitter is constructed based on an infrared-emitting diode of doped Galium Arsenide (GaAlAs) : the SFH 480 . The SFH 480 is a cylindrical IR diode, 4.75 mm in diameter and 7.5 mm long, with a narrow beam cone, co nvenient to create a very small opening (± 6 °) of the emitted infrared beam. The SFH 480 emits an infrared beam of a narrow spectral density centered on 880nm. It consumes very little electrical power and provides a very high intensity light output. The infrared sensor used in the design and implementation of the conditioner of the transmitted and scattered signals is a Silicon Pin photodiode: the Siemens BPW34F. It is shaped as a parallelepiped, with a receiving face is of 20 mm^2 of which $7mm^2$ for the sensor surface. The BPW34F is highly appreciated for its spectral sensitivity which is selective to the IR band (from 720 to 1110 nm), centered on 950 nm. It is of very high photo sensitivity and generates a current of 0.5 µA when it is illuminated below 1 $\mu W/cm^2$. Its dark current is very low (about 2 nA) when powered at 10V, which is particularly interesting for minimizing of the shift from zero in the output of the instrumentation system. The photo-current generated by the BPW34F increases linearly with lighting.

B. *Reagents and synthetic materials*

Natural surface water generally has a characteristic colour which depends on the nature of the colloidal particles dissolved or suspended. In order to simulate natural water, two different types of synthetic aqueous suspensions wee used, each containing a material of a different refractive index, namely, titanium dioxide and aluminum oxide. Thus the problem associated with systems of multiple type particles as in natural water was avoided. Both the titanium oxide (TiO_2), D3016, Size 1, and the aluminum oxide (Al_2O_3) used were white powders supplied by Riedel -de Haën, Germany and their particle sizes in aqueous suspension were measured with the MALVERN, USA Mastersizer 2000 E. The TiO_2 was an Anatase powder consisting of fine particles of uniform size (about 500 nm) and refractive index 2.49. The used is also a product of Riedel -de Haen, Germany. The Al_2O_3 was also of fine particles of uniform particle size (about 30µm) and refractive index 1.6 at the infrared wave length.

Preparation of synthetic suspensions was conducted in order to provide stable suspensions. The preparation of a synthetic suspension of titanium dioxide was done by gradually adding 250 mg of TiO_2 in 250ml of distilled water under magnetic stirring. The mixture was then kept under stirring while gradually adding a further 250 ml of distilled water to raise the volume to 500ml. Thereafter, 100 ml of a 2% solution of sodium hexametaphosphate salt (Riedel den Haen, Germany) was added while stirring. The mixture obtained (600ml) was stirred for 3 minutes and total the volume raised to 1L with distilled water. The entire suspension was sonicated for 1 minute with ultrasound in order to homogenize it. Finally, suspension pH was adjusted to 10 to improve the stability of the suspension. The resulting dispersion was allowed to stand for at least six hours to allow coarse particles to settle out, and the supernatant was collected to serve as stock suspension. The deposit was dried in an oven at 105°C to evaluate the mass of settled powder. The stock suspension was stored in a glass bottle tightly closed, to facilitate stirring before taking samples. The preparation of Al_2O_3 suspension was made by pouring instead 3.5 g of powder in the same conditions as in the case of TiO_2, but with two small differences: the sodium hexametaphosphate salt was not added; after sonication, the pH of the solution was rather adjusted to 5. The initial powder masses used were calculated so as to obtain final synthetic suspensions of turbidity 2 to 3 times the higher than the maximum rating of the standard commercial turbidimeter, HACH Ratio XR, (viz: 60mg / L for TiO_2 , 2.25 g / L for Al_2O_3, each corresponding to 2000NTU)

C. *Turbidity measurement and Experimental setup Optical Bench*

Figure 1 schematically shows the optical bench mounted for our experimental setup. It consists of an IR generator, a stilling well, a signal conditioner, multimeters and a central data logger.

