A Technical Evaluation of Capacitive Level Sensors for use in Hemodialysis Machines on Chambers Filled with Dielectric Fluid

A Master’s Thesis in Electrical Measurements carried out at Baxter International Inc. in Lund

Viktor Petersson
Viktor Stevander

Department of Biomedical Engineering
Lund University

Advisor: Matilda Träff
Lars Wallman

2016
A series of tests were performed to explore the limits of two capacitive level sensors using the principle of parallel finger layout (sometimes called comb fingers) for sensing. The goal was to present a decision basis for Baxter to use when choosing a sensor to implement in their next generation hemodialysis machine. The devices under tests were 1) sensor type A: developed in-house and 2) sensor type B: designed by a third party. A survey of the system and requirements on the sensor, followed by a brief overview of capacitance, permittivity, thermal expansion, and the Wien bridge oscillator converged in a set of tests. These tests determined 1) that both sensor types are able to measure the liquid level with fair accuracy in a controlled environment; 2) type A is more sensitive to temperature change and induced noise; 3) type A drifts over a 4 hour time period; 4) type A changes its resolution in different liquids; 5) type B cannot successfully measure liquid levels at a temperature of 96°C. The recommendation is to move forward with the type B level sensor and to further test the sensors’ durability over time and in different climates. The method used to measure in type B is unknown, making it hard to anticipate and to find solutions to problems that may occur in the future.
We have received a lot of help and support during our work of this thesis and would like give our thanks and acknowledgments to the persons who made all this possible:
Our advisor at LTH, Lars Wallman, for giving his support to us in the writing and help with administrative work at LTH.
Our advisor at Baxter, Matilda Träff, for all the encouragement and support through the whole process to be able to always move forward with our work.
Anette Lilja for all the help with administrative work at Baxter.
Our examiner at LTH, Johan Nilsson, and colleague at Baxter, Erik Torgny, for the help and discussion about EMC related problems in the test rig.
Russel Hughes at Baxter for the help in troubleshooting and understanding of the sensors.
Rickard Borgström and Rikard Wellander, colleagues at Baxter, for making us feel welcome and a part of Baxter.
Thank you all. We would also like to give our thanks to all of the employees at Baxter that made us feel welcome and helped us with various tasks.
## List of Figures

1.1 The blood path in a dialysis machine [1]. ........................................... 2
1.2 An overview of the liquid path in a dialysis machine [1]. ........................ 3

2.1 Basic parallel fingers layout. The red lines represent the path of the fringing field. ................................................................. 8
2.2 Simplified schematics of a Wien bridge oscillator ................................. 9
2.3 Simplified schematics of a Wien bridge oscillator ................................. 10
2.4 Gainplot .......................................................................................... 10

3.1 A simplified schematic of the front of the test rig. Dark blue represent the flow through the chamber and light blue the circulation path through the piston pumps. ......................................................... 12
3.2 A simplified schematic of the rear of the test rig. The dotted figures represent the placement of the equipment on the front. .............. 13
3.3 Connection paths on the circuitboard between the motor drivers and the DAQ ................................................................. 13
3.4 Electrical connection chart of the system when the test uses the piston pumps. The different lines from the power box represent different channels. Red = 24 V, Blue = 12 V, Green = 5/24 V, Black = Signal. .................................................................................. 15
3.5 Flowchart of the liquid path when the test uses the piston pumps. The main source of liquid comes from the Julabo heater. .... 15
3.6 LabVIEW was used for control and data acquisition. Front panel (a) serves as a GUI while the program is running. The block diagram (b) is used for creating buttons, functions etc. .............................. 17

5.1 Test 1: Liquid level 0 to 60 ml .............................................................. 26
5.2 Test 2: Plateau - 0 to 60 ............................................................... 26
5.3 Test 3: Differential step test ............................................................... 26

6.1 Shows the type A-sensors’ negative proportional output (blue line) against the liquid level (red dashed line) in the chamber. The scale is 30 Hz/ml. .................................................................................. 31
6.2 Shows the type B sensors’ calibrated output (blue line) against the liquid level (red dashed line) in the chamber. ........................................... 32

6.3 Type B sensor 3 and 4 have spikes that cause non-unique output for some liquid levels. ................................................................. 32

6.4 Output from sensor type A at liquid levels ranging from 0-20 ml. The variation in start frequency comes the physical properties of the sensors, giving them different capacitance in the beginning. ................. 33

6.5 Type B sensor output at liquid levels ranging from 0-20 ml. The spike in sensor 5 at 18 ml is an irregularity that could not be derived. ............ 34

6.6 Different type A sensors have different working frequencies. The deviation is around 10 % when performing test 1, where 1 ml corresponds to 38 Hz. ................................................................. 36

6.7 Shows the linearity for sensor type A. The deviation in test 2 is around 6-7 %. ................................................................. 36

6.8 Sensor type A repeatability and drift test. No drift is noted, it returns the same starting point throughout the test, the standard deviation is about 5-8 % in test 3, and 1 ml corresponds to 33.3 Hz. .................. 37

6.9 Repeatability test for sensor type B. All sensors begin at 0 % and have a standard deviation of about 8 % in test 1. .......................... 38

6.10 Shows the linearity for sensor type B. The standard deviation is about 8 % in test 2. ................................................................. 39

6.11 Shows a type B sensor with spikes that cause nonlinear behavior in the lower levels of test 2. ................................................................. 39

6.12 Sensor type B repeatability and drift test. No drift can be seen and the standard deviation is about 5-8 %. .................................................. 40

6.13 Behavior of sensor type A in test 1 for different liquids. The sensors begin at the same frequency in all three liquids. There is a great difference in frequency between the high and low point in cleaning and conductive fluid compared to RO-water. The scale is 16.7 Hz/ml for RO-water and 38.3 Hz/ml for conductive and cleaning liquid. .......................... 41

6.14 Linearity for sensor type A in test 2 for different liquids. The increase in deviation in filled chamber can be derived from the error when using a pipette. .......................... 42

6.15 Behavior of type B sensor in test 1 for different liquids. Starts at the same point for all liquids but has problem returning to 0 % for all conductive and cleaning liquid. ................................................................. 43

6.16 Linearity of type B sensors in test 2 for different liquids. The increase in deviation with increased liquid level can be derived from the error of using a pipette. ................................................................. 43

6.17 Output from sensor type A at a constant liquid level and circulation during four hours. It has a small drift of a total 6.3 % with increasing fluctuations near set point changes. .......................... 44
6.18 Output from type B sensors at a constant liquid level and circulation during four hours. The changes are small but unpredictable. The different start points could originate from many sources, such as a sensor not being as tight fastened to the chamber as the other or variations in angle to the chamber.

6.19 Type A sensors output at constant liquid level when inducing noise, incremented in steps. Induced frequency is described in table [6.2]. A small drop in frequency and increase in noise intensity at induced 700 kHz. Large drops, down 51% of the original chamber level, occur after 1.5 MHz. The change in induced frequency is hence affecting the output from the sensor (and through this the interpreted liquid level). The scale is 38.3 Hz/ml.

6.20 Sensor type B output at constant liquid level when inducing noise, incremented in steps. Induced frequency is described in table [6.2]. Level output and increased noise is seen with induced 3,000 kHz.

6.21 Sensor type A output in test 1 with induced noise at 700 kHz and 3,000 kHz. Note that the resolution is increased at 3,000 kHz noise, changing the scale from 40 Hz/ml (for 700 Hz noise) to 70 Hz/ml (3 MHz noise).

6.22 Sensor type B output in test 1 with induced noise at 700 kHz and 3 MHz. The high noise level below 20% comes from the use of a new chamber and not the induced noise.

6.23 Shows how type A sensors provide an output of greater liquid level in the chamber when the liquid drops in temperature. The total change is about 6.3% with a scale of 38.3 Hz/ml.

6.24 Shows how type B gives an output of lesser liquid level in the chamber when the liquid drops in temperature.

7.1 The type B sensor shows some problem measuring cleaning liquid at 96°C. The sensor was cooled down between the runs.

7.2 The output frequency of the type A sensor, where a lower frequency is the result of a higher conductivity.

7.3 The output frequency of the type B sensor, where a lower frequency is the result of a higher conductivity.

7.4 Shows how the type A sensor reacts to a change of BJT to MosFET transistors. MosFET gives a lower starting frequency due to its higher capacitance while also lowering the resolution of the type A.

7.5 Sensor type A output at different grounding points. Best results come from grounding both the test rig and the water. Conductive liquid was used since this introduced the largest amount of noise in the sensor.

7.6 Sensor type B output at different grounding points. Different grounding points had no impact on type B sensors since there was no problem with noise from the beginning.
List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Instruments and chemicals used in the test</td>
<td>19</td>
</tr>
<tr>
<td>3.2</td>
<td>Pipette 5 ml accuracy test data.</td>
<td>19</td>
</tr>
<tr>
<td>3.3</td>
<td>Pipette 1 ml accuracy test data.</td>
<td>19</td>
</tr>
<tr>
<td>5.1</td>
<td>Schematics over conducted tests, where the value in the boxes</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>represents the number of times a specific test on a specific sensor</td>
<td></td>
</tr>
<tr>
<td></td>
<td>was carried out</td>
<td></td>
</tr>
<tr>
<td>6.1</td>
<td>Displaying the normalised maximum standard deviation in percentage</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>of full chamber, calculated with the help of the Matlab function</td>
<td></td>
</tr>
<tr>
<td></td>
<td>std, measured between five runs on sensor type A 1-4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>and type B 1-5 and all liquids. The results can not be compared</td>
<td></td>
</tr>
<tr>
<td></td>
<td>to each other as much as giving a value on the repeatability of the</td>
<td></td>
</tr>
<tr>
<td></td>
<td>system</td>
<td></td>
</tr>
<tr>
<td>6.2</td>
<td>The sample interval in which noise of one frequency was induced.</td>
<td>47</td>
</tr>
<tr>
<td>A.1</td>
<td>LabVIEW sensor input</td>
<td>67</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

1.1 Main goal for the project

The reason for this project comes from a request by Baxter Lund to evaluate different capacitive level sensors and determine if it is possible to implement them in a dialysis machine. To be able to evaluate different sensors, one must first learn about the dialysis machine and the capacitive sensor’s role in the system, as well as have an understanding of the physics and electronics behind the sensor. All this in order to formulate relevant tests with high reliability and good validity.

