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TECHNOLOGY, COMMUNICATION AND TRANSPORT

PERFORMANCE EVALUATION OF AN ENVIRONMENTAL TEST CHAMBER

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THESIS
Abstract

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Abstract

The aim of this thesis study was to get all the useful information from the BGD 897/408B environmental testing chamber by doing different tests. Processing and analysing of the test results was done by comparing test results to IEC 60068-3-30 and MIL-STD 810 standards and, also, to specifications of the manufacturer. This way, solid conclusions for the operation of the testing chamber could be made.

Basic information regarding environmental testing was gathered from many regulations, standards, and materials released by different manufacturers of environmental testing equipment. Also, information of temperature and humidity as physical quantities was gathered.

By finding out quantities that needed to be verified, environmental tests were designed. The main areas concerned in the tests were the static and dynamic accuracy of temperature and RH control, interaction of these two quantities, and capabilities of the testing chamber.

In the future, the information gained from this study can be used to optimize test cycles to be as fast as possible, all the errors in the working principle of the chamber can be taken into account and only important results can be gathered from tests. By optimizing the environmental test, no time need to be wasted by doing irrelevant tests and lengths of the test periods can be designed to be appropriate.

Keywords
Environmental testing chamber, temperature, relative humidity, IEC-60068, MIL-STD

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Opinnäytetyön tarkoituksena oli kerätä kaikki tarpeellinen tieto BGD 897/408B olosuhdetestauskaapista tekemällä erilaisia testejä. Testitulosten prosessointi ja analysointi tehtiin vertaamalla testituloksia standardeihin IEC 60068-30 ja MIL-STD 810 sekä laitevalmistajan spesifikaatioihin. Näin pystyttiin tekemään luotettavia johtopäätöksiä testauskaapin toiminnasta.

Perustiedot olosuhdetestauksesta kerättiin erilaisista säännöksistä, standardeista ja eri laitevalmistajien jakamasta tiedosta koskien olosuhdetestauslaitteistoa. Lisäksi hankittiin tietoa lämpötilasta ja suhteellisesta kosteudesta fysikaalisina suureina.

Kun oli määritelty tarvittavat suureet, joita testeissä piti selvittää, pystyttiin niiden pohjalta suunnittelemaan olosuhdetestit. Tärkeimmät selvitettävät asiat olivat lämpötilan ja suhteellisen kosteuden säädön staattinen ja dynaaminen tarkkuus, lämpötilan ja suhteellisen kosteuden ristikkäisvaikutukset sekä olosuhdekaapin suorituskyky.

Tulevaisuudessa tämän opinnäytetyön tuloksia voidaan hyödyntää optimoimaan testisyklit mahdollisimman nopeiksi, kaikki olosuhdetestauskaapin säätövirheet voidaan ottaa testejä suunnitellessa huomioon ja vain tarpeellinen tieto voidaan kerätä testeistä. Kun olosuhdetesti optimoidaan, ei tarvitse käyttää turhaan aikaa tekemällä tarpeettomia testejä ja testijaksot voidaan suunnitella sopivan pituisiksi.

Avainsanat
Olosuhdetestauskaappi, lämpötila, suhteellinen kosteus, IEC-60068, MIL-STD

PREFACE

I want to thank all the people who made this thesis study possible. I want to especially thank Genelec Oy, which offered me this possibility to do such a wide scale study. I want to thank the R&D mechanical team leader Jaakko Nisula of the Genelec Oy. He helped me through the whole process and supported me when I had challenges considering the study. I also want to thank the R&D Director Aki Mäkivirta of the Genelec Oy. He helped me to understand what is crucial in a thesis study. He also helped me with parts of the study that were related to statistics, which were in a major role in this study. Finally, I want to thank my sister Mari Partanen (a doctoral researcher at the University of Oulu) who helped me with grammar and the structure of this thesis.

Iisalmi, 27.5.2019

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1 INTRODUCTION

Nowadays, it is critical to design products so that they can withstand all the environmental stresses there might be in the "real world". To get this information, suitable equipment is needed to do so. It's always possible to test these conditions at the environments where the products are normally used, but instead of this, an environmental testing chamber is usually a better alternative. With testing chambers, it is possible to control different climate conditions for example temperature and humidity. Some chambers are even able to speed up effects of the climate conditions, and this way a lifetime of different products can be estimated relatively accurately.

In this thesis, a certain environmental testing chamber's functions, accuracy, relation between temperature and humidity and other important factors about the chamber are studied. With this acquired information it is possible to do more reliable and faster tests in the future, and it is possible to design the testing procedures to meet necessities of each product that is to be tested. Also testing standards and relations are studied and information about environmental testing is gathered.

The environmental testing chamber's ability to control temperature and RH is the main topic in this thesis and this is studied by different empirical tests. From these tests the most descriptive things are gathered and presented by tables and graphs. Based on the information gathered these results are evaluated by different means.

