

Method and device for measuring the conductivity of a
pure or ultrapure liquid

5 The present invention concerns a method of
measuring the conductivity of a pure or ultrapure liquid,
notably water.

Measuring the conductivity of a liquid is important
in many industrial fields necessitating the use of
ultrapure water, in particular the chemical,
10 pharmaceutical, medical and electronics industries.

The conductivity of an aqueous solution is measured
by measuring the resistance of that solution across a
conductivity measuring cell that generally consists of at
least two conductive material components forming
15 electrodes.

A conductivity measuring cell is defined by its
cell constant, which proportionately links the measured
resistance to the conductivity of the solution. The cell
constant determines the accuracy of the cell's
20 measurements. It is therefore necessary to use cells with
a low constant to measure the conductivity of an
ultrapure liquid.

The conductivity measurement is affected by the
geometry of the cell: the total area of the electrodes
25 (s) and the distance between them (L). These two
parameters define the cell constant $k = L/s$.

Conductivity is a measure of the flow of electrons
through a substance. It is directly proportional to the
ion concentration, the charge on the ions (valency), and
30 their mobility. Their mobility is a function of
temperature and, consequently, the measured conductivity
also depends on temperature.

In theoretically pure water, the only two kinds of
ions present result from the dissociation of water into
35 H^+ ions and OH^- ions.

At $25^\circ C$ the theoretical conductivity of a sample of
water free of ionic contamination is $0.055 \mu S/cm$, i.e.

its resistivity (resistivity is the reciprocal of conductivity) is 18.2 MΩ.cm. The resistivity of a sample is determined from the equation $\rho = R/k$, proportionately relating the measured resistance R of the sample and the cell constant k. Water is considered pure or ultrapure for resistivity values greater than 1 MΩ.cm.

One valuable application of water conductivity measurement is to any purification system including a water conductivity or resistivity sensor.

When measuring conductivity, it is necessary to apply a potential difference to the terminals of the electrodes immersed in the solution. A potential difference in the form of electrical pulses induces a current related to the area of the electrodes. The greater the area of the electrodes, the lower the cell constant and the commensurately more accurate the measured current. Applying a potential difference also creates resistance and capacitance phenomena throughout the electrical circuit. In particular a capacitance that is directly linked to the geometry of the cell appears at the electrode-solution interface. A small cell with a low constant induces a high capacitance.

A conductivity measuring cell immersed in water is conventionally modeled by an equivalent electrical circuit representing the resistance and capacitance effects of the system.

The conventional approach ignores or compensates capacitance and resistance effects specific to the electrodes; thus the model of the water between the electrodes becomes purely resistive or, after simplification of the model, is assigned a series capacitance.

For example, in the prior art the capacitance effects of the cell are compensated by regular calibration and by using electrodes with an area that is sufficiently large to reduce the phenomenon. One way to solve this problem is to immerse the conductivity

measuring cell regularly in a solution of known resistivity and recalculate a cell constant to take account of the state of the electrodes.

Moreover, to be able to use the simplified model, and in order to reduce the risk of polarization, it is necessary to use electrical signals at a frequency that is accurately chosen as a function of the quality of the sampled water.

There are various prior art methods for determining the resistivity of a liquid. The methods described hereinafter are based on water modeled by an equivalent electrical circuit consisting of a capacitor in series with a resistor.

The central sampling method described in international patent application WO 88/01740 consists in periodically exciting the conductivity measuring cell. The output signal of the cell is analyzed over two different time periods during which the capacitance effects inherent to the cell are different. The signal obtained during the first interval is corrected for the capacitance effects on the basis of the signal differences between the two time intervals. The central sampling method and short wires eliminate from the solution equations the capacitance effects of the wires and the electrodes.

A second method for determining the resistivity of a pure or ultrapure liquid described in US patent application 2007/0024287 measures the alternating current passing through the conductivity measuring cell. The resistivity of the liquid is then calculated from the impedance difference between signals at different frequencies. An alternating electrical current at a precisely defined frequency is applied to the terminals of the conductivity measuring cell. The current is measured and the operation is repeated with a signal at a different frequency. The measured values being proportional to the impedances of the cell, the

difference between the impedances obtained at the different frequencies can be used to calculate the serial capacitance and resistance effects of the sample. It is then possible, for a given frequency, to determine
5 mathematically the resistivity of the liquid tested, including compensation of capacitance effects.