The main goal of the project is to evaluate two (by Baxter suggested) capacitive level sensors with respect to functions, stability, durability and reliability. It is desired that at the end of the thesis recommend one sensor model and, if possible, suggest further improvements.

1.2 History of the hemodialysis machine

The kidneys’ primary task is to filter out waste products from the blood and send it to the bladder. A damaged kidney lowers the filtration rate of the blood, leading to a buildup of waste products, such as urea and creatinine, in the blood system [2]. To avoid death caused by buildup of waste products, the blood could be cleaned through an artificial kidney in a procedure called hemodialysis.

The hemodialysis has a long history with many milestones and several role takers in its development. It started with the chemist Thomas Graham who studied the diffusion of liquids and the osmosis phenomenon. This lead to the discovery of the separation of crystalloid and colloid substances, more known under the name dialysis, in the mid-19th century. This would later be used in the making of the hemodialysis machine [3].

In the year of 1943 the first working hemodialysis machine was constructed, the maker was Willem Kolff also known as “the father of artificial organs”. It was constructed with 45 meters of sausage casing which was emerged into a wooden barrel filled with salt water. One end of the sausage casing was connected to an artery on the patient and the other end to a vein. While the blood was fed through the sausage casing the barrel was rotated to remove the impurities from the water. The first 15 tries to save human lives with hemodialysis failed, but in
the year of 1945, with some improvements, the first life was saved, a 67-year old woman with urea coma survived and lived for another 7 years [4].

Kolff’s artificial kidney had some problems, making it unsuitable for clinical use. The first problem was that the hemodialysis machine damaged the patients’ arteries and veins at the connection points to the extent that new arteries and veins had to be used for each new treatment. This presented difficulties connecting the machine to patients in need of several treatments. The second problem was that the excess liquid needed to be removed, which was not possible in Kolff’s machine.[4 i div. Länkar refen ska in här]

All this changed in 1946 when the first hemodialysis machine suited for clinical use saved a life. The maker was Nils Alwall, docent at Lund university and the new machine could handle the excess liquid, and later on even the problem with connection to the patient [5]. Alwall founded a company, named Gambro, with Holger Crafoord in the year 1961 and the first patent for the dialysis equipment was granted 1967. With this the mass production of artificial kidneys started [6]. Since then Gambro has continued their research and development which have led us to the hemodialysis machine that we see today.

1.3 Basic functions of a hemodialysis machine

The basic functions of a hemodialysis machine are the same today as they were in the machines from 1961. Blood from the patient flows through the extracorporeal circuit in a controlled and constant manner, with a flow around 250-300 ml/min in a standard dialysis (figure 1.1). Dialysis liquids are prepared in the machine, ensuring both the right composition of all the substitutes and the correct temperature of the dialysis liquid (figure 1.2). The temperature of the water should be around 36 to 40 °C, before mixing of the dialysis concentration. If the temperature exceeds 40 degrees the blood protein will start to take damage, hurting the patient.

![Figure 1.1: The blood path in a dialysis machine](image)

Incoming liquids are also exposed to large negative pressures. The reason for this is to discharge air from the water. The air bubbles could otherwise corrupt the flow- and conductivity measurements in the process, causing the quantity of
liquid drained from the patient to be too large or too small. Depending on both the time span of the treatment, ranging from 4 to 12 hours, and how much liquid that should be drained from the patient a certain flow rate and pressure is set. The normal flow for the dialysis liquid in a treatment lies around 500 - 1000 ml/min.

To make sure that nothing goes wrong with the dialysis, measurements of flow rate, liquid temperature and so forth are continuously collected and monitored. If there are any faults or abnormalities in the process the clams in figure 1.1 are closed, bypassing the patient, and the machine will give an alarm which notifies the operator [1].

1.4 Ethical issues using capacitive level sense

It is above all aspects such as improvement in reliability and lowered component costs that drives the development of the sensors. The improvements in reliability would lead to less need of maintenance and cost reduction resulting in a total lower cost of the machine. It will also open up possibilities for further improvements in the control of the machine.

The implementation of the sensor will not, at this moment, have any noticeable effect on the end user of the machine.

All the devices under test are RoHS compliance (Restriction of Hazardous Substances) and an implementation of the sensors should meet the demands of the Medical Devices Directive, which implies that it in the end needs to be CE-marked (Conformité Européenne) [7].
Introduction
2.1 The system and requirements on the sensor

The deaeration of dialysis fluid works by letting liquid pass through a chamber. The air bubbles will then float to the top and as more liquid passes through the chamber, the air will slowly replace the liquid and lower the liquid level in the chamber. When the liquid level is lowered below a certain point, a valve will open at the top of the chamber and evacuate the redundant air, which results in a re-increase of liquid level. A sensor placed at ~80% prevents liquid from entering the low pressure area, by notifying the system to close the valve. The sensors used today are either optical or magnetic sensors, which are digital, while adding an extra analog capacitive level sensor would act as extra security for the system. An analog level detector would offer better control and might even open up opportunities for further control concepts.

There is also a need for capacitive level sensors in the mixing chambers, where the dialysis fluids are mixed together. This means that the sensor has to be able to measure different liquids and liquids that changes concentration, without the need of recalibration.

There is a Component Functional Description (CFD) that lists all the requirements for the sensor. Some of the most important requirements are that it has to be able to detect two distinct levels (80% and 20%), and the sensor’s measurement should stay within 10 percentage point of the true liquid level. The reliability should be 99% during 40,000 hours of working time.

2.2 Capacitance

To understand the sensors and the test formulation, some basics about capacitance must first be covered.

Two conducting plates, positive and negative charged, will create a constant potential difference, $V$, between them. The potential difference causes an electric field

$$V = V_+ - V_- = -\int V \cdot dl.$$  \hfill (2.1)
Coulomb’s law
\[
E(r) = \frac{1}{4\pi\varepsilon_0} \int \frac{\sigma(r')}{r^2} \hat{r} \, da'.
\] (2.2)
states the proportion between the electric field, \( E \), and the charge-per-unit-area, \( \sigma \). Since both the charges and the potential differences are proportional to the electric field, it can be described as the capacitance \( C \equiv Q/V \).

Capacitance (measured in \([\text{Farad} = \text{Coulomb/Volt}]\)) is thus a geometrical and physical quantity that describes the proportionality between the charge, \( Q \), and the potential difference, \( V \), between two plates. The geometry is determined by parameters such as size, shape and separation between two plates.

The potential difference between two parallel plates can be described as
\[
V = \frac{Q}{A\varepsilon_0\varepsilon_r} d
\]
and (if the fringing field at the end can be omitted) the capacitance as
\[
C = \varepsilon_0\varepsilon_r \frac{A}{d}
\] (2.3)
where \( A \) is the overlapping area of the plates, \( d \) is the distance between the plates, \( \varepsilon_0 \) is the permittivity of free space and \( \varepsilon_r \) is the relative permittivity of the material between the two plates. This shows that the capacitance depends on both the geometrical and material properties \([8]\).

### 2.3 Permittivity

When a material is subject to an electric field, the molecules in the material will polarize. This polarization is proportional to the electric field and the relative permittivity, or dielectric constant, and describes how easily the material polarize when an external electric field is applied. Permittivity is a dimensionless unit and the value depends on the internal microscopic structure of the substance, and also external conditions such as temperature \([8]\).

The permittivity and temperature dependence in different materials is well documented. Water for example, has a relative permittivity of 80.100 at 20 °C, while air typically has a relative permittivity around 1.001 at the same temperature. A liquid level sensor uses this difference in permittivity between the liquid and the air to estimate the amount of liquid in the chamber \([9]\).

The relative permittivity is, as stated above, dependent on temperature. For water, the relative permittivity can be estimated using
\[
\varepsilon_r(T) = a + bT + cT^2,
\]
where \( a = 0.24921e + 03 \), \( b = -0.79069e + 00 \), \( c = 0.72997e - 03 \), at a temperature, \( T \), range between 273-372 K, in nominal atmospheric pressure \([10]\).

From the equation, one can simply see that the relative permittivity and therefore also the parallel plates capacitance will change quadratically with the temperature.
2.4 Thermal expansion and contraction

As well as changes in the temperature changes the permittivity of liquids, it also changes the volume. This phenomenon is known as thermal expansion/contraction. When a liquid is heated there is an energy increase in the atoms from the thermal energy. This will increase the oscillation amplitude of the atoms, expanding the liquid. If the volume change is small relative to the initial volume the thermal expansion/contraction can be estimated with a first degree equation

\[ \Delta V = \beta V_{\text{init}} \Delta T \]  

(2.4)

where \( \Delta V \) is the volume change, \( \beta \) the approximated thermal expansion coefficient collected from [11], \( V_{\text{init}} \) the initial volume, and \( \Delta T \) the temperature change collected from [12].

