Design and Implementation of an Electromagnetic Sensor for Wastewater Monitoring towards Process Optimisation of Electrocoagulation Treatment

Rodriguez, J. (1); Rodriguez, W. (2); Pereira, F. (2); Hernandez, C. (2); Friedrich, B. (1)

Aim of present research work was to design and to implement an electromagnetic-sensor (EMS) for wastewater monitoring of treated effluents after the electrocoagulation-process (ECP). The EMS should deliver a feedback signal able to per-form online monitoring of treated effluents in order to control efficiency and reliabil-ity of the wastewater purification step. The main target is to improve the mass and energy balance of the ECP, while providing real-time protection against environment and water resource contamination. The experimental results confirmed the feasibility of magnetic permeability for the measurement of the ionic content in metal containing fluids and introduced an efficient methodology for online monitoring. The project was realized within the cooperation between RWTH Aachen University and its Colombian partner university, Pontificia Bolivariana UPB, enabling joint projects towards process optimisation of electrocoagulation, started with partial funding from DAAD and COLCIENCIAS.

As described by the United Nations on its World Water Development Report, industry is an essential engine of economic growth and therefore critical to the achievement of the UN Millennium Development Goals. Taking into account that global annual water use by industry is expected to rise from estimated 725 km^3 in 1995 to about 1,170 km^3 by 2025 [1], aim of today's development in the industrial wastewater treatment technology field must be the implementation of methodologies for the reuse and recycling of process effluents using a closed-loop approach.

For this reason, electrochemical technologies for wastewater treatment like electrocoagulation ("EC") must be optimised especially, if those are supposed to replace conventional and non-sustainable techniques like the chemical precipitation. In doing so, the development of a sensor for a quantitative analysis of process effluents after EC-treatment is a sub-target of the current research at IME Process Metallurgy and Metal Recycling at RWTH Aachen University. A successful online measurement system shall help to improve mass and energy balance of the EC-process by enabling a more efficient management of electric power in real-time.

In this way, the proposed methodology combined with the use of renewable energy resources for power generation, could help to mitigate concerns due to water use by industries, without compromising related issues like global warming. This could be particularly helpful in the event of technology transfer, taking into account the fact that much of this water abstraction increase will take place in developing countries now experiencing rapid industrial development [1]. Fig. 1 shows industrial water usage per region, compared with other main uses.

State-of-the-art

The proposed methodology for online monitoring of industrial process effluents is part of a research programme on industrial wastewater treatment for a more efficient removal of metallic contents from process effluents, based on an electrochemical technology called electrocoagulation ("EC"). Opposite to conventional treatments like chemical precipitation which rely

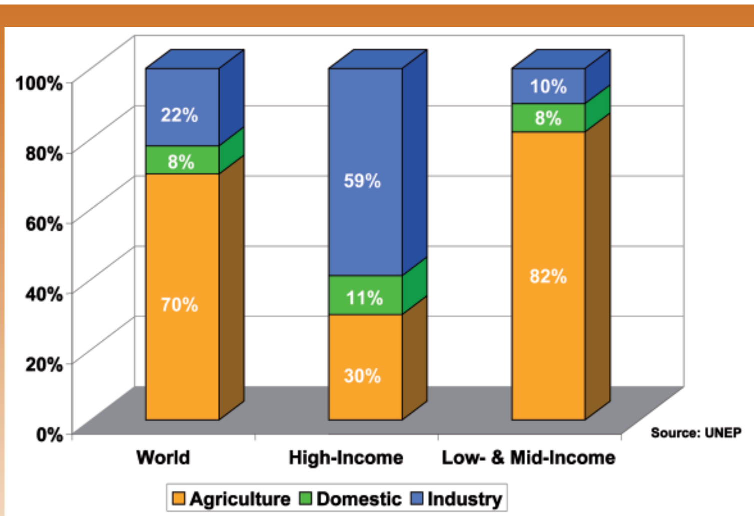

Fig. 1: Competing water uses for main income groups of countries [1]