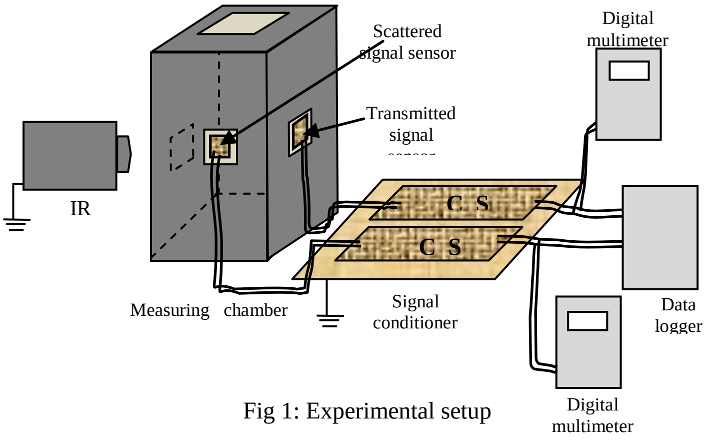

Fig 1: Experimental setup

The IR generator is a simple electronic circuit which comprises a stabilized power supply, regulated at 5V/500 mA, adjustable from 0 to 5 volts , and coupled to the transmitting diode (SFH480) via a protective resistor of 100Ω and a very thin electric cable .

The conditioner of the turbidity signal that was designed and constructed is an electronic circuit comprised of two independent stages: a conditioning signal stage for light transmitted at 180° and a conditioning signal stage for light scattered at 90°. The entrance to each floor is interfaced by a photodiode (BPW 34F) that will convert directly the luminous flux received into electric current of the order of micro Ampere. The current thus generated is converted into voltage and amplified by devices based on operational amplifiers of high input impedance. The amplification gain of the scattered signal conditioner is calculated to be 13.6 times higher than that of the transmitted signal. The output signal conditioner has a very high signal to noise ratio, a stability and a minimum threshold measurement very apt to interface with a datalogger, a microcontroller for data processing or digital multimeters.

The stilling well is a dark and opaque chamber, shaped as a parallelepiped (51x51mm x 10cm). It is made of polystyrene plates, and then covered with black tape. It is constructed so that its internal dimensions best match the dimensions of the measurement cell of the standard turbidimeter HACH Ratio XR, ie, be 27 x 27mm x 9.5 cm. Three small square holes of $1cm^2$ x 1cm depth are drilled therein on three sides of the stilling well : one to let in the incident light , the other at 180° to allow the transmitted light through and the third at 90° to collect the scattered light. The IR emitting diode, and the two sensors are each placed in one of the three holes, and connected by very thin cables to their electronic circuits. No collimating device is inserted between the transmitter and the IR sensors. The optical path is 3.7 cm for each viewing angle.

IV. RESULTS AND DISCUSSION

A. *Turbidimetric and nephelometric measurements on water*

Figure 2 shows measurements of signals: scattered at 90° and transmitted at 180° of turbid water samples. The turbid water was simulated by synthetic suspensions prepared according to the protocol presented in Section 3.2. The reference for zero turbidity is distilled water.