The liquids used for measurement in the thesis are water-based liquids with a greater volume change over the temperature range than is acceptable for equation 2.4. To be able to use equation 2.4, the temperature range needs to be divided into smaller spans in which the relative volume change is small. This gives the recursive equation

\[ \Delta V_{n+2} = \beta_{n+1} (V_n - \Delta V_{n+1}) \Delta T_{n+1}, \quad V_0 = V_{\text{init}}, \quad \Delta V_1 = 0, \quad n = 0, 1, 2, \ldots \]  

(2.5)

\[ \Delta V = \sum_{n=2}^{x+2} \Delta V_n \]  

(2.6)

2.5 Parallel fingers layout

This section discusses the parallel fingers layout with the help of the more standardised and known parallel plates layout. Parallel plates are when two capacitive plates have their biggest area against each other, as just before you clap your hands, while parallel fingers are laid out as in figure 2.1.

If two parallel plates were placed on either side of the chamber, while measuring the liquid level, the distance between the plates would be relatively large. According to Coulomb’s law (equation (2.2)), the intensity of the electric field is degrading with the square of the distance, \( \frac{1}{r^2} \), resulting in a sensor that would be too insensitive to level changes in the chamber.

Parallel finger (or comb finger as it is referred to in some literature) layout is composed of two plates parallel to each other with the larger area against the liquid. The excited voltage induces an electric field into the medium and makes it possible to detect the so-called fringing field (represented by the red field lines in figure 2.1). By shielding the backside of the sensor, the electric field is rejected from one side of the sensor, forcing it to go through the chamber while preventing it from detecting changes on the wrong side of the sensor.

As earlier described, a shorter distance between the plates in parallel fingers gives a stronger electric field and as a result a sensor with bigger capacitive change. The field in the center of the sensor has the shortest distance to travel
Figure 2.1: Basic parallel fingers layout. The red lines represent the path of the fringing field.

between the plates, giving it a more dominant area of the sensor. The sensor will then be more sensitive in changes along the Z-axis and lesser sensitive in the X- and Y-axis, which is a prominent attribute in a level sensor. The large sensitivity in one dimension makes it important to place the sensor in a position orthogonal to the liquid surface.

The geometry of the parallel plates is not entirely the same as parallel fingers, but the principle of the parallel plates can nonetheless be used to describe the physics behind the parallel fingers. The difference in geometry makes for some difficult calculations, why numerical methods often are used to describe the capacitance dependence on water level [13].

The capacitance between the parallel finger, the capacitance between two “legs”, serves in sensor type A (section 3.1.1) as a capacitance in a RC-circuit (figure 2.2). When the capacitance change it also changes the filter and resonance behavior of the oscillator. The oscillator used in sensor type A works under the principles of a Wien bridge oscillator.
2.6 Wien Bridge Oscillator

Sensor A uses an RC oscillator to determine the change of the sensor capacitance, which is dependant of the liquid level in the chamber. The type of oscillator that it uses is variation of a Wien Bridge Oscillator. A Wien Bridge oscillator consists of an RC network and an op-amp (operational amplifier), connected as in figure 2.2. The RC network creates a second order band pass filter, as in figure 2.3. C1 in figure 2.3 will have high reactance at low frequencies, not letting the low frequencies through, while C2 will have a low reactance for high frequencies short circuiting the signal to ground. The frequency with the greatest amplitude in figure 2.4 is the resonance frequency of the band-pass filter and can be calculated with equation

\[ F_R = \frac{1}{2\pi RC}, \text{where } R_1 = R_2 = R \text{ and } C_1 = C_2 = C. \] (2.7)

This makes the band-pass filter to selectively pass the resonant frequency when white noise is applied to the circuit. To simplify the equation, the filter capacitances are assumed equal. The resonant frequency will change in a similar way if only one capacitance changes, but lead to more complex equations.

The RC network also has a lead and lag effect on the signal, lead for low frequencies and lag for high frequencies while having zero phase shift at the resonant frequency. This means that the resonant frequency will be in phase with the inputs of the op-amp while canceling both the negative and positive feedback, creating oscillation in the circuit. To make the circuit to continually oscillate the gain resistors will have to be set to a gain of the op-amp that equals 3. The change in capacitance changes the resonant frequency of the band-pass filter, where a greater capacitance results in a reduced frequency [14].

Figure 2.2: Simplified schematics of a Wien bridge oscillator
Figure 2.3: Simplified schematics of a Wien bridge oscillator

Figure 2.4: Gainplot
3.1 Devices under test

3.1.1 Sensor type A

Sensor type A is developed in-house at Gambro/Baxter, uses a parallel finger layout and a modified Wien bridge RC-oscillator circuit to generate a frequency, measured with a frequency counter. The sensor is supplied with 24 V DC and uses a median filter with a window of 7 samples to reduce outliers. Other than the median filter there is no signal processing done in the sensor. This filter is not expected to have any significant influence on the sensors' performance in aspects such as delay and loss of data.

3.1.2 Sensor type B

Sensor type B is a capacitive sensor made by an external company. While the specification covers the implementation in the system (supply voltage, communication commands etc.), it does not mention anything about the actual technique used for the level sense. Known is that the sensor uses capacitive technology to sense a water-based liquid through the chamber wall. The sensor is supplied with 5 V DC and the current is lower than in sensor type A, resulting in an overall lower power consumption for sensor type B.

The output from the sensor is a value between 0 and 99 that represents percentage of the liquid level in the chamber, with a resolution of 1 %. There is a high possibility of filter(s) embedded in the software on the sensor-chip that filters some outliers and other naturally occurring inconsistencies.

3.2 Hardware

A test rig was built solely for the purpose of evaluating the sensors. The reason for this was to extract the functionality essential for the sensors without the complexity of a full machine.

The test rig used was built on a robust frame with a metal plate to fasten the equipment on (figure 3.1). A mount for the test chamber was fixed at the top of
the test rig. The chamber used in the tests was a 60 ml chamber of polypropylene where the sensor wall was 2.4 mm thick. Two pumps of piston sort were used to fill and drain the chamber. The piston pump model was used due to its exact water displacement for each stroke [15]. The two piston pumps were controlled by two five phase stepper motors with a step angle set to 0.72°. The rotational speed of the five phase motors were set with the help of a clock frequency, where each clock pulse made the motors rotate 0.72°. By controlling the clock frequency for each of the two motors the fill and drain rate could be set separately. Combining the knowledge of clock frequency (rotational speed) of both five phase motors and the displacement of the liquid within each stroke for the piston pumps, a fairly accurate estimation of the current water level in the chamber could be calculated in software. The pumps were controlled through 24 V drivers that set the step angle, rotation direction, rotation speed and decided if the windings in the motors should be connected or not (figure 3.2).

Communication between the drivers and the PC went through a DAQ NI-6102 from National Instruments. The DAQ was in itself linked to the drivers via an optocoupler, which created a galvanic isolation to protect the equipment. The DAQ used two clock channels to set the motor speed (one for each motor) and two digital signals to set the direction. All channels and wires from the DAQ were connected to the drivers via a circuit board to facilitate future changes. There were also two switches soldered on the circuit board that turned off the windings of the motors, making it possible to move the motors by hand (figure 3.3).

Piston pumps has a tendency to clog if there are not a continuous flow through them. To prevent clogging a gear pump with a DC motor was used in the test rig.
Figure 3.2: A simplified schematic of the rear of the test rig. The dotted figures represent the placement of the equipment on the front.

Figure 3.3: Connection paths on the circuitboard between the motor drivers and the DAQ.
The gear pump provided a continuous flow through the piston pumps (light blue liquid path in figure 3.5). The DC motor for the gear pump was supplied with an arbitrary voltage from a power box.

To keep the liquids at the right temperature (fixed or varied) through the whole test, a Julabo F25-ME water bath was used. The Julabo water bath had the ability to both heat and cool the liquid in the bath. Communication to the Julabo heater was done by RS-232 bus, which meant that an ATEN UC-232A converter for RS-232 to USB had to be used for communication with the PC. Julabo had an internal PID-controller, why only set points were needed for it to control the water temperature, freeing some computational power on the PC.

Both sensors tested in the thesis communicated over a RS-485 bus. Since there was no port for the bus on the PC provided by Baxter, a USB to RS-485 converter was used, which simulated a COM port on the computer.
3.2.1 Connection and Flowchart

The electronics in the test rig were connected as in figure 3.4 in all tests, and the flowchart for the tests that included the piston pumps are described in figure 3.5.

**Figure 3.4**: Electrical connection chart of the system when the test uses the piston pumps. The different lines from the power box represent different channels. Red = 24 V, Blue = 12 V, Green = 5/24 V, Black = Signal.

**Figure 3.5**: Flowchart of the liquid path when the test uses the piston pumps. The main source of liquid comes from the Julabo heater.
3.3 Liquids

RO-water, reverse osmosis-water, is made by pressurising water against a semipermeable membrane only allowing the $H_2O$-molecules to pass through it. This creates water that has low amounts of ions and other larger particles [16]. Because of this the conductivity of RO-water is in the region of $\mu S/cm$ and acts as a neutral liquid in the tests as well as base for the mixed fluids.

Conductive fluid, salt water, was also used in the testing of the sensors. The liquid was mixed to a conductivity around 15 mS/cm with the help of RO-water and salt. Conductive water is a good carrier for electric currents and will thus be expected to enhance disturbances through the liquid.

Citric acid ($C_6H_8O_7$) is one of the liquids used for cleaning in the hemodialysis machines. The one used in this thesis was a mix of 2 % citric acid and 98 % RO-water. During a cleaning procedure in the machine the cleaning liquid is heated to a temperature of 96°C.

3.4 Software

3.4.1 Data Acquisition

LabVIEW, Laboratory Virtual Instrument Engineering Workbench, (developed by National Instruments) were used in the thesis as the main program for data acquisition, as well as control of the motors and temperature bath.