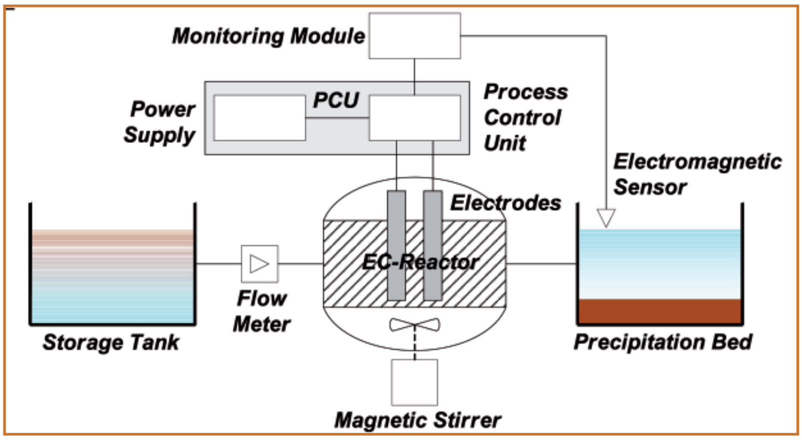

Fig. 2: Process schema of EC-treatment with integrated monitoring sensor

on neutralization only, EC-treatment combines two removal mechanisms acting simultaneously: the anodic dissolution and the cathodic deposition. An EC-reactor is an arrangement of metal plates based on sacrificial anodes, which get dissolved into water as hydroxylions by means of an electric current [2]. Besides the fact of removing dissolved metals without increasing the content of neutral salts, further advantages of the EC-process are operating conditions in pH-neutral range and the formation of potential usable hydrogen gas towards a sustainable autarkic operation [3].

Fig. 2 describes the concept for online monitoring of process effluents. Aim of present research work is the design and implementation of an electromagnetic sensor for the monitoring of process effluents after the EC-treatment. The sensor shall deliver a feedback signal able to perform real-time control of current density supplied to the EC-reactor. Like this, online monitoring of treated effluents shall improve mass and energy balance of EC-process, while enabling a more effective protection of soil and water resources from contamination with metallic contents.

Despite reliable and well-established methods for analysis of metallic contents in solutions like the Atomic Absorption Spectroscopy ("AAS") or the Inductively Coupled Plasma ("ICP"), these methods require preparation of samples and expensive operating conditions. Due to this, such methods are unable to perform in online mode, reason why several investigations have been conducted over the last 30 years on alternative analytical methods like the electronic tongues.

Electronic tongues ("ET") for liquid analysis, based on functional principles of biological sensory systems, developed rapidly during the last decade [4]. Electronic tongues can be described as semiconductor devices, which make use of electrochemical reactions in order to detect elements dissolved in a sample, among them metal ions. Their functional principle is based on an arrangement of electrodes interconnected by a semiconductor media with a given conductivity. Fig. 3 describes the functional principle of an electronic tongue, where a semiconductor media (R) for instance of chalcogenide glass, is doped with materials with an affinity for the specific element to be detected. Once the electrode probe is submerged into the sample, the ionic content reacts changing the conductivity between the electrodes. From this measurement and the pH value of the solution, an approximated value of metal concentration of the specific element can be extrapolated. The selectivity and reliability of electronic tongues are much less than analytical methods like AAS or ICP. Nevertheless, ET represents a good choice for online monitoring as reported in some conducted projects, one of them implemented in Braunschweig/Germany, where copper, lead, cadmium, zinc, chrome and iron were detected in synthetic and river effluents [5]. However, with regard to detection of metal ions, strong errors were found to be from 5 to 30%, which according to the authors is acceptable for environmental monitoring, especially considering the capability of sensor array to work reliably at a low ppb concentration level [6].

Materials and Methods

Takin into account all the advantages as an electrodeless and non-invasive measuring technique, the design of an EM-sensor was carried out based on the principle of a conventional electric transformer. Fig. 4 describes the analogy between an electric transformer and the implemented prototype for wastewater monitoring. Instead of using an iron core our EM-sensor introduces a hollow core made of glass, where treated effluents flow inside. Like this, collected sample acts as a magnetic permeable media promoting flow of magnetic flux from the primary to the secondary winding.