This thesis was done in collaboration with Genelec Oy. Genelec Oy was established in 1978 and its location is in Iisalmi, Finland. From the beginning, company's idea has been to develop high quality studio monitors. Genelec manufacturers and designs monitors for professional use but monitors for home use and AV-installation are also developed. Genelec Oy provided workplace, needed equipment and lot of expertise during this thesis study, which made this thesis possible. (Genelec Oy, 2019)

1.1 Abbreviations and definitions

Abbreviation	Definition
Climatogram	Graph where different kinds of climate elements can be presented
EPS	Expanded polystyrene
IEC	International Electrotechnical Commission
PUR	Polyurethane
RH	Relative Humidity
Uniformity	Uniformity is defined as the maximum deviation of quantity in the measurement area

2 ENVIRONMENTAL TESTING

Environmental testing, also called environmental conditioning, can be defined as practises in which specimens are subjected to natural or artificial environmental conditions mimicking storage, installation, use, and transportation conditions. Then their performance can be monitored, and reliable conclusions of their performance can be made. (Finnish Standards Association SFS, 2014, p. 11)

Environmental tests are done by immersing test samples to artificial environments. This is done with the help of an environmental testing chamber. There are different sizes of chambers, from small laboratory ones to huge rooms where you can even drive with a car (CSZ, Cincinnati Sub-Zero, 2019 a). On top of humidity and temperature, some chambers also have vibration tables or salt spray nozzles, which makes it possible to test different sort of environmental stresses. (NTS, 2019)

2.1 Environmental test methods

2.1.1 Climatic tests

There is vast scale of environmental tests. First, there are climatic tests that are done for studying how products and parts can handle different climatic and weather conditions. Usually, in these tests, temperature and humidity are the main parameters that are monitored. These conditions can be still so that, for example, temperature and humidity remain at the same level for the whole duration of testing. The other possibility is that there are different temperature and humidity cycles where these quantities vary at a desired range. In addition to temperature and humidity, other environmental conditions can be studied; for example how sea water corrodes materials, how air pressure affects cargo in planes, or how the radiation of sun affects materials. (Finnish Standards Association SFS, 2014, pp. 11-14)

2.1.2 Mechanical tests

Secondly, there are mechanical tests. There are impact tests that are used for example for testing how packaging can handle impacts caused by rough handling during transportation. In addition, there are vibration tests, where for example vibration caused by truck during transportation can be studied. There are also tests e.g. how robust joints and fasteners are, how good sealings are against leakage of fluid and ingress. (Finnish Standards Association SFS, 2014, pp. 11-14)

2.1.3 Accelerated tests: HALT, HAST, HASS, ESS and 85/85

These tests are developed to shorten the time required to see desired changes in test samples during testing. These tests require testing equipment that have been specifically developed for these tests. The key information that is found with these tests is connected to the lifetime of test samples. (TT Electronics, 2019)

The purpose of HALT (Highly Accelerated Life Testing) is to quickly reveal design faults and mistakes during the development phase. Test samples are exposed for environmental cycles in which temperature, humidity, and mechanical properties like vibration can be adjusted in an accelerated speed. These test cycles are not meant to simulate environmental conditions where product normally operates, but the purpose of the test is to find the design errors that could occur in the early stage in the lifecycle of a product. Also, the gap of the product's maximum operating limit and actual operating limit are found with this test. (TT Electronics, 2019)

HAST (Highly Accelerated Stress Test) is very similar to HALT, but in HAST only temperature and humidity are controlled. So, lifetime estimates can be given to products based on this test, if the primary failure mode is caused by climatic conditions. (TWI Ltd, 2019)

HASS (Highly Accelerated Stress Screening) is related to HAST. When the normal and maximum operating limits are found, it is possible to design suitable tests that need to be done in the production to avoid product's failure in the early stages of its lifetime. HASS is developed for this purpose. Basically, HALT is used for testing products in the design phase of the product, and HASS is used for testing products in the production phase. (TT Electronics, 2019)

ESS (Environmental Stress Screening) is very similar to HASS. The main difference between these tests is that in HASS, testing conditions are above normal operating limits and in ESS, these conditions are below normal operating limits. The ESS is meant for products that already have extreme operating limits, so there isn't any sense to use HASS. (TT Electronics, 2019)

85/85-test is an accelerated reliability test meant to test electronics' life cycle. As the name implicates, climatic conditions of this test are the temperature of 85 °C and RH of 85 %. The test lasts 1000 hours, which is relatively long when compared for example with HAST. There will be a bias applied to the test sample for the duration of the test. (Vishay, 2017)

2.2 Standards and regulations

There are many different standards that are used to test environmental stress to different kind of products and there are also many regulations that can help to decide the best methods for every kind of different testing situation. In this thesis only the most useful of these standards are addressed considering what kind of testing could be done with the environmental testing chamber that was used in this thesis study.

2.2.1 IEC Standards

The International Electrotechnical Commission (IEC) is non-profit quasi-governmental organization which has been founded 1906. Members of this organization are National Committees and these Committees choose experts from different fields of business from their representative countries to work as their deputies. This organization publishes International Standards and manages Conformity Assessment Systems considering electrotechnology. (IEC, 2019)

The standard including all environmental tests is called IEC 60068, and this standard is separated into three parts. The part one describes the basic knowledge of environmental testing and requirements. The second part includes all tests for different applications and how to execute them. The third part includes supporting documentation and guidance, in other words all the background information. The second and third part are also further divided into smaller categories. (Finnish Standards Association SFS, 2014, p. 11)

The parts of IEC 60068 standards that are the most interesting considering testing with the environmental testing chamber is studied in this thesis are:

1. IEC 60068-2-1: Test A: Cold
2. IEC 60068-2-2: Tests B: dry heat (sinusoidal).
3. IEC 60068-2-14: Test N: Change of temperature
4. IEC 60068-2-30: Test Db: Damp heat, cyclic (12 h + 12 h cycle)
5. IEC 60068-2-64: Vibration, broadband random and guidance
6. IEC 60068-2-65: Vibration - Acoustically induced method
7. IEC 60068-2-78: Damp heat, steady state
8. IEC 60068-3-4: Supporting documentation and guidance - Damp heat tests
9. IEC 60068-3-5: Supporting documentation and guidance – Confirmation of the performance of temperature chambers
10. IEC 60068-3-6: Supporting documentation and guidance - Confirmation of the performance of temperature/humidity chambers
11. IEC 60068-3-7: Supporting documentation and guidance – Measurements in temperature chambers for tests A and B (with load)
12. IEC 60068-3-11: Supporting documentation and guidance – Calculation of uncertainty of conditions in climatic test chambers

In Figure 1, a test cycle used in IEC 60068-2-30 standard is presented. Parts of this test cycle are somewhat similar to Test 3 presented in Chapter 3.2.3. So, information from this test cycle can be used to verify the results of Test 3. The set RH in this test is 95 % and the set temperatures are 55 °C and 25 °C. The RH tolerance is presented as the hatched area and the temperature tolerance is generally ± 2 °C, but at 25 °C, the tolerance seems to be ± 3 °C. (Germanischer Lloyd SE , 2012).

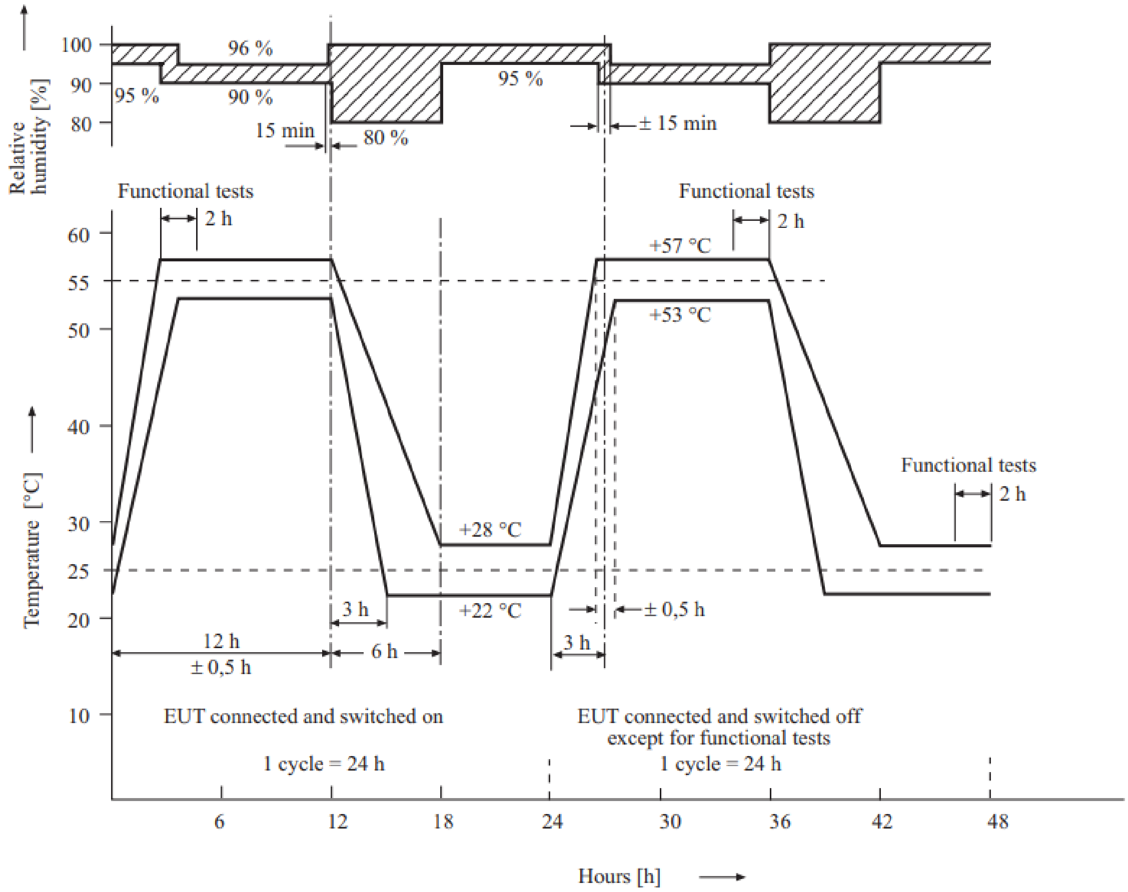

FIGURE 1. Test cycle and tolerances of IEC 60068-2-30 (Germanischer Lloyd SE , 2012)

2.2.2 USA defence standards

These standards are provided by the USA military, and they are prepared to standardize objectives of U.S Department of Defence. These standards with defence handbooks and defence specifications are prepared to achieve interoperability, make products reliable and meet certain requirements, make products sensible considering logistics and other defence-related objectives. These standards are also used by organizations outside of military, for example by industry. (Melton, 2019, pp. 2-4)

MIL-STD are the military standard documents. They are made to uniform technical and engineering requirements for modified commercial methods, processes, practises and procedures to satisfy needs of the military. (Melton, 2019, p. 4)

TABLE 1. MIL-STD 810 specifications

	Temperature (°C)	RH (%)
General tolerance	± 2	± 5
Method 507.6	-	± 4*

* When temperature is decreasing [+4; -10]

MIL-STDs relevant considering tests that could be done with Biuged's testing chamber are: MIL-STD-810, Test method standard Environmental Engineering Considerations and Laboratory Tests and MIL-STD-202, Test method Standard Electronic and Electrical Component Parts.