LabVIEW is a graphical based language where the programs are built using “blocks” rather than written commands. These blocks are connected to each other with “wires” that determine the order of execution and data flow in the program. The program in itself is divided into two windows called “front panel” (figure 3.6a) and “block diagram” (figure 3.6b), where the block diagram is used for creating buttons, loops, functions etc. The front panel serves as the GUI when the program is running, showing real-time graphs, buttons and switches that can be accessed while the program is running. [17]

One of the benefits of using LabVIEW was the extensive library of mathematical functions and subroutines in combination with an immense catalogue for communication protocols for hardware drivers. These benefits shortened the time of programming needed compared to other languages, such as C or Visual Basic. The greatest tool in LabVIEW was the modularity of the program (giving it the ability to create subroutines of a program), since many of the subroutines were used in all the test programs.
(a) The LabVIEW front panel displays different controls that can be accessed while the program is running.

(b) A LabVIEW block diagram that shows how blocks and wires are used to create a program. This specific block diagram comes from Test 2.

*Figure 3.6:* LabVIEW was used for control and data acquisition. Front panel (a) serves as a GUI while the program is running. The block diagram (b) is used for creating buttons, functions etc.
3.4.2 Post Processing

Post-processing of the data collected from LabVIEW was done in Matlab. The data were then divided into different categories by test, model, sensor number, liquid on which the sensor was tested, and temperature of the liquid. The data was then normalized in length and outliers noted and removed. Data from sensor type A was collected in its original frequency while the data from sensor type B was normalized on the chip. Mean value and standard deviation were calculated using Matlab’s built-in methods. No filter was added when processing the data.
### 3.5 Summary - Used instruments and chemicals

<table>
<thead>
<tr>
<th>ID-number</th>
<th>Type</th>
<th>Brand</th>
<th>Calibration status</th>
</tr>
</thead>
<tbody>
<tr>
<td>7385</td>
<td>Powerbox, 2 channel, 280 W</td>
<td>TTI EX354RD</td>
<td>Not Calibrated</td>
</tr>
<tr>
<td>5045</td>
<td>Powerbox, 2 channel, 420 W</td>
<td>TTI CPA400IDP</td>
<td>Next Cal 02 2017</td>
</tr>
<tr>
<td>Two 24 V Motor drivers</td>
<td>VEXTA ER-4091</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Two 5 phase motor</td>
<td>VEXTA PK369AW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>04309085</td>
<td>Piston pump</td>
<td>Iwaki Hicera Pump V-15ASP06-04</td>
<td></td>
</tr>
<tr>
<td>04309086</td>
<td>Piston pump</td>
<td>Iwaki Hicera Pump V-15ASP06-04</td>
<td></td>
</tr>
<tr>
<td>24 V DC Motor</td>
<td>PREMOflo 9944 120 13821</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2/13-407/11</td>
<td>Gear pump</td>
<td>Galabro K2000/300/2</td>
<td></td>
</tr>
<tr>
<td>Heating bath</td>
<td>JULABO</td>
<td></td>
<td></td>
</tr>
<tr>
<td>150Q</td>
<td>RS485 to USB Converter</td>
<td>UC232A</td>
<td></td>
</tr>
<tr>
<td>150Q</td>
<td>RS485 to USB Converter</td>
<td>USB-RS485 WE</td>
<td></td>
</tr>
<tr>
<td>Pipette, 5 ml</td>
<td>Satorius Proline Plus 1-10 ml</td>
<td>Not Calibrated prior to test.*</td>
<td></td>
</tr>
<tr>
<td>Pipette, 1 ml</td>
<td>Labcyt 691501 4500</td>
<td>Not calibrated. Accuracy checked prior to test.*</td>
<td></td>
</tr>
<tr>
<td>3268</td>
<td>Conductivity meter</td>
<td>WTW PH/ION/Cond 750</td>
<td>Calibrated 12 2015</td>
</tr>
<tr>
<td>3144</td>
<td>Conductivity measurement cell</td>
<td>WTW TETRACON 325</td>
<td>Calibrated 12 2015</td>
</tr>
<tr>
<td>3144</td>
<td>Thermometer</td>
<td>Testo 110</td>
<td>Calibrated 02 2016</td>
</tr>
<tr>
<td>RO-water</td>
<td>Citric Acid 2 %, RO-water 98 %</td>
<td></td>
<td>15 mS/cm</td>
</tr>
</tbody>
</table>

**Table 3.1:** Instruments and chemicals used in the test

*Pipette accuracy check:
This test is needed to calibrate the pipette and validate the results. Place beaker with water on Metter Toledo scale. Set pipette at 5 ml and 1 ml respectively (this is the volume used in the test). Take water with pipette and put in beaker. Read value. The pipette accuracy test data is presented in table 3.2 and table 3.3. The accuracy is ±0.07 ml when adding 5 ml liquid and ±0.01 ml when adding 1 ml liquid in the chamber.

*Table 3.2:* Pipette 5 ml accuracy test data.  
*Table 3.3:* Pipette 1 ml accuracy test data.
4.1 Formulating tests

4.2 Formulating tests

Some things to consider when formulating the tests were the relevance, reliability and validity in the test itself as well as access to equipment. There was also a limit to how many sensors that were available for testing and the amount of tests that could be done on each one of the sensors in the time frame given for the thesis. The sensor is meant to be used in the next generation dialysis machine, which means that it was impossible to test them in an existing unit. Focus was on collecting qualitative data, acquired from the test rig, and look at trends in the data.

The requirements from the CFD (Component Functional Description) and the placement in the system stated that the sensor had to work between 20 - 80 % of full tank with a margin of error at maximum ±10 % in, at least, 3 different liquids (RO-water, Conductive fluid and Cleaning fluid). The temperature within the system during a treatment could differ between 36 - 40°C while the liquid during cleaning reaches a temperature of 96°C.

4.2.1 Relevance

According to theory, the relative permittivity could vary for different liquids, why it was relevant to test the sensor’s performance against the different liquids. In the same way as the relative permittivity changes with different liquids, it could as well change with temperature, making it necessary to test the sensors against different temperatures in the liquids. The whole measuring range, 0 - 100 %, was used in all tests to evaluate the sensor’s linearity and performance in all points. A dialysis session takes up to 4 hours why it was desired to test the performance during a long, consecutive time period.
4.2.2 Reliability

The first thing checked when considered reliability was if the sensor was consistent in itself, which was done by performing the same test on the same sensor multiple times and study how much it varied between sets. Second was to test if the model was consistent between sensors, i.e. if one sensor gave the same result as another one if they were of the same model. This meant the tests had to be formulated in such a way that they were repeatable with sufficient accuracy.

4.3 Error sources

The output from sensor type A was given in Hz with an approximate starting point at 40-42 kHz. The frequency decreased as the liquid level increased. The output from a pre-calibrated sensor type B was given in percent of full tank.

Method repeatability was checked in test 1-3 by running the tests with 4 sensors type A and 5 sensors type B, 5 times each. The tests were executed during a month and small variations in the liquids concentration may have occurred.

There were a number of error sources in the measurements:

- Pump error: the structure of the piston pumps delivered liquid only half the period. The maximum phase error from the piston pumps was ±3 ml or ±5 % (rectangular distribution [18]) of the total volume.

- Pipette: the error of the pipette was calculated by weighing tap water. The error was measured to be ±2 % of the volume for every pumping, or ±0.04 % (normal distribution) of the total volume in worst case scenario.

- Sensor resolution: the sensor resolution was measured to ±0.5 % for sensor type B while it for sensor type A was dependent on the liquid.

- Fluid concentration: unknown. The liquid concentrations may have differed since conductive and cleaning fluid had to be remixed at different occasions.

- Room temperature variation: the temperature was stable during test and this error assumed negligible.

- Steam: the relative permittivity for steam was according to theory close to same as air why this was assumed negligible.

- Air bubbles: unknown. The effect of air bubbles were dependant of where they occur in the chamber. The effect of air bubbles on the sensor wall may cause the type A sensor to change its level by one set point. Bubbles on the walls had no noticeable impact on sensor type B. Air bubbles in the tubes were a possible source of the error in the start-up part of the 4 h test (test 5).

- Flow rate: steady during tests and assumed negligible.

- Noise: the error caused by grounding can be read about in “Other findings - Noise and grounding” (section 7.4).
• Sensor drift: tested with no major significance in the result.

• Human error: the tests that were executed using the pumps were fully automated and hence assumed negligible. A human error in tests executed using pipette showed a significant variance in the data and could therefore be prevented. The human error is for this reason assumed negligible.

• Liquid on chamber walls: unknown. The amount of liquid as well as its impact on the result could not be measured.
Chapter 5

Implementation

5.1 Tests

To implement the tests, a test scheme was first created (as shown in Table 5.1) to get a good overview of all the tests. There were a total of 8 tests constructed: two tests with three different liquids and four tests realised using one liquid. The tests conducted on only one liquid looked at behavior in the sensors that were more coherent in one specific liquid, why there was no need to test in all three liquids. The availability constraint brought the reason for using four sensors of type A, and five sensors of type B. All the tests were done on a 60 ml chamber. Step by step instructions on how the tests were executed are explained in the appendix.

<table>
<thead>
<tr>
<th>Liquid</th>
<th>RO-water</th>
<th>Conductive liquid</th>
<th>Cleaning liquid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td>Test 2</td>
<td>Test 3</td>
<td>Test 1</td>
</tr>
<tr>
<td>A 1</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>A 2</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>A 3</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>A 4</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>B 1</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>B 2</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>B 3</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>B 4</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>B 5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 5.1: Schematics over conducted tests, where the value in the boxes represents the number of times a specific test on a specific sensor was carried out.