A function generator delivers a sinusoidal waveform into the primary winding acting as the transmitter ("V_p"). Then the generated magnetic flux flows through the glass toroid, more exactly through the ionic con-

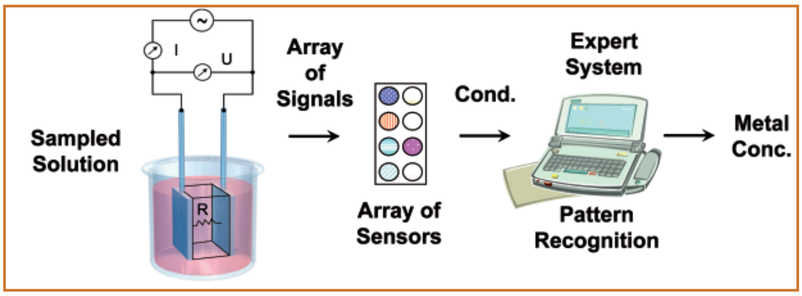

Fig. 3: Functional principle of electronic tongues for online analysis of metallic contents

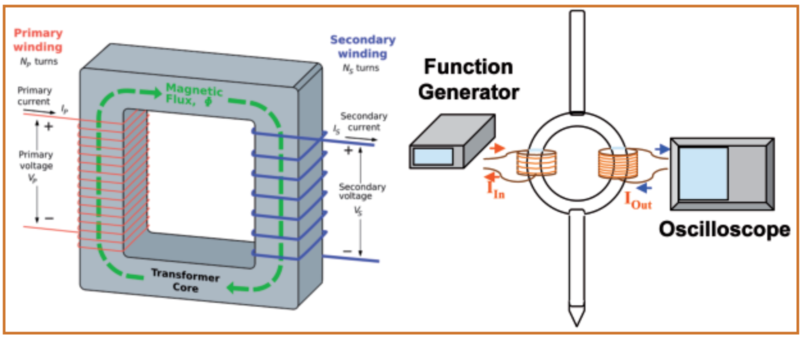

Fig. 4: Analogy between electric transformers and implemented prototype

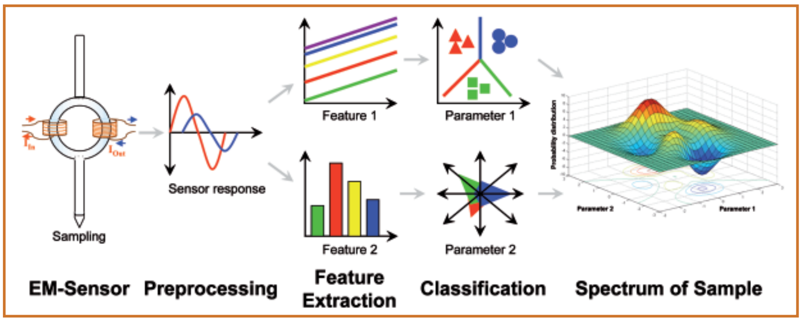

Fig. 5: Spectrum of sample derived by analysis of frequency response of wastewater measured by EM-sensor using pattern recognition techniques

tent dissolved in the sample, then the secondary winding collects the transmitted signal and displays it on a digital storage oscilloscope ("V_s"). From the V_s-V_p ratio (see formula 1), it is possible to obtain a measurement of the gain, given in decibels ("dB"), which describes a proportional behaviour according to ionic content present in the sample.

$$Gain_{dB} = 20 \cdot \log_{10} \cdot \frac{V_s}{V_p} \qquad (1)$$

The challenging target is to identify parameter sets enabling identification of individual metal concentrations in complex solutions by varying frequency and projecting system response via multivariate analysis and pattern recognition techniques. Although this method will not provide an absolute measurement of metallic content requiring calibration for each kind of effluent, process control and monitoring of wastewater treatment can be performed from an analysis of the spectrum obtained from the system response measured by EM-sensor. Fig. 5 shows a schematic approach of a discriminant analysis of frequency response towards this spectrum.

Unfortunately there is no scientific literature explaining any concept of magnetic permeability in wastewater monitoring. However, taking a closer look to the effect induced by the flow of electrons through a coil, electromagnetic theory describes the formation of magnetic field lines, represented in fig. 6 by black dotted lines. Then a gradient vector (B) representing the magnetic flux appears parallel to the concentric axis of this cylinder, being this a very small section of the glass toroid.