MIL-STD-810's first part contains information on how to prepare documentation and material needed to do successful environmental tests, what has to be taken into consideration during tests, terminology, equipment, and management of tests all together. The second part describes all different tests that can be done to materials and products, for example temperature, humidity, vibration, and shock. The third part of the standard contains huge amount of data of different environmental conditions around the world. The general tolerances of MIL-STD-810 for temperature and humidity are presented in Table 1. These tolerances are applied if individual test methods do not specify otherwise. For example, there is a tolerance from method 507.6-Humidity in Table 1, where a specified RH tolerance is stated. (Department of Defence, 2014, pp. 2-3, 26-27, 224)

As the name suggests MIL-STD-202 introduces uniform methods to test electronic and electrical components. There are different environmental tests and, also, physical and electrical tests. These tests are categorized in the standard depending on their type. (Department of Defence, 2015, p. 5)

2.3 Testing with empty chamber vs product testing

There are two kinds of cases how the test could be done. First is doing the test with chamber empty also known as Operation Qualification (OQ). The other way is Performance Qualification (PQ) meaning doing the test with product/products inside of the chamber. The minimum load and worst case for temperature fluctuations in the chamber are achieved in OQ method. Due to this fact, it would be ideal situation considering this thesis work. This is because of what needs to be found out, is how reliable manufacturers specifications of the chamber are. The fully loaded chamber is also more stabilized because of the thermal mass of the product, so with empty chamber this facilitation is also excluded. (Moody, 2018); (Rotronic, 2019 a)

2.4 Mapping study

The most common reason to do a mapping study are the regulations on certain industries. In these cases, mapping studies are quite mandatory, and they are conducted regularly. Some products have regulated storage conditions, like certain temperature and humidity. In these cases, it is absolutely critical to do the mapping study, because for example in large storage rooms, there might be hot and cold spots in some places of the room. Pharmaceutical industry is one of the industries in which storage conditions are critical, and that industry has many regulations to follow. For example, many countries and WHO (World Health Organisation) have their own regulations. There are also other international regulations. (PharmOut, 2016)

Other reason why one would might want to do a mapping study is to find out the working principle for, for example, environmental testing chamber. This is also the reason behind this thesis study. This mapping study does not strictly follow any regulations. Rather, it takes parts from standards and regulations which give the most useful information. In addition, after this mapping study, it would be ideal to have basic knowledge how test cycles should be developed, so that they are as fast as possible, but at the same time, it should be possible to gather all the needed information from the test results.

There are eight critical steps when preparing a mapping study.

1. To understand why the mapping study needs to be done. For example, regulations and understanding the working principle of an environmental testing chamber.
2. To have basic knowhow of the testing chamber. For example, where the sensors need to be positioned and how to operate the chamber and data acquiring system.
3. To understand the objective of the study. For example, what the study will prove, what parameters need to be tested, and the duration of measurements.
4. To do an encompassing and clear testing plan.
5. To confirm that testing equipment and software work as they should and that sensors are calibrated.
6. To understand how to get the needed results out of the testing software and how to compare results from sensors with results from the testing chamber itself.
7. To make sure how the monitoring of the test will be conducted.
8. To be observant and cautious when starting the test and the data logging system, so that all needed things are taken care of. (Rotronic, 2019 a)

2.5 Temperature and humidity in environmental testing chamber’s process

2.5.1 Temperature

There are basically three cases that effect how the temperature of the chamber changes. First is to heat air with the heater if the temperature is increased or cool the air with the refrigerating system if the temperature is decreased. Second thing is to heat the inner structures of the chamber. And finally, the third thing that effects temperature change is heat loss through structure of the chamber into ambient air outside the chamber. On top of these there is thermal radiation from heater, but in the case of the test chamber, transferred heat energy from heater through radiation to the chamber was deemed to be so little, that it was not taken into consideration.

An air to air plate exchanger is used to heat the air inside the chamber. This can be calculated Equation 1. This equation is basically heat transfer version of Newton’s law of cooling (also known as Fourier’s law), but U-term takes into consideration multiple heat transfer coefficients:

$$q = UA\Delta T \tag{1}$$

Where:

q = heat transfer [W]

U = overall heat transfer coefficient [W/(m^{2}K)]

A = wall area [m^2]

ΔT = temperature difference [°C]

$$U = \frac{1}{\frac{1}{h_{ci}} + \frac{s_n}{k_n} + \frac{1}{h_{co}}} \tag{2}$$

Where:

k_n = thermal conductivity of material in layer n [W/(mK)]

h_{ci}, h_{co}= inside or outside wall individual fluid convection heat transfer coefficient [W/(m^{2}K)]

s_n = thickness of layer n [m]

The other factor that can bring more heat energy to the system is the hot steam that is used to humidify the chamber. This of course is only the case when air inside the chamber is humidified and heated simultaneously. There is more information from the humidity in chapter 2.6.2.