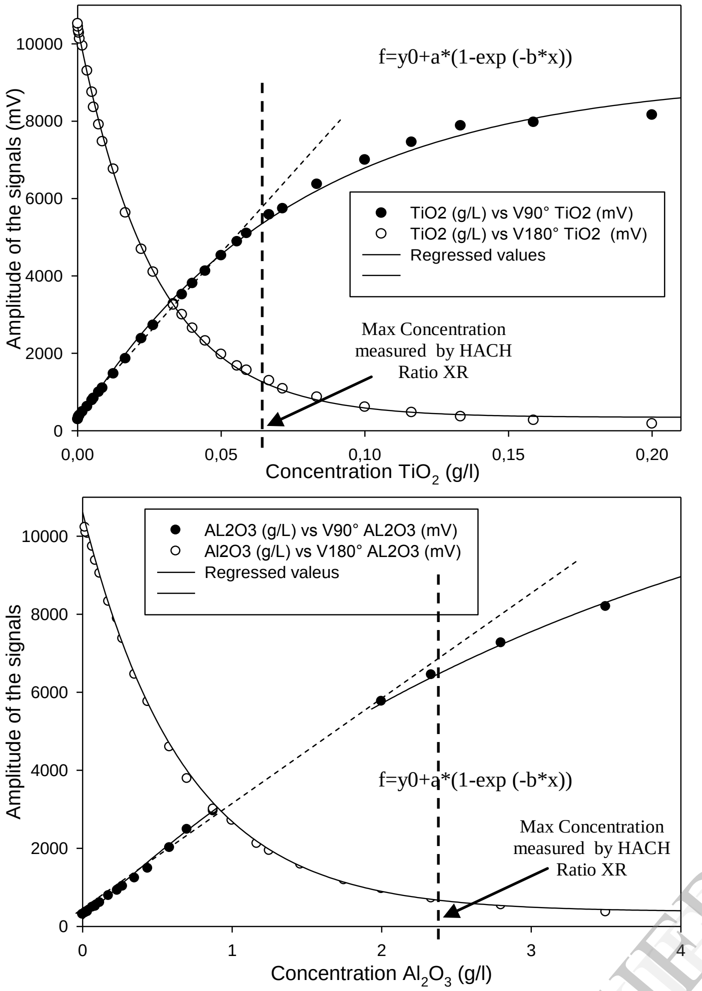

Figure 2: Profile of scattered and transmitted signals versus concentration

Each of the graphs shows that the scattered signal at 90° has a rising exponential profile while the transmitted signal at 180° has a falling exponential profile. They represent nephelometric and turbidimetric measurements of turbidity respectively. Their correlations with mathematical regression are 0.997 and 0.999 respectively. On the areas of the linear concentration, the correspondence concentration - signal is larger (2.5 times) and efficient with nephelometry. This operating form of device is said to be direct since it directly expresses the concentration of suspended particles in terms of measurable electric magnitudes. Electrical output variables are stable and suggest that the device is easily exploitable and viable in the monitoring and static measurements of the concentration of suspended matter, mainly in laboratories, treatment and supply of drinking water plants, or in waste water management.

Figure 3 shows that the application of the decimal logarithm on the signals transmitted at 180° (as provided by the Beer Lambert Law) substantially extends the linear range of concentration of suspended particles. For each suspension, the linear part is substantially equal to that obtained by nephelometry. The linear correlations are obtained in the order of 0.995.