The proposed model for magnetic flux transfer on dissolved metals in wastewater contemplates a rearrangement of the ionic content in the sample, building an infinitesimal wire right in the center of this toroid. Through this array, the magnetic flux can be assumed to flow from the primary to the secondary winding, since pure water itself is a diamagnetic medium and therefore a dielectric material (insulator).

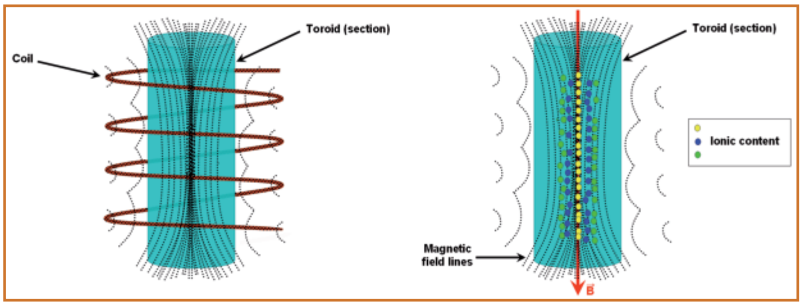

Fig. 6: Proposed model for magnetic flux transfer on ions in wastewater

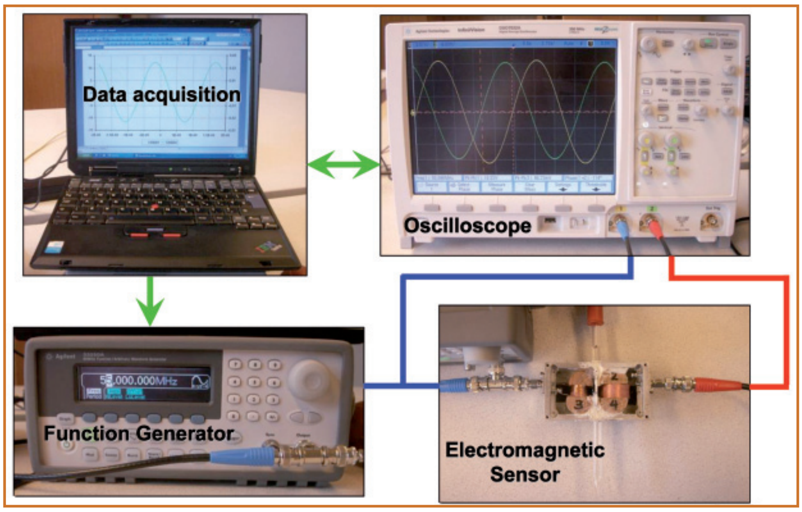

Fig. 7: Hardware set-up for measurement of magnetic permeability at IME

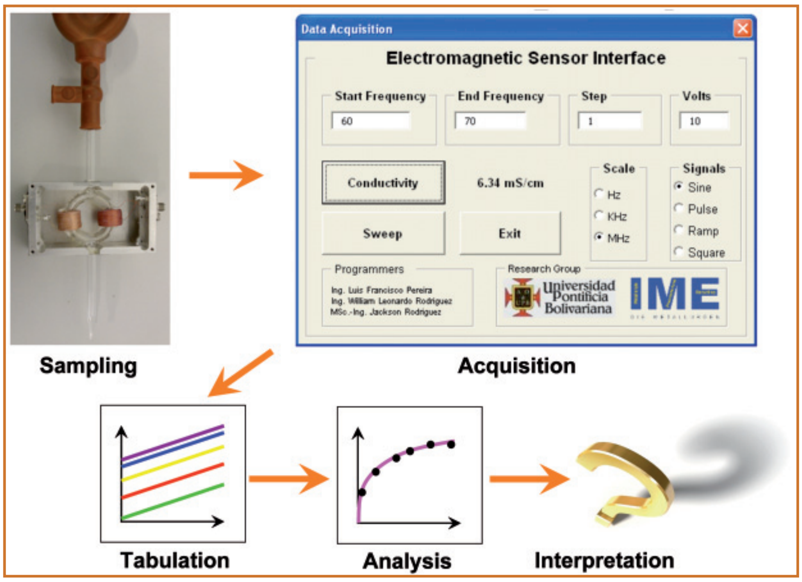

Fig. 8: Applied empirical research methodology

Fig. 7 describes the implemented hardware setup for the measurement of magnetic permeability available at IME. The EM-sensor transmits a sinusoidal signal through its primary winding, delivered by an arbitrary waveform generator 33250A from Agilent Technologies. On its secondary winding the received signal is measured and displayed on a digital storage oscilloscope DSO7032A as well from Agilent Technologies, which is proportional to the value of magnetic permeability of the sample. Differences in magnitude and phase from the transmitted and the received high frequency signals can be digitally measured and stored with high accuracy and versatility via the USB-port, using the provided VBA programming interface (Visual Basic for Applications) integrated directly on Microsoft Excel.