The above methods have limitations. Firstly, they limit the size of the electrodes and the cell constant. Then, to limit polarization, a conductivity measuring
10 cell must be used at a particular frequency, as a function of a limited range of conductivity values of the liquid concerned. Finally, aging of the cell electrodes (passivity, corrosion, etc.) causes modification of the capacitance at the electrode-solution interface which
15 cannot be controlled.

The conductivity of a small sample can be measured using a conductivity measuring cell provided with micro-electrodes, as described in French patent application No. 0655276, for example. This is because of the small
20 size of the electrodes and because a high level of performance of the sensor, i.e. a low cell constant, is maintained. It has nevertheless been found that using micro-electrodes, thanks to their small size, can produce large capacitance effects, which can no longer be
25 ignored. It is then necessary to revise the model of the cell in water.

As indicated above, the theoretical model of a conductivity measuring cell immersed in water is represented by an equivalent electrical circuit diagram consisting of numerous resistors and capacitors, in
30 series or in parallel, characterizing the behavior of the components of the system. The occurrence of capacitance phenomena when using micro-electrodes must then be taken into account in the model. It is immediately apparent
35 that adding a capacitor in series with the single resistor of the simplified model is no longer sufficient to represent the electrical behavior of the cell during

tests.

The present invention therefore uses, as in US-6232786, a new model for a conductivity measuring cell immersed in water, including in the equivalent electrical circuit diagram a capacitor in series with a parallel-connected combination of a resistor and a capacitor. The benefit for micro-electrodes of this new model is considerable. It is nevertheless important to note that this new model does not apply only when using micro-electrodes, and that it is equally applicable to concentric electrodes and to measurements on solutions of lower quality.

Thanks to the present invention, it is generally possible to take into account the effects of serial and parallel capacitances in the electrical model of highly pure water to measure the conductivity accurately. The invention also detects foreign bodies present in the sample.

To be more precise, the present invention proposes a method of measuring the conductivity of a pure or ultrapure liquid, notably water, using electrodes, which consists in determining the conductivity by modeling the liquid in the form of an equivalent electrical circuit diagram comprising a resistor R , a capacitor C_p in parallel with the resistor R , and a series capacitor C_s , and is characterized in that it includes the steps of applying series of reference excitation signals at different frequencies, reconstructing the spectrum of the output signal by aggregating discrete measurements taken at the given frequencies, comparing the reconstructed empirical signal with a theoretical model, minimizing the difference between the theoretical model and the empirical signal obtained to extract therefrom the triplet R , C_p , C_s , and further determining if the extracted triplet R , C_p , C_s corresponds to a situation of disturbance of the measurement and, if so, the nature of the disturbance by using a calculation of the probability

to belong to a family of situations recorded in a database.

According to preferred features, where appropriate combined:

- 5 - the reconstructed spectrum of the output signal is subjected to temporal interpolation to increase the resolution of the signals at intermediate frequencies and/or to extrapolation of the frequencies in order to take into account frequencies that are inaccessible experimentally;
- 10 - the comparison is effected between the Fourier transformed function of the reconstructed empirical temporal signal and the Fourier transform of the theoretical model or between the reconstructed empirical temporal signal and the inverse Fourier transform of a Fourier transform of the theoretical model;
- 15 - the minimization step uses differential norm multidimensional non-linear minimization, preferably in the form of the Powell method or the Simplex method with linear programming;
- 20 - the disturbance corresponds to the presence of a foreign body, notably a particle, a non-miscible contaminant, or a gas bubble;
- 25 - the excitation signals are applied in the form of pulses, preferably squarewave pulses;
- the range of frequencies of the excitation signals is from 50 Hz to 5 kHz or from 100 kHz to 20 MHz; and
- 30 - the conductivity is measured by means of micro-electrodes.

The invention also relates to a device for measuring conductivity of a pure or ultrapure liquid, notably water, characterized in that it includes control means for executing the method defined above.

35 According to preferred features of this device, where appropriate combined:

- the control means include a microcontroller;

- the microcontroller is connected to a conductivity measuring cell excited by a pulse generator or a reference signal generator; and

- the or each conductivity measuring cell is provided with micro-electrodes.

The invention finally relates to a water purification system including the above conductivity measuring device.

Other advantages of the present invention will become apparent on reading the following description, which is given with reference to the drawings, in which:

- figure 1 represents the equivalent electrical circuit model of the present invention for a highly pure liquid;

- figure 2 is a general diagram of a method of the present invention for determining the conductivity and parameters of sampled water;

- figure 3 is an electronic circuit diagram of one embodiment of a system of the present invention for measuring electrical properties of water;

- figure 4 represents the algorithm of one embodiment of a microcontroller of the present invention;

- figure 5 shows in more detail a signal preprocessing phase of the algorithm;

- figure 6 shows in more detail a phase of the algorithm that determines parameters of the tested sample.