25
5.1.1 Test 1: Liquid level 0 to 60 ml

In Test 1 (figure 5.1) the chamber was filled with an inflow of 143.7 ml/min and a simultaneous outflow of 35.9 ml/min, resulting in a fill time of 33.4 s for the 60 ml chamber. When the chamber was fully filled with liquid, the pump flow switched and emptied the chamber at the same rate as it was filled. This cycle was repeated six times in one test. Test 1 was then repeated five times on each sensor before switching to the next sensor to satisfy the reliability constraint while also giving a good overview of the sensors’ behavior.

5.1.2 Test 2: Plateau - 0 to 60 ml

Test 2 (figure 5.2) was a plateau test where the chamber was filled to a certain level whereupon 200 samples, over 15 s, were taken before proceeding to the next level. Each step between levels was 10 ml (16.67 % of full tank), starting at 0 ml and ending on 60 ml. The liquid was inserted into the chamber by pipette of 2 times 5 ml. This test was done five times on each sensor where one tester did two runs and the other tester did the remaining three, which made it possible to notice an eventual human error, i.e. the test was not going to be repeatable if the results differed between repetitions conducted by different testers. The objective with the test was to survey if the sensors had stability at one level and if some levels had greater deviation than others.
5.1.3 Test 3: Differential step test

Test 3 (figure 5.3) was a differential step test where the chamber was filled at a slow pace to 10 ml (16.67 %) and emptied again. This was repeated two times, and then filled up to 20 ml (33.33 %), emptied, and so forth up to 60 ml (100 %). The reason for the double 10 ml step was to check known problems with the sensors at low levels. The inflow when filling was 71.9 ml/min while the outflow was 35.9 ml/min, and vice versa when the tank was to be emptied.

The relative slow pace and the varying pattern in the test was designed to look for drift in the sensors. Drift is when the sensor output changes over time independent of the level change. The drift would show as an increase in the lower turning point, "lifting" the curve in the plot. The linearity could also be surveilled by measuring the high turning point and comparing it to the levels in test 2 (section 5.1.2), and/or by checking if the line between a low and high point is linear.

5.1.4 Test 4: Plateau - 0 to 20

The previous tests revealed problems with the sensor at low liquid level in the chamber. A test was designed to evaluate the problem and is referred to as test 4. The chamber was filled from 0 ml to 20 ml (33.33 % of full tank) with steps of 1 ml (1.67 %). On each level a set of 200 samples was taken. This test was only done on the liquid were the problem with the lower level was most dominant, which was salt water with a conductivity around 15 mS/cm.

5.1.5 Test 5: Four hours closed circulation

Test 5 was constructed with regards to how a real four hour dialysis treatment works. A normal treatment lasts around four hours and the nominal level in the chamber lies around 80 %. The flow through the chamber varies from treatment to treatment, depending on the amount of liquid that should be drained from the patient, but should be in the regions of 500 to 1000 ml/min. Because of the high flow through the chamber the piston pumps could not be used. Even though they are exact and strong they also have the downside that they are slow, only reaching roughly 400 ml/min at max speed. Instead the gear pump, used for water circulation through the piston pumps, was used to create a flow just under 1000 ml/min. The gear pump was connected to both the drain and fill channel of the chamber, closing the circulation in the system to ensure that the volume stayed the same throughout the whole test. The results from this test would show if any drift is to be expected from the sensor when running a full treatment. The way the test was performed induced a large amount of air bubbles in the system. The results would hence reveal if the sensors has any trouble collecting data in such environment.
5.1.6 Test 6: Incremented noise frequency

As explained in section 5.2 there were known EMC problems with the type A sensor. To get an overview of how the sensors performed at different noise levels a test with induced and varying noise was created. The result of test 6 was used to find the most troublesome frequencies for the sensors, which then were used in test 7. Test 6 was implemented by fixating the water level for all sensors and runs, so the amount of water wouldn’t affect the noise coupling between runs. A function generator was connected to the test rig, the starting frequency was selected and the amplitude set to 5 Vpp (voltage peak to peak). The sensor collected 200 samples before the frequency was increased and the procedure redone for the next frequency. The frequencies tested were 600 kHz, 700 kHz, 800 kHz, 900 kHz, 1 MHz, 1.5 MHz, 2 MHz, 2.5 MHz and 3 MHz.

5.1.7 Test 7: Induced noise 0 to 60

Test 7 was created to investigate the sensors’ noise performance over the whole measurement range. This was done by selecting two frequencies from the result of test 6 and induce them in turns while performing test 1 (section 5.1.1). The frequencies selected were 700 kHz and 3 MHz, with 5 Vpp. Test 7 was only conducted on two sensors of each type, for the reason being that the noise behavior was similar for all sensors in test 6, giving that performing test 7 on all sensors would not give any new information. The test was executed with two runs on each sensors and each different noise frequency.

5.1.8 Test 8: Temperature slope

There is a known correlation between the temperature and the dielectric constant in the material between the conductive plates (section 2.3). To see to which extent this may affect the measurements with a capacitive sensor, test 8 was created. The liquid was heated up to around 64°C and inserted into the chamber. Measurements were then taken continuously from the sensor as the temperature of the liquid slowly approached room temperature by thermal exchange with the room. The temperature of the liquid was measured every 10 minutes with a Testo 110 thermometer for almost 2 hours, until it reached 26°C.
5.2 Encountered Problems

The first tests realised on the sensors type A clearly showed that noise was a major problem. Even though the documentation of the type A showed that there were precautions made when constructing the sensor to minimize noise. Ferrites placed at strategic points, e.g. at drivers and motors, and also replacing the drivers gave no identification of the origin of the problem. A last try with grounding the test rig was made, which resulted in a stable signal out from the sensor. There were many coupling paths from the motors and drivers to the test rig. This made the electric potential of the rig shift, which then was coupled to the sensor. The connection to protective earth made the electrical potential stable for the test rig, thus no noise was induced to the sensor.

There were some drawbacks using piston pumps in the tests. One of the drawbacks were that the pumps only pumped liquid 50% of each motor rotation. This came from the piston pump first filling up the piston with liquid the first half of the rotation, only to pump out the liquid in the second half of the rotation. This created a problem in test 2 (subsection 5.1.2) when the start/stop position wasn’t constant, causing the water level to vary at each level, making the runs incomparable to each other. The solution was instead to use a pipette. To overcome the level of uncertainty caused by inexperienced human, the test repetitions were split between two testers, where each tester conducted an equal amount of repetitions on the same test.

Halfway through the testing there was a discussion regarding the chamber. From this it was concluded that the chamber wall that holds the sensor in place, was too high, resulting in the type A sensor not reaching the bottom of the chamber. The chamber was then modified and the upper wall removed. Test 4 (subsection 5.1.4) was constructed to see the difference in the lower levels on the modified chamber.

The original approach of test 8 (subsection 5.1.8) was to heat water in the water bath and circulate it through the chamber. The thermal exchange with the room was greatly prominent in the tubes, resulting in a difference in temperature between the heater and the chamber. In absence of a digital thermometer that could communicate with the PC and log the temperature continuously, a fully automatic test using the pumps were excluded. Instead a chamber was filled with hot liquid (salt water) to an arbitrary level and let cool down by thermal exchange between the liquid and the room to 26°C. The temperature was logged manually at equidistant time periods.
The first part of this chapter consists of three main topics: repeatability; consistency; and if the sensors are predictable in different fluids. That gives a good overview of the sensors. Followed are results from tests (test 5 through 8) that concentrate on more specific areas. Section 6.1 will investigate if the sensors changes their output when the liquid level in the chamber changes. In section 6.2 the repeatability of the system are studied, to see if a sensor gives the same output if the test is repeated. Section 6.3 analyse the sensors’ reaction to different liquids. The remaining sections, 6.4-6.7, discuss the results of test 5-8, found in section 5.1.

6.1 Sensors’ output versus liquid level

Both sensor models change the output when changing the liquid level in the chamber. The type A sensors gives one unique frequency that is negative proportional to the liquid level in the chamber (figure 6.1), while the type B sensors gives the liquid level as a percentage of full tank. The error bars in the plot are one standard deviation apart and show that the liquid level can be deterministically determined at certain levels.

![Figure 6.1: Shows the type A-sensors’ negative proportional output (blue line) against the liquid level (red dashed line) in the chamber. The scale is 30 Hz/ml.](image)
The output of the type B sensor is a percentage of full chamber, unique for every level (figure 6.2). There are exceptions to the unique output of type B, where two of them have spikes (6.3), leading to the same output for different levels. The spikes are said to be a mathematical interpretation problem and solved in the latest software update.

The error bars in the plots in figure 6.1 and 6.2 show that it exists distinct intervals for every unique liquid level. Both sensors are therefore able to unambiguously determine the liquid level in the chamber.

**Figure 6.2:** Shows the type B sensors’ calibrated output (blue line) against the liquid level (red dashed line) in the chamber.

**Figure 6.3:** Type B sensor 3 and 4 have spikes that cause non-unique output for some liquid levels.
The uncertainty at low liquid levels opened up for test 4 (section 5.1.4) to check if it was possible to measure the lower levels distinctively. The results are shown in figure 6.4 to 6.5. The linearity is good after 3 ml for both sensor type A and type B, with the exception of sensor type B3 and B4 in figure 6.5. This suggests that the problem with neither of the sensors covering the whole measurement range does not come from the sensors’ physics, but from the chamber’s plastic not being hydrophobic enough to handle quick level changes at lower liquid levels. If a more hydrophobic plastic were to be used, the surface tension would be able to pull down more of the liquid from the chamber walls, resulting in better measurements in the lower part of the chamber.