In regard to the applied methodology based on the empirical research model, fig. 8 describes the five major steps to assess the measured results. The first step is defined as "sampling" and refers to design and implementation of the required hardware able to produce useful and reproducible signals required to analyze and to define any particular behavior. "Sampling" also represented a major challenge when working at high frequencies due to electromagnetic noise. For this reason, a metallic case with special SMC-connectors for coaxial cables was implemented. This was realized in order to get rid of external noise while improving accuracy and reproducibility of measurements towards the second step, the acquisition of data.

Data acquisition takes advantage of automation techniques already integrated in some electronic devices like waveform generators and digital storage oscilloscopes from Agilent Technologies, using standard interfaces as VBA for instance. Using conventional macro tools on Microsoft Excel, a graphic user interface GUI was developed enabling automation of data acquisition and delivering large data sets directly as tables on Excel spreadsheets simplifying the evaluation procedure.

Finally, third, fourth and fifth step, tabulation, analysis and interpretation respectively, referred to evaluation of empirical data that allowed to characterize the relation between magnetic permeability and concentration of the ionic content in the treated effluents. This novel methodology based on an electrodeless non-invasive measurement shall help to improve and automate EC-treatment of wastewater.

In order to assess the reliability of the EM-sensor in measuring industrial effluents with metallic contents, the EC-treatment of synthetic and industrial wastewater was investigated. Fig. 9 shows the appearance of synthetic samples in concentrations of 1, 10, 100 and 1000 mg/l of copper, nickel and zinc, as three elements often present in industrial effluents. On the other side, industrial wastewater before and after EC-treatment was assessed towards operation under real conditions.

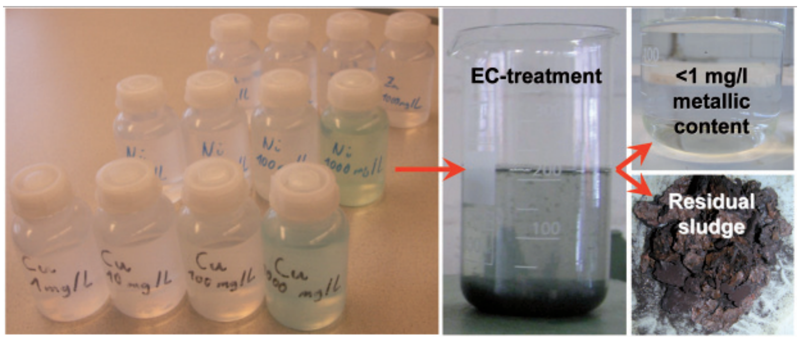

Fig. 8: Synthetic and industrial wastewater before and after EC-treatment

Results and Discussion

The aim of this research was focused on the detection of a dependence between the metallic concentration of synthetic samples and the electromagnetic signal measured by means of a first prototype that has been designed and constructed for this purpose. Fig. 10 shows a correlation between gain, measured in decibels (dB), and the metal content from synthetic samples, with 1, 10, 100 and 1000 mg/l of Cu, Ni and Zn respectively. Suitable frequencies for these solutions ranged from 500 kHz up to 5 MHz. From the green line describing the system response for deionised water as reference, a proportional