It should be noted that the following description is given by way of nonlimiting example.

To measure the conductivity of a pure or ultrapure liquid, such as water, it is necessary to model it by means of an equivalent electrical circuit diagram embodying the cell-solution interface and the electrical properties of the liquid.

The electrical effects of the connecting wires between the electrodes and the surrounding electronic systems are also taken into account, and are modeled by a

capacitor.

The resistances of the model, which are of the order of one ohm, can be ignored compared to the resistivity of the pure or ultrapure liquid.

5 The model can then be revised and the liquid modeled in accordance with the present invention by the equivalent circuit 10 shown in figure 1. This comprises a capacitor 11 in series with a parallel-connected combination of a capacitor 12 and a resistor 13.

10 The conductivity of the tested sample is determined by a method conforming to the general diagram 14 (figure 2). This method is based on the characteristics of the liquid, notably in a Fourier or Laplace space, and detects abnormal situations by comparing the
15 characteristics of the tested liquid with various predetermined models.

To be more precise, the general diagram 14 shows a conductivity and temperature measuring cell portion 15 excited by an electrical pulse from an electronic
20 excitation system 16 controlled by an algorithm executed by a microcontroller 18.

The temperature measuring electronics are conventional (for example a Wheatstone bridge) and are not described in more detail here. Note, however, that
25 they link the measured parameters of the liquid to temperature and therefore take into account the influence of temperature on those parameters.

The excitation applied to the conductivity measuring cell 15 induces an electrical current between
30 its two electrodes. The response to the excitation, disturbed by its passage through the solution, is routed to the microcontroller 18 by an electronic measuring system 17.

The received signal is then processed and
35 interpreted by the algorithm of the microcontroller 18, which outputs the resistance and capacitance parameters 19 of the tested solution. The algorithm of the

microcontroller 18 triggers an alarm 20 if the sample in question is contaminated, for example by solid particles or air bubbles.

5 As represented by the circuit 21 in figure 3, the electronic excitation and measurement part of one embodiment of the present invention includes a pulse generator 22 or a reference signal (squarewave, sinusoid, sawtooth, etc.) generator. This generator can be a voltage or current source, but here it is designed to have the following two characteristics:

- the peak-to-peak voltage between the electrodes never exceeds 1.23 V, to avoid dissociation and autoprotolysis of the water, and
- the mean voltage of the signal is zero.

15 Although a pulse defined by a current source can be used, excitation by a voltage source is more practical to use and control in an electronic circuit. Any type of pulse can be used: squarewave, sinusoid, sawtooth, etc. Here this signal is of limited bandwidth and meets the above conditions, of course. In practice it is preferable to use a squarewave signal because such signals are easier to manipulate with an electronic circuit.

20 The pulse generator 22 feeds a conductivity measuring cell the two electrodes 23 and 24 whereof (here micro-electrodes) are shown in figure 3. The electrodes 23 and 24 are controlled by switches 31 and 32 of the generator 22 to excite both electrodes with the same reference signal, thereby eliminating the risk of dissymmetry.

30 The signal from the cell is amplified and processed by an operational amplifier 26, and resistors 27 and 28 accurately set the signal gain. A reference signal V_{REF} is applied to an input of the operational amplifier 26. The resistors 27 and 28 are selected by a gain resistor selector 33. The voltage signal V_s from the operational amplifier 26 is converted from an analog signal to a digital signal by an analog-to-digital converter 29, and

35

the signal is then routed to the microcontroller 18.

Here (see figure 4) an algorithm 30 of the microcontroller 18 for determining parameters of the system (conductivity deduced from the resistance, series
5 capacitance and parallel capacitance) includes firstly a preprocessing phase 31 for improving the quality of the digital signal to facilitate its analysis.

The signal is then analyzed during a vectorial extraction phase 32 to determine the parameters of the
10 system. These are routed to a database to associate them with a situation tested during a learning phase 33. The parameters from the extraction phase 32 are then compared to the prerecorded situations 34 during a detection phase 35.

Depending on whether the parameters identified come
15 from a contaminated or uncontaminated sample, the alarm and post-processing phase 36 triggers an alert 20 in respect of the quality of the sample and/or communicates its parameters 19 (cf. figure 2) to a display unit that is not shown in the figures.