Figure 6.4: Output from sensor type A at liquid levels ranging from 0-20 ml. The variation in start frequency comes the physical properties of the sensors, giving them different capacitance in the beginning.
Figure 6.5: Type B sensor output at liquid levels ranging from 0-20 ml. The spike in sensor 5 at 18 ml is an irregularity that could not be derived.
6.2 Method repeatability

The results in this section display how much the results vary when performing several runs of the same test with the same sensor.

Method repeatability was checked by running the test procedure with 4 sensors type A and 5 sensors type B, 5 times each between the February, 25 and the March, 30. The liquids were changed a few times between the tests and small variations in concentration may have occurred. Test 1 and test 3 were done by one person, and test 2 were done by 2 persons (since it required human interaction).

The mean value of 5 runs are plotted along with the standard deviation for the different liquids and can be seen in figure 6.6 to 6.12. The output has no normalization or added filters. The other liquids plotted had similar characteristics and will not be displayed in this report. The error bars are located one standard deviation up and one down from the mean curve. The normalised maximum standard deviation for each model is shown in table 6.1.

<table>
<thead>
<tr>
<th></th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type A</td>
<td>17</td>
<td>8.55</td>
<td>12</td>
</tr>
<tr>
<td>Type B</td>
<td>8.8</td>
<td>8.5</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 6.1: Displaying the normalised maximum standard deviation in percentage of full chamber, calculated with the help of the Matlab function std, measured between five runs on sensor type A 1-4 and type B 1-5 and all liquids. The results can not be compared to each other as much as giving a value on the repeatability of the system.

6.2.1 Repeatability for sensor type A

The repeatability of the measurements is approximately 90 % for test 1 (figure 6.6), 93-94 % for test 2 (figure 6.7) and 92-95 % for test 3 (figure 6.8). In some instances the deviation exceeds 12 % . When testing with the conductive liquid it tends to give bigger variations at low liquid levels (high frequency). Test 3 has larger variations in the beginning than at the end of the test. This corresponds well to the result in the previous section, with the high uncertainty at low liquid levels. Unlike test 1, test 3 measures all the way down to empty chamber, which can be derived as a direct cause of the slow pace, allowing the liquids to be completely drained from the walls.

The measured standard deviation was higher than expected from the error sources. One of the reasons for this could be the effect of liquid on the walls, which was stated as unknown in the error sources (section 4.3). The standard deviation in test 2 confirms this theory since there is no water on the chamber walls in this test.
**Figure 6.6:** Different type A sensors have different working frequencies. The deviation is around 10 % when performing test 1, where 1 ml corresponds to 38 Hz.

**Figure 6.7:** Shows the linearity for sensor type A. The deviation in test 2 is around 6-7 %.
Figure 6.8: Sensor type A repeatability and drift test. No drift is noted, it returns the same starting point throughout the test, the standard deviation is about 5-8% in test 3, and 1 ml corresponds to 33.3 Hz.
6.2.2 Repeatability for sensor type B

The repeatability of the measurements is approximately 93-94 % for test 1 (figure 6.9), 98-99 % for test 2 (figure 6.10) and 96-97 % for test 3 (figure 6.12). The spikes shown in figure 6.3 are displayed in 6.11 as non-linearity. The standard deviation is still low (approximately 6-7 %), but type B sensor 3 and 4 will still be excluded from test 5, 6, 7, and 8, because of the noted inconsistencies (spikes) in the sensor.

Test 3 for sensor type B shows the same characteristics as test 3 for sensor type A, with correct measurements in the low liquid levels. This further confirms that the plastic in the chamber are not hydrophobic enough to be able to handle the fast level changes in test 1.

![Figure 6.9: Repeatability test for sensor type B. All sensors begin at 0 % and have a standard deviation of about 8 % in test 1.](image-url)
**Figure 6.10:** Shows the linearity for sensor type B. The standard deviation is about 8% in test 2.

**Figure 6.11:** Shows a type B sensor with spikes that cause non-linear behavior in the lower levels of test 2.
Figure 6.12: Sensor type B repeatability and drift test. No drift can be seen and the standard deviation is about 5-8 %.
6.3 Measurements in different liquids

The results in this section will determine if (and how) the sensor output changes between different liquids. A perfect sensor does not discriminate between the liquids and does not require re-calibration when the liquid is changed.

6.3.1 Sensor type A with different liquids

As can be seen in figure 6.13, the type A sensor has a much wider frequency range for conductive and cleaning liquid than it has for RO-water. This is not shown as much in figure 6.14, but the trend is still there. The linearity is good for all liquids, but the different range may result in the need for the type A sensors’ high point to be recalibrated every time the liquid is changed during a treatment.

Figure 6.13: Behavior of sensor type A in test 1 for different liquids. The sensors begin at the same frequency in all three liquids. There is a great difference in frequency between the high and low point in cleaning and conductive fluid compared to RO-water. The scale is 16.7 Hz/ml for RO-water and 38.3 Hz/ml for conductive and cleaning liquid.
4.16
4.18
4.2
4.22
4.24
4.26
4.28
4.3
4.32
4.34

Type A/Sensor1/Test2/22 °C

Figure 6.14: Linearity for sensor type A in test 2 for different liquids. The increase in deviation in filled chamber can be derived from the error when using a pipette.

6.3.2 Sensor type B with different liquids

The type B sensor does not have the same problem with different ranges as type A, but the problem with not measuring the lower part of the chamber becomes more prominent in cleaning and, especially, conductive liquid, as can be seen in figure 6.15. The type B sensors gives corrupt measurements below 23 %, for conductive liquid, and have non-linearities, that have a large deviation between runs, up to approximately 30 %. The linearity (seen in figure 6.16) is good for all liquids, with low deviation.
Figure 6.15: Behavior of type B sensor in test 1 for different liquids. Starts at the same point for all liquids but has problem returning to 0% for all conductive and cleaning liquid.

Figure 6.16: Linearity of type B sensors in test 2 for different liquids. The increase in deviation with increased liquid level can be derived from the error of using a pipette.
6.4 Test 5: Four hours closed circulation

It will in this section be presented how the sensors behaves during a time period corresponding to a full treatment in terms of drift and other unexpected behavior.

6.4.1 Test 5: Type A

Sensor 2 for type A has a settling time in figure 6.17 which occurs in a short time frame and for a reason that cannot be derived by looking at temperature and other environmental effects. It may be caused by a large amount of air bubbles settling in the moment the motor start. The settling time is a problem that will be overlooked in the rest of this section. Figure 6.17 shows that the type A had a consistent inclination between the different sensors. It can also be seen in figure 6.17 that the sensor type A starts to oscillate between two set points before each step to an increased and more stable frequency. During the testing the frequency change were approximately 140 Hz for the sensors, corresponding to around 5.6 % for conductive liquid.

Since the drift for the type A sensors seems to be consistent an implementation of a compensation for this could be done in its software.

When the sensor drifts between two set points, a small variation in the amount of air bubbles can be enough to make the sensor oscillate between the two frequencies. The amount of air bubbles on the wall closest to the sensor changes slightly all the time, but never sufficient enough to force a sensor to change set point other than when it is already in between two set points. The oscillation
could cause a problem for the derivative part of a PID controller if the sensor output is to be used directly as an input for the PID. The noise caused by the air bubbles is of unknown amplitude, making it hard to know if it could be fixed by changing the resolution of the sensor, or if that would make the sensor shift multiple set points instead. Another way is to implement a low-pass filter, which would remove the oscillation, whilst slow the system down as well as creating a possible stationary error. Different approaches to a solution have to be considered, depending on the application and surrounding system.

6.4.2 Test 5: Type B

Sensor 1 for type B seems to have a short settling time in figure 6.18, this one as well is caused by air in the system. This problem will be overlooked for the same reason as in type A. In figure 6.18, the two big spikes in sensor one are most likely connected to the air bubbles induced into the chamber. Because of this, these spikes will be ignored from here on. It could also appear to only be four sensors in the plot but sensor 3 is constant at 81 % throughout the whole test. Figure 6.18 also shows that type B sensors had a more random behavior in between sensors than the type A sensors had. All sensors, except sensor 5, showed no drift or a small drift in the sensor. Sensor 5 showed a behavior which represents a drifting behavior. The largest change in sensor 5 was from 80 % to 76 % during the test.

Since the type B is not consistent between the sensors, it gets both higher and lower level inconsistently throughout the test, a software compensation will be hard to implement. The largest change for the type B is 4 percentage point (excluding the spikes) and there are two sensors that have a constant value throughout the test. This shows that the type B, even with the randomness between the sensors, has a steady level over all, with only small variations within the sensors themselves.
Figure 6.18: Output from type B sensors at a constant liquid level and circulation during four hours. The changes are small but unpredictable. The different start points could originate from many sources, such as a sensor not being as tight fastened to the chamber as the other or variations in angle to the chamber.
6.5 Test 6: Incremented noise frequency

This test was implemented to get an overview of how the sensors behaved with different noise induced into the test rig. The induced noise starts at 600 kHz, since a quick frequency sweep showed no problems under 600 kHz. An exception was the 80 kHz due to the clock frequency set by the oscillator crystal. Frequencies over 3 MHz will make both models switch their output with the induced frequency, why there are no induced frequencies over 3 MHz. The plots (figure 6.19 and figure 6.20) displays from the averaging of three runs. The samples covering each frequency are clarified in table 6.2 below.