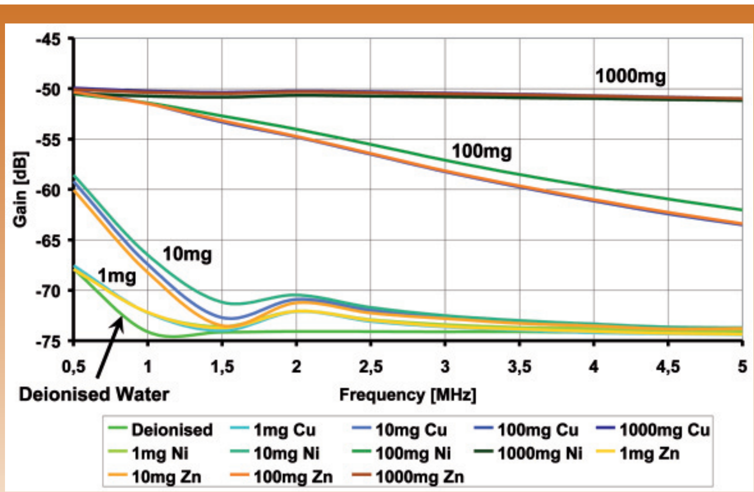

Fig. 10: Gain response during frequency sweep of synthetic metal containing solutions from 500 kHz to 5 MHz

dependence of the ionic content is clearly noticeable with the magnitude of the electromagnetic signal. This effect proofs the proposed principle and can be addressed to the magnetic permeability.

In order to assess the feasibility of magnetic permeability for the characterisation of real industrial wastewater, the frequency sweep had to be modified ranging from 60 to 70 MHz. Several undesired effects were observed mostly due to noise and required signal conditioning. Fig. 11 compares the frequency responses of the EM-sensor first for a selected industrial wastewater sample (pH=2), second after selective metal removal via electrocoagulation (pH=3), and third after chemical precipitation using lime (pH=9), with comparison to the deionised water as reference sample (pH=7). From this diagram a proportional change of the magnetic properties for the same effluent can be seen either after selective removal of copper content using EC or after complete removal of all metallic content at a high pH value using lime. Following this experience a first similitude between the magnetic permeability and electric conductivity could be realized, which motivates to continue in developing this method further for complex industrial effluents.

For a systematic investigation 20 different samples with known values of conductivity were prepared using sodium chloride. Fig. 12 shows the dependence of the magnetic permeability in the frequency range from 60 to 70 MHz for each of these samples including deionised water with the lowest gain around -70dB. From this result, a logarithmic distribution of gain can be perceived with an increasing value of electric conductivity, dependence which can be seen in fig. 13. Despite the fact that the measurement of gain, as an indicator of the magnetic permeability, and the electric conductivity are based on completely different principles, inductive and galvanic respectively, this result shows surprisingly a proportional correlation between those magnitudes. There is no doubt that magnetic permeability and electric conductivity represent the very same magnitude in the ionic range.

Although there is no information available about technical details of commercial inductive conductivity sensors (e.g. from Mettler-Toledo, see Fig. 14), such devices seem to work similar to the one developed at IME. Among the advantages of this electrodeless and non-invasive measuring technique, its insensitivity to fouling, scaling and strong acids makes it the ideal choice to monitor industrial effluents in chemical, petrochemical, and pulp & paper industry [6].

Conclusions and Outlook

After successful continuation of research activities towards the optimisation of industrial wastewater treatment via electrocoagulation, a first stage for the design and implementation of an online sensor for wastewater analysis has been accomplished. Taking advantage of all benefits involving this electrode-less and non-invasive method for conductivity measurement, the implemented electromagnetic sensor delivers an indication of the total ionic content of the solutions. The general technical feasibility of using magnetic permeability as methodology for online monitoring

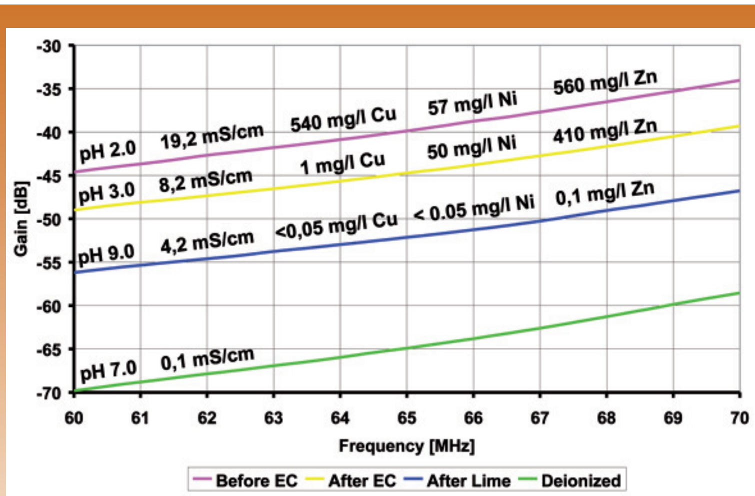

Fig. 11: Gain response during frequency sweep of an industrial sample before and after purification treatment (via conventional lime neutralisation and electro-coagulation)