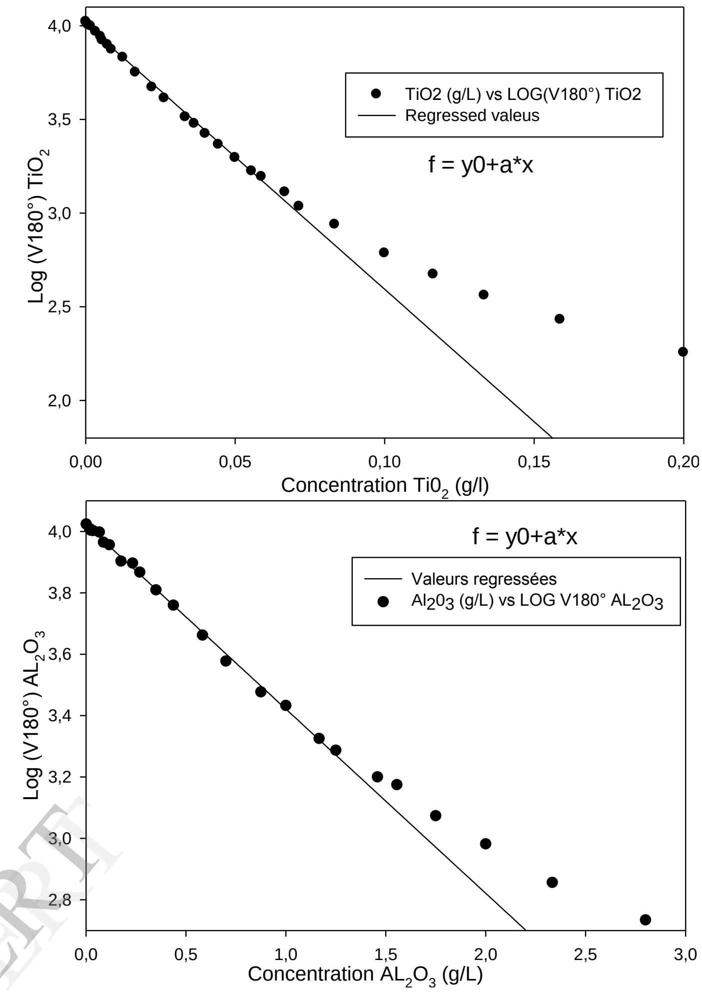

Fig 3: Profile of the logarithm of the transmitted signal versus suspension concentration

An indirect calibration of our device in NTU units has been made in accordance with the common methodology developed by Lawer (1995). It consisted of measuring the turbidity of each sample using our device (in mV), and then compared them with the measurements (in NTU) obtained from the commercial turbidmeter HACH Ratio XR. Figure 4 presents our scattered and transmitted signals in Nephelometric Turbidity Units. The maximum measurement range of the Hach Ratio XR turbidmeter is 2000 NTU.

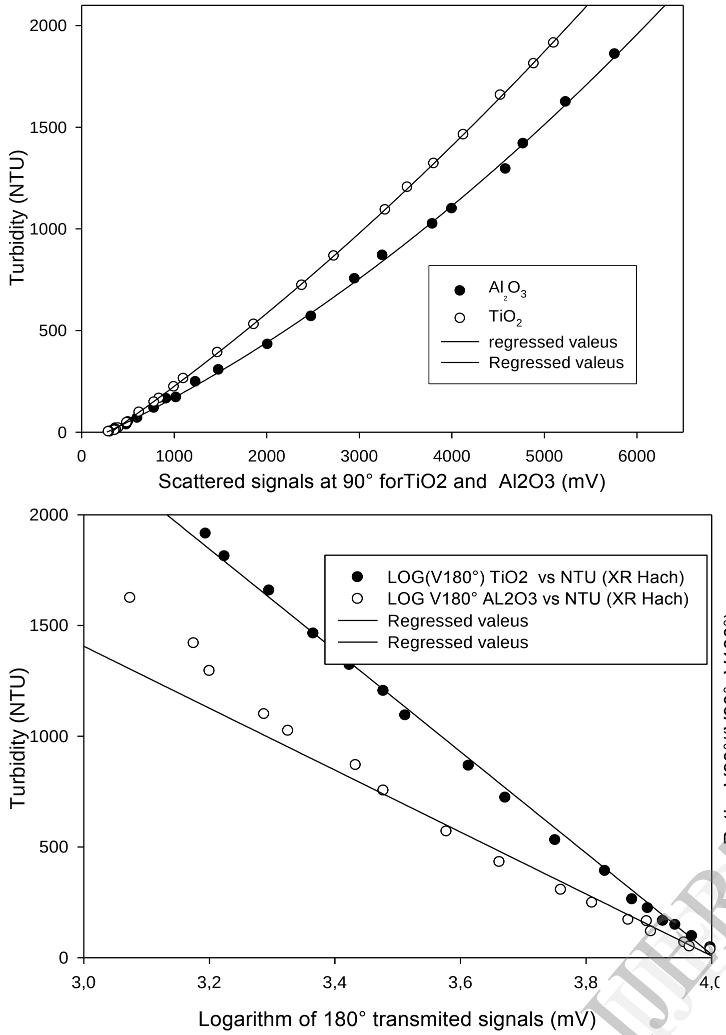

Fig 4: Profile of turbidity in NTU based on the transmitted and scattered signals