Heating of air inside the chamber and the inner structure of the chamber, which mainly consists of steel racks where test samples can be placed, steel plates in the inner walls and if testing is done with test samples, then also the thermal mass of the test samples. Heat energy needed for these can be calculated with heat transfer formula presented in Equation 3:

$$Q = mc\Delta T \tag{3}$$

Where:

Q = heat energy [J]

m = mass [kg]

ΔT = temperature difference [°C]

Heat loss through walls can be calculated as stated in Equation 2, but there are no h-terms and there are multiple s-and k-terms. This modified equation can be seen in Equation 4:

$$q_{Conductive} = \frac{\Delta T A}{\left(\left(\frac{s_1}{k_1}\right) + \left(\frac{s_2}{k_2}\right) + \cdots + \left(\frac{s_n}{k_n}\right)\right)} \tag{4}$$

2.5.2 Humidity

Firstly, it is important to understand the difference between relative and absolute humidity. Relative humidity is a relation of water vapor in air and needed water vapor in air for saturation, expressed as percentage. And absolute humidity means of how much water mass is in a specific volume of air. For example, if temperature increases and absolute humidity remains the same, relative humidity decreases. In this thesis, the humidity results are expressed as relative humidity. (Yumi Alanoly, 2008)

One usual way to produce water vapour is by boiling water in the boiler. Heat energy needed to warm water in a specific temperature into 100 °C can be calculated with Equation 3. But because water's phase also changes from liquid to vapor more heat energy is needed. In Equation 5 energy needed for vaporization is stated:

$$Q_r = rm \tag{5}$$

Where:
r = specific latent heat of vaporization [J/kg]

There are two ways to humidify air: adding water or water vapour into air. In either case, the amount of water that is needed to change air to a specific humidity, can be calculated with Equation 6:

$$m_w = v\rho(x_C - x_A) \tag{6}$$

Where:
m_w = mass of added water [kg/s]
v = volume air flow [m^3/s]
ρ = density of air [kg/m^3]
x_C = humidity ratio at the end [kg$_{water}$/kg$_{dry\ air}$]
x_A = humidity ratio at the beginning [kg$_{water}$/kg$_{dry\ air}$]

Approximate values for humidity ratio can be taken from Mollier diagram, which is a graphic presentation of air temperature's moisture content's and enthalpy's relationship. This diagram can be seen in Figure 2. Values in this graph are empirically studied. (Engineering ToolBox, 2003)