In practice, a series of reference excitation signals is applied to the terminals of the electrodes. Each signal corresponds to a given frequency between 50 Hz and 5 kHz. Referring to figure 5, during the
25 preprocessing phase 31, the digitized signal from the analog-to-digital converter 29, corresponding to a given frequency, is filtered, here by a median filter 37, to eliminate aberrant measurement points. It is then subjected to low-pass filtering 38 to eliminate high
30 frequencies. By aggregating all the series of digital signals, the spectrum of the output signal is reconstructed for the given frequencies in the form of a curve of voltage as a function of period. Finally, the signal is subjected to temporal interpolation and
35 extrapolation 39 to increase the resolution at intermediate frequencies and to sweep a range of frequencies that are not accessible experimentally. From

twenty discrete measurements, for example, a spectrum of 200 values of voltage as a function of frequency can be constructed, sweeping a range from 100 Hz to 5 kHz. This method of processing the signal produces a greater
 5 quantity of data at high and low frequencies and avoids the loss of measuring time necessary to sweep the entire frequency spectrum with high resolution. The measured signal is at this stage a preprocessed temporal signal with good resolution and a good signal-to-noise ratio,
 10 ready to be analyzed.

Here (see figure 6), the parameters of the system (the conductivity deduced from the resistance R, the series capacitance Cs and the parallel capacitance Cp) are determined using an algorithm
 15 extracting the solution triplet (R, Cs, Cp). The preprocessed (notably interpolated) temporal signal from the preprocessing phase 31 can be processed by two methods.

The first way of processing the preprocessed temporal signal (see the left-hand portion of figure 6) begins with a transformation 41 to obtain its transfer function in a Fourier or Laplace space. The fast Fourier transform function (FFT) obtained in this way is compared with the FFT of the model 42 of the liquid, which
 25 corresponds to theoretical parameters of the output signal. In the case of excitation by a squarewave signal, the model of the output signal is given by the following equation, in which T is the duration of the pulse:

$$H(j\omega) = (1 - e^{-j\omega T}) \frac{1}{j\omega C_s} + \frac{R}{1 + j\omega R C_p}$$

30 Comparison of the Fourier transform function obtained experimentally and that obtained from the theoretical model is effected during a phase 43 of establishing a differential norm between the empirical vector and the model vector. Differences between the
 35 experimental and theoretical results are determined during this phase. At this stage of the algorithm

determining the solution vector (R, C_s, C_p) , the disparities between the two transfer functions are optimized during a phase 44 of multidimensional non-linear minimization of the differential norm between the model and the signal for which an adjustment is being effected. Thanks to this optimization, the differences tend toward zero on modifying the values of the three parameters of the theoretical model. It is effected using mathematical optimization methods, for example of the kind using calculation of first derivatives (gradient methods), preferably the Powell method or the Simplex method with linear programming. After optimization, the parameters of the system can be fully determined (the modeled curve has been determined that best matches the empirical curve corresponding to the real data acquired), and the algorithm therefore provides access to a solution vector (R, C_s, C_p) .

The conductivity of the sample is derived from this vector using the equation $C=R/k$ defined above.

The second way to process the preprocessed time signal (see the right-hand part of figure 6) is for the FFT of the model of the liquid 42 to be inverted during a phase 45. The model of the liquid is then a time signal homogeneous with the preprocessed time signal. The two signals are compared in the same way as in the first method of determining the vector (R, C_s, C_p) , based on a phase 43 of establishing a differential norm and an optimization phase 44.

The parameters are therefore known. The present invention nevertheless stores the vectors of three parameters associated with the measured temperature in a database during a learning phase 33 (see figure 4). The basic algorithm is therefore preferably provided with a library of prerecorded situations and can throughout its use enrich that database with results obtained from tests.

Storing a large number of situations enables acquisition of vectors (R , C_p , C_s) under normal conditions and under conditions where there is significant disturbance to one or more of the parameters R , C_p and C_s , for example the presence of an air bubble or a resin bead coming from the liquid purification system, followed by establishing polynomial functions linking R to C_p and C_s based on the parameters obtained in this way and used in the detection phase 35 described hereinafter.

Thus when the parameters of the sample have been determined, following the extraction phase 32, they are compared with the situations stored in the database during the detection phase 35. Using standard mathematical methods (standard deviation calculation, Gaussian error dispersion), the probability is then calculated of the vector (R , C_p , C_s) that has been determined belonging to a family of situations corresponding to a normal condition or to a disturbed condition, and, if so, which.