On the whole for extended standard turbidmeter measurements, the turbidity in NTU is a quadratic function ($y = ax + bx^2$) of the amplitude of the scattered signal at 90°. Moreover, this quadratic form can be strictly divided into two linear zones of measuring turbidity. Two reasons may explain the presence of these two zones of linearity: the phenomenon of multiple scattering at high concentrations of suspended particles (beyond 500 NTU), and the possible formation of aggregates between particles when the concentration becomes high. For the specific case of titanium dioxide, the turbidity in NTU is very close to a linear function of the logarithm of the transmitted signal. Thus, the device has a very good resolution and adapts very well to the measurement of low and high turbidity; moreover it can be used to determine diffusion and absorption coefficients of samples.

B. *Ratio measure of water turbidity*

Figure 5 shows the ratio measures of concentration of the suspended material obtained with our apparatus.

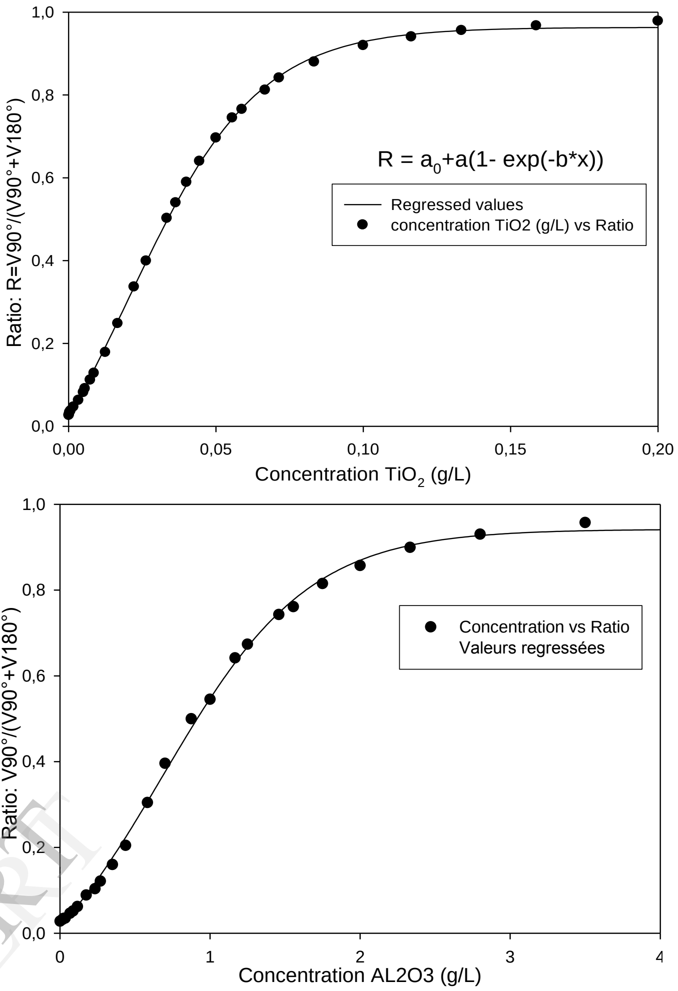

Figure 5: Ratio measure as function of concentration

The ratio measures of turbidity show a rising exponential profile, identical to that obtained by nephelometry. However, it must be said that this profile is slightly sigmoidal, especially in the case of aluminum oxide where the curvature is visible in the unsaturated zone. This curvature may reflect the threshold concentration at which the phenomena of multiple scattering and / or formation of aggregates begin to appear. This can be presented as an advantage of ratio measurement when the particle size becomes large. It can be said as a first approximation that the ratio measures with infrared is roughly equivalent to nephelometric measurements.