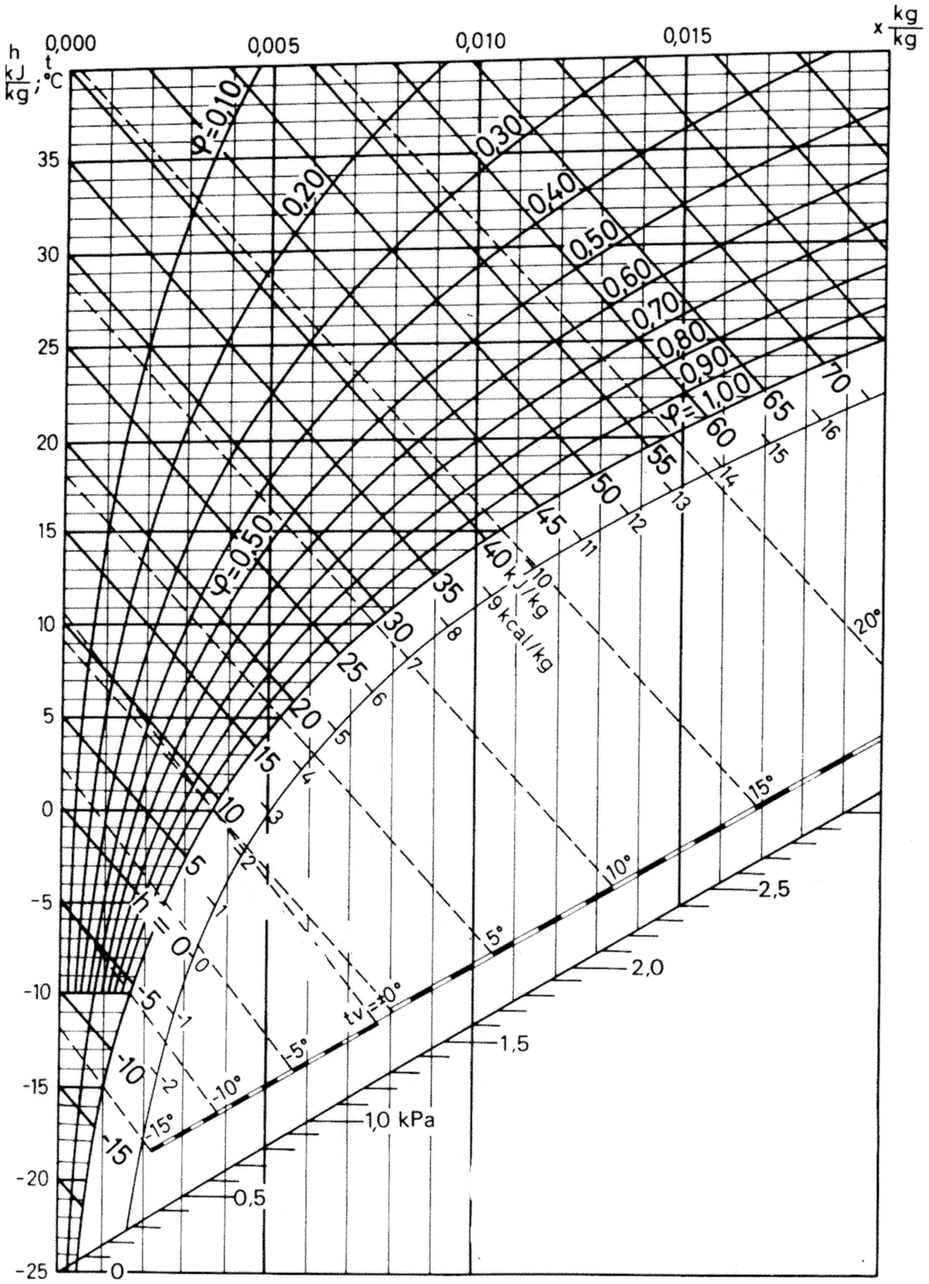

FIGURE 2. Example of Mollier diagram (Engineering ToolBox, 2003)

In dehumidifying process, the water is simply removed from the air through condensation. Condensation process is called cold finger method, and it is explained in chapter 3.1.3. Heat energy released during condensation can be calculated with Equation 5 and mass of water released with Equation 6, since the process is basically the same as in humidifying but backwards. One factor that also effect dehumidifying speed is how much water the cold finger can condensate on its surface. Factors that affect this phenomenon are surface area and temperature of the cold finger.

In chapter 3.1.3 there is more practical information how these equations are used in practise in the environmental testing chamber.

3 TEST CHAMBER EVALUATION

3.1 Environmental testing chamber

The environmental testing chamber studied in this thesis work, was made by Biuged Laboratory Instruments (Guangzhou) Co. Ltd, and its model was BGD 897/408B. With this chamber it was possible to provide different environmental conditions by adjusting temperature and RH-values. (Biuged Laboratory Instruments (Guangzhou) Co. Ltd, 2019)

The measurements of the chamber were 600 mm wide, 850 mm high and 800 mm deep. There were two racks where products to be tested are put. The chamber's specifications can be found in Table 2. It is also possible to do different kind of test programs with the chamber, to do cyclic tests where the chamber changes temperature and RH-values in a certain period of time and also keeps these values in a desired level for a certain period. Also, the changing rates of temperature and RH can be modified to satisfy the needs of tests by giving specified time for steps in program. (Biuged Laboratory Instruments (Guangzhou) Co. Ltd, 2019)

TABLE 2. Chamber's specifications (Biuged Laboratory Instruments (Guangzhou) Co. Ltd, 2019)

	Temperature (°C)	RH (%)
Range	- 20 – (+130)	20 - 98
Uniformity	2	2-3 / 5 *
Stability	0,5	2
Average change rate increasing	3,5	-
Average change rate decreasing	1,0	-

* ≤ 2-3 % RH (≥ 75 %) and ≤ 5 % RH (≤75 %)

3.1.1 Wet and dry bulb method

The principle behind the machines ability to measure RH lies in wet and dry bulb method. In this method, there are two temperature sensors, and one of these is the dry bulb sensor, which is left as it is. On the other hand, the other sensor is wrapped in a wetted wick and this sensor will work as the wet bulb. Next, temperature sensors are put in the same space with each other and temperature readings are taken from both. The temperature reading from the wet bulb should be lower than that of the dry bulb. Now, comparing two temperature readings, it is possible to calculate the RH of the space. Application that uses wet and dry bulb method is called a psychrometer. (Keey, 2011) The mostly commonly used psychometric formula is called Sprung formula (Nakahama, 2019, p. 5). The calculation method can be seen in following Equation 7:

$$e = e_{sw} - A * p(t_d - t_w) \tag{7}$$

Where:

e =partial pressure of water vapor pressure

e_{sw} =saturation water vapor pressure

A =psychometric coefficient=0,000662(K-1) (if wet bulb is not frozen and wind speed is over 2,5 m/s)