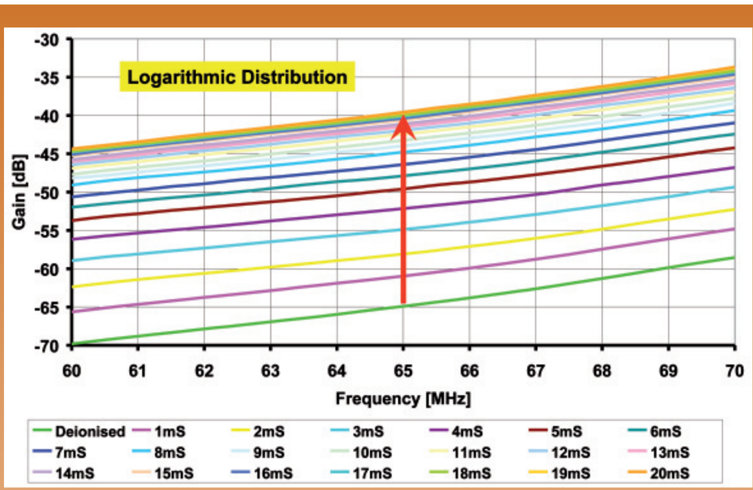

Fig. 12: Gain response during frequency sweep of NaCl-solutions at given conductivity values

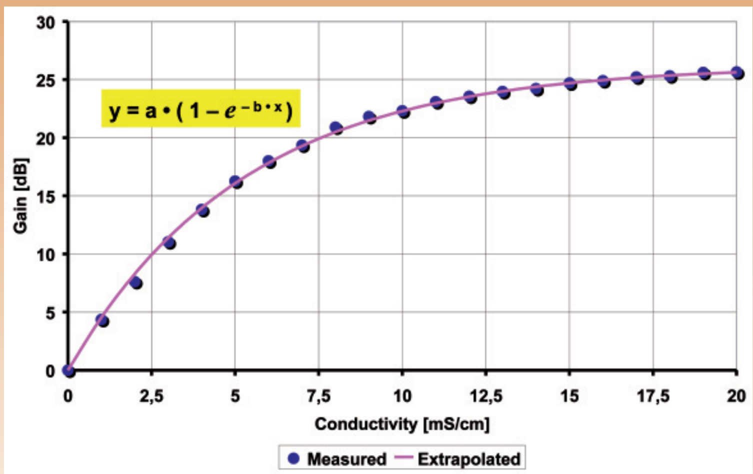

Fig. 13: Gain response during frequency sweep of NaCl-solutions at given conductivity values.

of effluents before and after a purification step has been confirmed.

The electromagnetic sensor delivers an accurate measurement of conductivity and due to its contactless approach it is insensitive to fouling, scaling or even strong acids, which makes it ideal for online monitoring of wastewater streams. The challenging sub-target of identifying parameter sets enabling identification of individual metal concentrations in complex solutions could not be confirmed up to now and remains a continuing research goal.

Looking forward to the next stage of research at IME, the integration of the electromagnetic sensor feedback into the power supply will be carried out, in order to implement a closed-loop process control enabling improvements of mass and energy balance in wastewater treatment, especially for the electrocoagulation process. By means of an expert system, monitoring of process effluents after EC-treatment shall be performed in real-time, while introducing a more efficient and secure way to protect environment and water resources from contamination.

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(1) Jackson Rodriguez, Prof. Dr.-Ing. Bernd Friedrich, IME Process Metallurgy and Metal Recycling, RWTH Aachen – Germany

(2) William Rodriguez, Francisco Pereira, Carlos Hernandez, UPB Pontificia Bolivariana University, Bucaramanga – Colombia

Fig. 14: Inductive conductivity sensor from Mettler-Toledo