C. *Influence of power on the incident light source and on turbidity measures*

Influence on nephelometry and ratio measures

The light output of an infrared emitting LED being proportional to the voltage at its edges, or to the current across it, the study of the influence of the power of the incident beam on the nephelometric measurements consisted in varying polarization voltage of the infrared diode and then assessing its contribution to the behavior of scattered signals at 90°. We successively powered the IR LED by 1.22 Volt, 1.65 Volt, and 2.75 Volts. The contributions of each polarization voltage are recorded in Figure 6. It is important to note that all previous curves were obtained for the case where the IR LED was supplied at 1.65 Volt.

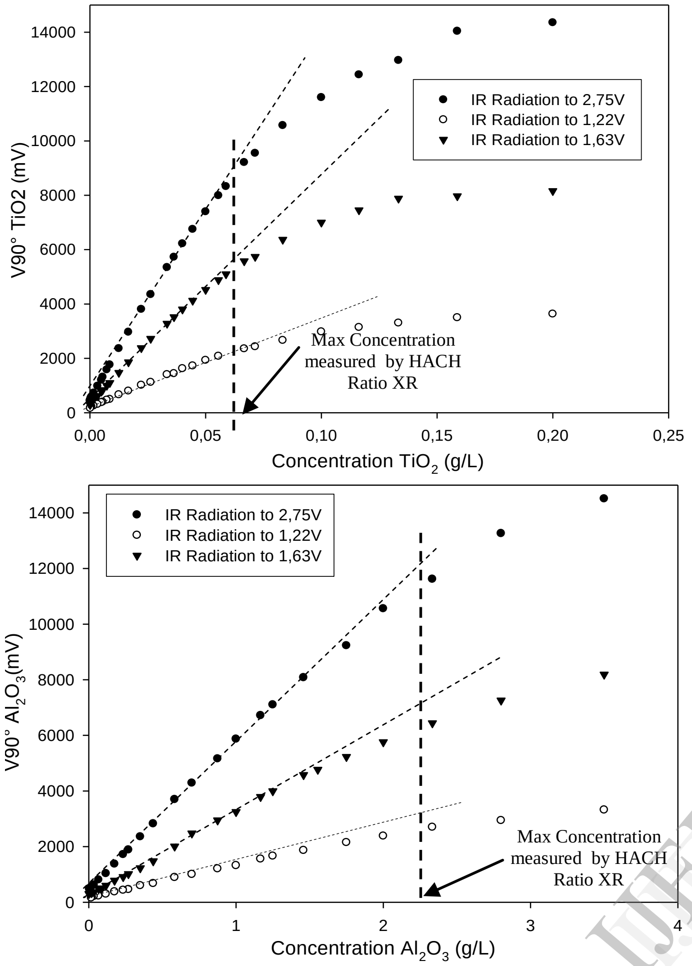

Fig 6 : Signals scattered for different power source of the incident light versus suspension concentration

The curves in Figure 6 show that, whatever the material in suspension, the power of the incident infrared beam is only influences the amplitude and slope of the scattered signal, which means that the power of the incident beam greatly improves the accuracy of measurement. It does not improve or change the linear range of the turbidity measurement. The same observations were made in the case of ratio measures

V. CONCLUSION

We have shown that it is possible using a simple device, to operate and make a direct, rapid and simultaneous comparison of the three conventional optical techniques for measuring turbidity. This is of great importance in a research context where the result of turbidity measurement depends on the measurement technique used. The prototype of infrared turbidimeter that we propose allows stable and accurate measurement of turbidity. It is very insensitive to variation of the particle size in suspension. It easily adapts to the monitoring of the turbidity with very good correlation, facilitating its coupling with the implementation of data bases of turbidity measurements of water during processing.

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