t_d =dry bulb temperature

t_{sw} =wet bulb temperature

p = atmospheric pressure

3.1.2 Controller

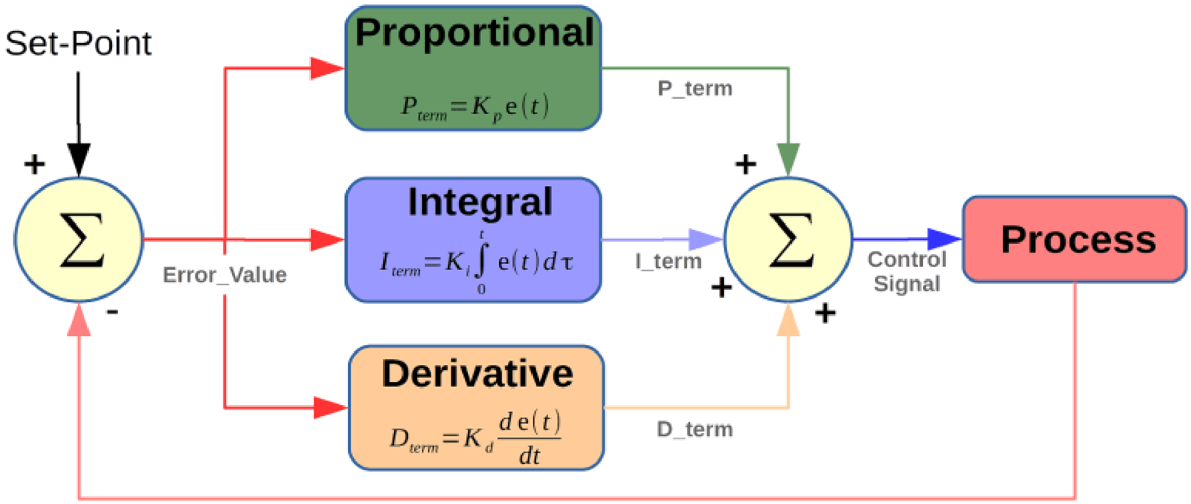

FIGURE 3. Block diagram of PID controller (Microcontrollers Lab, 2019)

The climate chamber's ability to control the RH and temperature values, so that they would match with the set values, lies in PID-controlling. PID-controller's purpose is to force feedback to match a set point, for example our chamber's heating system turns on if the measured temperature is lower than the set temperature (Omega Engineering Inc., 2019 b). PID control algorithm consists of three main areas: Proportional, Integral, and Derivate response. The working principle of a PID-controller is presented in Figure 3's block diagram. In this block diagram there is a certain set value, and then there is a current value of measured quantity, which is called process value. Now, when difference between these values is known, proportional, integral, and derivate term can be applied accordingly. These three terms are summed together, and they produce a control signal, which adjusts the process value. Then this cycle starts again from the beginning, and the cycle is repeated until the wanted set value is reached. (Microcontrollers Lab, 2019)

The proportional term (also known as Error term) is dependent on the set value's and measured value's proportional difference. For example, the bigger the difference between values is, the bigger the error term is. Proportional term also has such a feature that if output that proportional term applies to the process is too large, the system may become unstable and start to oscillate. (National Instruments, 2019)

The integral term sums up the proportional terms and tries to apply a correction factor to fix cumulative error that forms during multiple proportional terms. For example, if the climate chamber's temperature remained below the set temperature in a long term, the integral term would raise the temperature considering this fact. But because the integral term tries to drive the cumulative error to a zero, it will not stop the heating when wanted temperature is reached, resulting in an overshoot. (Omega Engineering Inc., 2019 b)

The derivate term's main function is to try to minimize the overshoot that the integral term applies. The derivate term doesn't fix the error itself. Rather it modifies the change rate of error fixing, applied by integral term. This means for example in the climate chamber's temperature controlling that derivate term tries to flatten the overshoot resulting more horizontal line in the diagram of the readings. (Omega Engineering Inc., 2019 b)

In Figures 4–7 there are descriptive diagrams of how different PID parameters can influence step response. First in Figure 4 there is a low proportional term influencing the response, and as so the curve is too low from wanted level, which is presented as red dashed line. Then, in Figure 5, a higher proportional term has been applied, which has caused that the curve has approached the desired level, but at the same time it has started to oscillate and, overall, it remains under the desired level at the end. Now in Figure 6, the integral term has been applied at the top of the proportional term, which has caused even more oscillation, but now the wanted level is achieved. Finally, in Figure 7, the derivate term has been applied on top of the other two, which has calmed down the oscillation and the desired level is pretty much achieved.

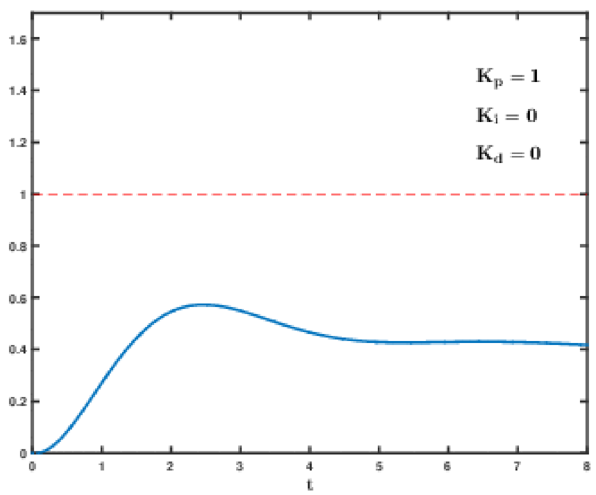

FIGURE 4. Example of step response when small proportional term K_p is applied (Physicsch, 2015)

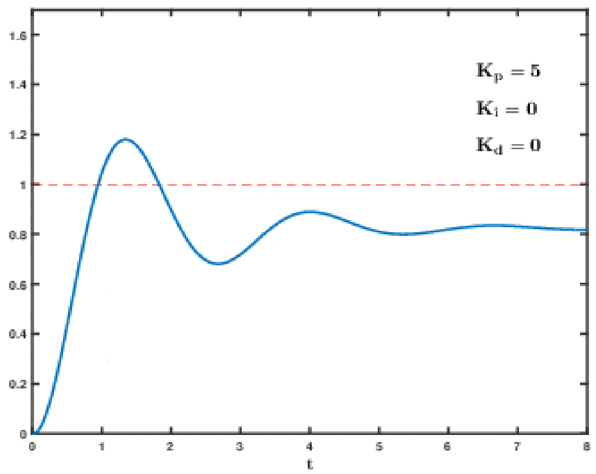

FIGURE 6. Example of step response when bigger proportional term K_p is applied (Physicsch, 2015)