<table>
<thead>
<tr>
<th>Freq [kHz]</th>
<th>600</th>
<th>700</th>
<th>800</th>
<th>900</th>
<th>1000</th>
<th>1500</th>
<th>2000</th>
<th>2500</th>
<th>3000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample</td>
<td>1-200</td>
<td>201-400</td>
<td>401-600</td>
<td>601-800</td>
<td>801-1000</td>
<td>1001-1200</td>
<td>1201-1400</td>
<td>1401-1600</td>
<td>1601-1800</td>
</tr>
</tbody>
</table>

**Table 6.2:** The sample interval in which noise of one frequency was induced.

6.5.1 Test 6: Type A

The type A sensor show the same noise intensity on each frequency step, which is the same that been seen in previous tests with no induced noise. The noise level is higher on the 700 kHz step for type A sensors 2, 3 and 4. There is also a small drop at 700 kHz for type A sensor 2 and 3. It is also clear in figure 6.19 that all type A sensors frequency start dropping at 1.5 MHz and continuing to do so. This drop in frequency corresponds in the sensor believing that the level in the chamber increase. The variance on each step seems to otherwise be same over all the steps. Other than this the sensors move in the same pattern for all the type A sensors. The 700 kHz frequency is one of the frequencies picked from test 6 to be used in test 7. The reasons for this are the higher noise level and higher variance at this frequency, as well as the small drop in frequency that was noted. For the second frequency the 3 MHz was chosen, since the 3 MHz frequency had a large drop in sensor output frequency compared to the 700 kHz. It is also of interest to see if the substantial difference in frequency by itself has any other effects on the sensors.
Figure 6.19: Type A sensors output at constant liquid level when inducing noise, incremented in steps. Induced frequency is described in table 6.2. A small drop in frequency and increase in noise intensity at induced 700 kHz. Large drops, down 51% of the original chamber level, occur after 1.5 MHz. The change in induced frequency is hence affecting the output from the sensor (and through this the interpreted liquid level). The scale is 38.3 Hz/ml.
6.5.2 Test 6: Type B

Figure 6.20 shows that the type B sensor is stable for most frequencies and only has a small percent change at the higher frequencies in the test. The variance of sensor 1 comes from one of the runs starting at 73 % and the two other runs at 72 %, which gives a misleading picture of the variance since the sensor is stable in each run by itself. The 3 MHz frequency is used in test 7 since it gives both an offset and introduces noise into the type B sensors. Induced noise at 700 kHz is also the chosen frequency to compare the results between sensor type A and type B in test 7. There is some noise at 1.5 MHz step on sensor 1 and 3.

![Figure 6.20: Sensor type B output at constant liquid level when inducing noise, incremented in steps. Induced frequency is described in table 6.2. Level output and increased noise is seen with induced 3,000 kHz.](image)

6.5.3 Test 6: Comparison

The changes between steps are much smaller in sensor type B than in type A. The noise level is, for type A, consistently high through the whole frequency spectra, while it for type B only starts to show at higher frequencies. Sensors type A are ergo more sensitive to noise than type B and are therefore in need of some sort of harmonic noise cancellation filter.
6.6 Test 7: Induced noise 0 to 60

From the results in test 6 two frequencies were chosen for test 7 (700 kHz and 3 MHz). The reason for test 7 is to determine if the amount of liquid influenced the results seen in test 6. This will show if there is a combination of frequency and liquid level that is especially bad, if the frequency only creates an offset on the sensor or if the noise creates an unexpected behavior.

The original chamber broke during test 5 (see section 5.1.5) and was replaced by one with the liquid input channel at the top (instead of the bottom). This induced noise when the stream of liquid reached too close to the sensor wall on the way down. All measurements below 40 % are therefore corrupt and should not be taken into consideration.

6.6.1 Test 7: Type A

In figure 6.21 it can be seen that the output from each sensor always is higher for the 700 kHz frequency compared to the 3 MHz, which matches the results from test 6. The change in frequency range is prominent between the two frequencies (2600 Hz for the 700 kHz noise against 4100 Hz for the 3 MHz noise).

There was a slightly higher noise level noted at 700 kHz in test 6. This is not as conspicuous in test 7, where both sensors have a consistently low noise level for all liquid levels. The 3 MHz frequency increases the noise in the output as the liquid level rises. This corresponds well to the result seen earlier in test 1.

The main reason for the enhanced noise is probably due to the increased liquid area closest to the sensors, increasing the coupling path to the sensor. This will have an even greater effect if the liquid used is a conductive liquid due to the coupling paths noise enhancement. The large change of frequency range between full and empty chamber could be a problem if the noise spectra in a machine changes greatly during a treatment.

6.6.2 Test 7: Type B

The effect of the new chamber is considerably prominent in the results for type B (figure 6.22). As seen in figure 6.22 the output from each sensor is consistent for both of the noise frequencies. The large deviation (seen as error bars in figure 6.22) indicates that the noise level is higher for the 700 kHz noise than the 3 MHz noise.

The type B sensors seem to handle disturbances in a good way without any large deviations. It also has the advantage of not changing its output dependent on the induced frequency, as the type A does. The only change that could be noted was that the 700 kHz had a higher noise level which could not be seen in test 6.
Figure 6.21: Sensor type A output in test 1 with induced noise at 700 kHz and 3,000 kHz. Note that the resolution is increased at 3,000 kHz noise, changing the scale from 40 Hz/ml (for 700 Hz noise) to 70 Hz/ml (3 MHz noise).

Figure 6.22: Sensor type B output in test 1 with induced noise at 700 kHz and 3 MHz. The high noise level below 20% comes from the use of a new chamber and not the induced noise.
6.7 Test 8: Temperature

Test 8 was designed to show an indication on the sensors’ liquid temperature dependence. The temperature was measured manually with a digital thermometer whilst the sensor output was collected continuously through LabVIEW.

6.7.1 Test 8: Type A

Figure 6.23 indicates that type A sensors has liquid temperature dependence. The type A sensor, when reaching the starting value around 40600 Hz, follows the temperature curve. The frequency decrease is higher in the start of the test, where the temperature degrades faster, than in the end of the test. The reason for the fast inclination at the start is unknown.

Dependence in temperature is in line with theory that states the relative permittivity ($\epsilon_r$) is dependent on temperature [10] and the relation between the capacitance and $\epsilon_r$ in parallel plates. Decrease in temperature results in a greater $\epsilon_r$, leading to a greater capacitance which, as stated in section 2.6, gives a lowered frequency out.

**Figure 6.23:** Shows how type A sensors provide an output of greater liquid level in the chamber when the liquid drops in temperature. The total change is about 6.3 % with a scale of 38.3 Hz/ml.
6.7.2 Test 8: Type B

Figure 6.24 shows that type B changes its output and that the output is dependent of the temperature, though compared to the type A sensors it decreases with 2% instead of increases in level output. The change is faster in the beginning than in the end, following the quick temperature decrease in the beginning of the test. It is difficult to pinpoint where the change comes from since the method for the type B sensor is unknown. One theory is that the change comes from the thermal compression of the liquid that follows a lowering of temperature. A decrease in temperature by 38°C corresponds to a thermal compression of 0.84 ml or 1.4%.

Figure 6.24: Shows how type B gives an output of lesser liquid level in the chamber when the liquid drops in temperature.
7.1 96°C cleaning process

Some problems were encountered with type B while running test 1 with cleaning liquid at 96°C. Figure 7.1 shows that the low value drifts away, approaching 60%. A hypothesis is that the circuit, which is rated for 70°C ambient temperature, gets heated to almost 96°C since it is in close range of the hot liquid. This may create problems for the microprocessor or other IC’s (integrated circuits). The type B sensor went back to normal behavior after it had cooled down and was cooled down between runs.

![Figure 7.1](image)

**Figure 7.1:** The type B sensor shows some problem measuring cleaning liquid at 96°C. The sensor was cooled down between the runs.
7.2 Broken chamber

7.2.1 Problem

The sensor does not receive any data under 70 % when performing tests with saltwater.

7.2.2 Isolating the problem

It occurred after 2 weeks of, almost constant, circulating a salt- and RO-water mix (conductive fluid) at 70-80 % level in the chamber. The liquid was never changed.

The sensor used in the original test was replaced with a new one, but without any change. When the chamber was replaced with a different one, the measurements went back to normal.

A thorough cleaning of the chambers outside at the sensor side with alcohol did not improve the result. A longer flush with RO-water through the chamber made the results go back to normal and perform as normal with RO-water. When the saltwater was introduced to the system again, the system worked for one filling before it went back to not register under 70 %.

The chamber then had a few days of dry rest, and when the same tests were performed again, the level under which the sensor gave no measurements had been lowered to about 40 %. The problem could however be recreated by filling the chamber to 70 % with saltwater and letting the liquid circulate in the chamber for about 40 h.

The resistance inside the chamber where there had been salt water was in the magnitude of $\sim 0.5 \, \text{M} \Omega/\text{cm}$, and infinite at the the top, both inside and outside. It became harder to get any measurements after a few times, suggesting it was a thin film of salt that was scratched off.

7.2.3 Plots

Figure 7.2 - 7.3 shows three different runs, using saltwater with a conductivity of 15 mS/cm. The yellow plot is a normal run on the chamber long before it broke. The blue plot is on the faulty chamber which had been resting for a couple of days, and the red plot is measurements on the chamber after recreating the problem. The issue with the sensor type B not reaching less than 20 % has been seen in different liquids and derived to be a problem with the sensor.
Figure 7.2: The output frequency of the type A sensor, where a lower frequency is the result of a higher conductivity.

Figure 7.3: The output frequency of the type B sensor, where a lower frequency is the result of a higher conductivity.
7.2.4 Discussion

The thoughts are that the circulating salt water creates a biofilm on the chamber wall that can hold saltwater when the chamber is empty. Salt has a higher conductivity than air, and the film created in the plastic closest to the sensor leads the electric field from the sensor too well, making it believe the level is higher than it really is. The much lower frequency of the type A sensor (figure 7.2) confirms this as the much lower frequency output is a direct result of an increase in conductivity.