The behavior of the capacitances and the resistance is closely linked to the type of contamination. One example is the detection of an air bubble. The small size of the micro-electrodes means that it is possible to detect the presence of air bubbles that falsify the resistance measurement and therefore the value of the conductivity of the solution. Thus in the presence of a bubble the resistivity of the liquid is affected by the resistivity of air. Note also that the values of the capacitances diverge. Note further that in this particular situation the value of the series capacitance tends to fall relative to a solution free of contamination whereas that of the parallel capacitance tends to rise. In the presence of a resin bead, the values of the capacitances vary very significantly and more than in the presence of an air bubble, whereas the value of the resistance remains substantially the same.

The specific variations of these parameters are sufficiently large to be noteworthy and the risk of confusion with a sample free of contamination is eliminated by the comparison following the detection phase 35.

Once it has been determined that the parameters of the system belong to a given condition and their values have been determined, the alert and post-processing phase 36 provides access to the values of these parameters and/or to the value of the conductivity, for example on a display unit, and determines if the sample is contaminated or not and, if so, the type of contamination and how to remedy the problem. For example, the algorithm can trigger purging commands to restart the tests under better conditions.

A valuable application of this nonlimiting example of the present invention is to measuring the conductivity of a pure or ultrapure water solution, notably in water purification systems.

Numerous other variants are feasible as a function of circumstances, and the present invention is not limited to the example described and shown.

Note in particular that the microcontroller can be replaced by a generic processor or a dedicated digital signal processor (DSP). More generally, any electronic component comprising at least an arithmetic and logic unit will be suitable.

In applications other than the typical applications of detecting air bubbles or resin beads, the range of frequencies of the excitation signals can be different, in particular from 100 kHz to 20 MHz in applications that are more oriented toward life sciences (cytometry, identification of bacteria, etc.).

CLAIMS

1. Method of measuring the conductivity of a pure or ultrapure liquid, notably water, using electrodes
5 (23,24), which consists in determining the conductivity by modeling the liquid in the form of an equivalent electrical circuit diagram (10) comprising a resistor R (13), a capacitor Cp (12) in parallel with the resistor R (13), and a series capacitor Cs (11), and is
10 characterized in that it includes the steps of:

- applying series of reference excitation signals at different frequencies,
- reconstructing the spectrum of the output signal by aggregating discrete measurements taken at the given
15 frequencies,
- comparing the reconstructed empirical signal with a theoretical model,
- minimizing the difference between the theoretical model and the empirical signal obtained to extract
20 therefrom the triplet R (13), Cp (12), Cs (11), and
- further determining if the extracted triplet R (13), Cp (12), Cs (11) corresponds to a situation of disturbance of the measurement and, if so, the nature of the disturbance, by using a calculation of the
25 probability to belong to a family of situations recorded in a database.

2. Method according to claim 1, characterized in that the reconstructed spectrum of the output signal is subjected to temporal interpolation to increase the
30 resolution of the signals at intermediate frequencies and/or to extrapolation of the frequencies in order to take into account frequencies that are inaccessible experimentally.

3. Method according to claim 1 or 2, characterized
35 in that the comparison is effected between the Fourier transformed function of the reconstructed empirical temporal signal and the Fourier transform of the

theoretical model or between the reconstructed empirical temporal signal and the inverse Fourier transform of a Fourier transform of the theoretical model.

4. Method according to any one of claims 1 to 3,
5 characterized in that the minimization step uses differential norm multidimensional non-linear minimization, preferably in the form of the Powell method or the Simplex method with linear programming.

5. Method according to any one of claims 1 to 4,
10 characterized in that the disturbance corresponds to the presence of a foreign body, notably a particle, a non-miscible contaminant, or a gas bubble.

6. Method according to any one of claims 1 to 5,
15 characterized in that the excitation signals are applied in the form of pulses, preferably squarewave pulses.

7. Method according to any one of claims 1 to 6, characterized in that the range of frequencies of the excitation signals is from 50 Hz to 5 kHz or from 100 kHz to 20 MHz.

20 8. Method according to any one of claims 1 to 7, characterized in that the conductivity is measured by means of micro-electrodes.

9. Device for measuring conductivity of a pure or ultrapure liquid, notably water, by means of electrodes
25 (23,24), characterized in that it includes control means (18) for executing the method according to any one of claims 1 to 8.

10. Device according to claim 9, characterized in that the control means include a microcontroller (18).

30 11. Device according to claim 10, characterized in that the microcontroller (18) is connected to a conductivity measuring cell excited by a pulse generator (22) or a reference signal generator.

12. Device according to claim 11, characterized in
35 that the or each conductivity measuring cell is provided with micro-electrodes (23, 24).

13. Water purification system including a device according to any one of claims 9 to 12 for measuring the conductivity of water.