The problem was recreated with a continuously flow of salt water for two weeks. A capacitive sensor is more sensitive to changes in the environment, why the suggested next move is to research if this could happen during a normal usage of the chamber. The problem could be resolved with a cleaning with CleanCart C (citric acid anhydrate powder) and hot water, which resulted in the chamber working as normal again.
7.3 BJT vs MosFET Transistor in sensor type A

In an attempt to lower the noise level in the type A sensors, all BJTs (Bipolar Junction Transistor) were replaced with MosFETs (Metal oxide semiconductor Field Effect Transistor). The transistors that were switched corresponds to the amplifiers in section 2.6. The reason being that the BJT’s BASE EMITTER-connection has diode properties that let through some noise and demodulates the signal. This connection does not exist in the MosFET.

The result (figure 7.4) shows a clear offset, 1270 Hz, between the MosFET version and the BJT. The frequency range was lowered from 1920 Hz to 990 Hz. BJT shows more noise than the MosFET, which has almost no noise at all. The offset has its origin in the transistor’s difference in inner capacitance. A MosFET transistor increases the total capacitance in the circuit which lowers the starting frequency of the RC-oscillator. The increase in capacitance is also the reason for the lowered resolution since the resolution is proportional to the ratio between the sensor capacitance and the capacitances in the RC-circuit. A greater capacitance in the transistor (and thereby the circuit) will therefore result in a lesser impact of the change in capacitance from the sensor capacitance. Even though the noise was reduced after the modification, it did not make up for the drop in resolution and the modification was restored.

![Figure 7.4](image-url)

*Figure 7.4:* Shows how the type A sensor reacts to a change of BJT to MosFET transistors. MosFET gives a lower starting frequency due to its higher capacitance while also lowering the resolution of the type A.
7.4 Noise and grounding techniques

There were many possible coupling paths from both the DC motor and the five-phase motors to the test rig. This resulted in the test rig having a floating potential that varies with the motors, creating noise in the sensors. There was also a coupling path between the liquid in the chamber and the sensors, i.e. noise that is induced into the liquid will also transfer over to the sensors when a conductive liquid is used. Type B sensors did not show any direct problems with noise (black line in figure 7.6) in the same way as type A did (yellow line in figure 7.5). The ways to solve the noise problem were therefore tested on sensor type A. Grounding points were implemented in both the test rig, by connecting the sensor ground to the test rig, and the liquid path, by connecting the liquid to the safety ground. Tests were then conducted with each of the points on their own and together.

In figure 7.5 it is shown that grounding of the test rig (red line) reduces the noise when the chamber is empty, and that the noise then is increased when the chamber fills up. Grounding the liquid path (green line) reduces the noise in full chamber but is indifferent when the chamber is empty. By combining the two, all noise is reduced (black line). Only grounding of the test rig were made in the tests based on the fact that it is not possible to ground the liquid in that part of the system in a real machine. Grounding the liquid would then make the tests misleading.

Figure 7.5: Sensor type A output at different grounding points. Best results comes from grounding both the test rig and the water. Conductive liquid was used since this introduced the largest amount of noise in the sensor.
Other findings

Figure 7.6: Sensor type B output at different grounding points. Different grounding points had no impact on type B sensors since there was no problem with noise from the beginning.
Other findings
8.1 Recommendation

The recommendation for Baxter is to move forward with sensor type B. The sensor is more sophisticated than type A in the sense that most of the problems it has can be fixed with software. A downside is however that the technique used for measuring is unknown, making it improbable to theoretically foresee any problems that may occur in the future.

The type B sensors also has, as seen in section 7.1, problems measuring liquids at high temperatures. This is not a critical problem that could be dangerous in treatments, but could cause an inconvenience when cleaning the machine.

The chamber used should be one with inflow at the bottom of the chamber, not at the top, since it otherwise introduces unwanted noise. The material of the chamber, PP-plastic, will work but can be a problem if there would be a need to have fast changing levels in the chamber. The reason being that it is not hydrophobic enough, creating water drops on the sensor wall. The "broken chamber problem" should not be a problem since the liquid in the machine is switched and the machine is cleaned between each treatment. The tests that were the reason of the broken chamber were done with the same salt water in a sunny room for 2 weeks with no cleaning, which does not correspond to anything that is possible in the machine. It still shows just how sensitive a capacitive sensor is to environmental changes and the importance of always having a clean chamber.

8.2 Why not type A?

Sensor type A does not measure the liquid level directly. Instead it estimates the level by measuring the relative permittivity. This is a reckless way to do it since the relative permittivity depends on other environmental variables than the actual liquid level. The temperature shown in test 5.1.8 is such a case. A higher temperature decreases the dielectric constant of water, fooling the sensor to believe the volume has decreased, while in reality the thermal expansion rose the level.

Type A sensors have some difference in the working range for different sensors. The characteristics are however the same, why a normalization of the results
shows only small differences. The different frequency ranges for type A sensors in different liquids is a greater problem and could lead to the fact that there is a need for recalibration of the high set point to be able to handle both different liquids and changes in the liquids as in the mixing chambers.

The way type A sensors measure the liquid level is, in a way, primitive and any improvements that can be made are mostly physical layouts and hardware. The sensor is robust when it comes to high temperature changes, but changes in dielectric constants when the temperature changes are misleading to the actual liquid level. Most of the disturbances are within the range of ±10 %. It is uncertain if the disturbances could be kept under 10 % for all possible configurations, especially at higher liquid levels.

8.3 FDC1004

It could be of interest to study another sensor setup. The one in mind is a three plate capacitance sensor that makes use of the FDC1004 CDC (Capacitance to Digital Converter) from Texas Instruments. The basic principle of this can be seen in [19]. The main advantage of this is that it will not need any calibration, either for different liquids or temperatures, since it uses two of the plates to calculate the $\epsilon_r$ in both the air and liquid while the third is used to sense the level in the chamber.

8.4 Future tests and remarks

The next steps in testing would be to study how the sensors manage in changes of both temperature and humidity during a longer period of time. This could be done by placing the sensor and the chamber in a climate chamber and doing continuous runs on the sensor. One concept to test would be to see what happens when the water in the air condensates on the backside of the sensor and on the sensor wall inside the chamber, since the sensors has proven to be sensitive to drops.

There is also a need to test how the sensor would manage a lifetime test in the real system. One of the reasons being that it has not been studied how durable the sensor is to temperature changes in both the liquid and the ambient temperature. It has also been noted that the chamber becomes immeasurable after 2 weeks of continuous salt water circulation, why there is a need to make sure this does not happen during a normal lifetime of the sensor.
References


Step by step instruction

A.1 When the test uses motor pumps

1. Make sure the tubes are connected as in figure 3.5.
2. Fill the JULABO heater with liquid. If there has been a change in liquid from previous test, the tubes need to be flushed to make sure there is no old liquid remaining.
3. Set JULABO to remote configuration under option/config/remote. An ’R’ will then be lit on the display.
4. Turn on the powerboxes and set the supply voltage to 24/5 V (depending on sensor), 24 V to the motor pumps, and ~17 V to the gear pump.
5. Check the sensor’s pins against the RS485 to USB adapter.
6. Open up the LabVIEW Main VI for the test that should be run.
7. Set all the communications settings according to the table A.1.
8. Enter the wanted temperature in the temperature slot.
9. Press the run-button.
10. The test will now run until it’s done. When it’s finished, a dialog window will ask where the data file should be saved. Wait to save until the chamber is empty.

<table>
<thead>
<tr>
<th>Function</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baud rate</td>
<td>230400</td>
</tr>
<tr>
<td>Data bits</td>
<td>8</td>
</tr>
<tr>
<td>Parity</td>
<td>None</td>
</tr>
<tr>
<td>Stop bits</td>
<td>1</td>
</tr>
<tr>
<td>Flow control</td>
<td>None</td>
</tr>
<tr>
<td>Com sensor</td>
<td>0 = Measure</td>
</tr>
<tr>
<td></td>
<td>1 = Low setpoint</td>
</tr>
<tr>
<td></td>
<td>2 = High setpoint</td>
</tr>
<tr>
<td></td>
<td>3 = Calibrate</td>
</tr>
<tr>
<td>VISA resource name</td>
<td>Check 'Device Manager’</td>
</tr>
</tbody>
</table>

Table A.1: LabVIEW sensor input
A.2 When the test requires a pipette

1. Make sure the tubes are connected as in figure 3.5.
2. Fill the JULABO heater with liquid. If there has been a change in liquid from previous test, the tubes need to be flushed to make sure there is no old liquid remaining.
3. Set JULABO to remote configuration under option/config/remote. An ‘R’ will then be lit on the display.
4. Turn on the powerboxes and set the supply voltage to 24/5 V (depending on sensor), 24 V to the motor pumps, and ~17 V to the gear pump.
5. Check the sensor’s pins against the RS485 to USB adapter.
6. Open up the LabVIEW Main VI for the test.
7. Set all the communications settings according to the table A.1.
8. Enter the wanted temperature in the temperature slot.
9. Press the run-button.
10. The program will ask if there should be done one more test. If one more test is desired, wait to click and continue to the next step. If not; skip to step 14.
11. Fill the pipette and pour it in the chamber from the top. This should be done two times with the 5ml pipette for 10 ml step, and one time with the 1 ml pipette.
12. In the question box “One more test?” in LabVIEW: press “YES”.
13. Wait for the program to collect measurements and go back to step 10.
15. The program will now ask where the data file should be saved. Wait to save until the chamber is empty.