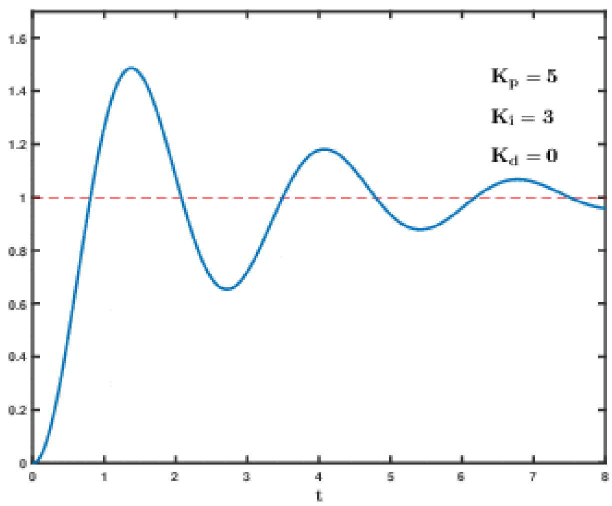

FIGURE 5. Example of step response when proportional term K_p and integral term K_i are applied (Physicsch, 2015)

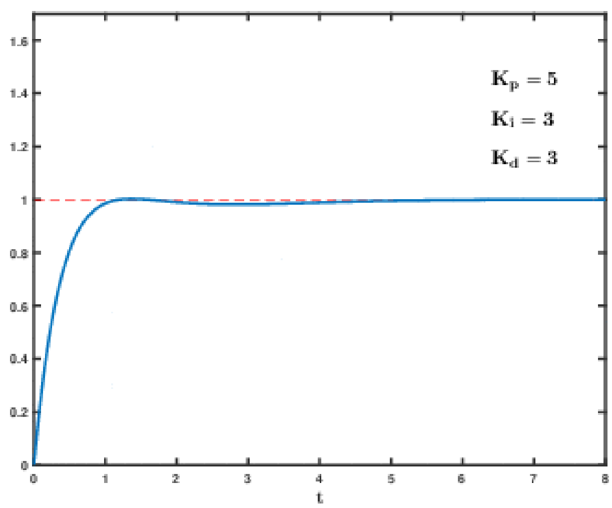

FIGURE 7. Example of step response when proportional term K_p, integral term K_i and derivate term K_d are applied (Physicsch, 2015)

3.1.3 Temperature and humidity control systems

Cooling and heating are the two functions needed to control temperature. It's also important that the test chamber can distribute the desired temperature evenly on every spot inside of the chamber. This is achieved by designing the test chamber's structure right. (Angelantoni Test Technologies Srl, 2019)

One way to heat the chamber is with an electric fan heater that consists of a fan and resistive heating coils. The coil package is heated to a high temperature, and air is conducted through it with the help of the fan. Then, through the ventilation system, air is conducted to the chamber itself. (Connection Magazines, Build, 2019)

The working principle of the cooling system is usually the same that is used in a normal refrigerator. The closed system consists of four components: an expansion valve, an evaporator, a compressor and a condenser. A block diagram of this cycle can be seen in Figure 8. First the cold and low-pressure liquid refrigerant is conducted to the evaporator through the expansion valve. It changes into gas in the evaporator and cools the air there. Then, the fan blows the cold air to the chamber. Next, the low-temperature low-pressure refrigerant continues its way to the compressor where it changes to a high-temperature and high-pressure gas. Then the refrigerant continues to the condenser where it relinquishes its heat and it turns back to liquid. Now the liquid goes back to the expansion valve and the cycle can start again from the beginning. (Berg Chilling Systems Inc., 2017)

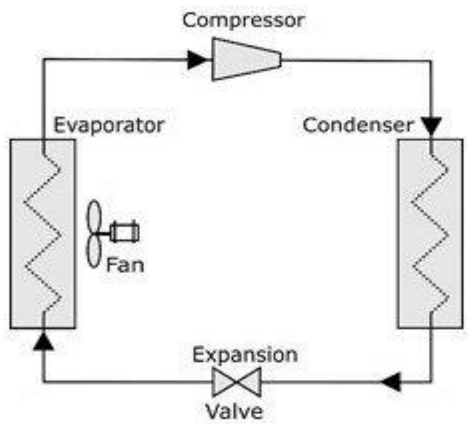

FIGURE 8. Block diagram of refrigerator's working principle (Angelantoni Test Technologies Srl, 2019)

The working principle of the humidifier is usually very simple. The chamber has an electric heater that boils water and then the hot steam that forms during boiling is conducted into air flow that the air circulation fan creates. There can be problems with low temperature control due to this humidifying method, since the boiling process produces heat (CSZ, Cincinnati Sub-Zero, 2019 b). Dehumidification system is based on the so-called cold finger method. There is an object that has a cold surface. When the warmer high-moisture air is conducted to go past this object, moisture from the air condenses to the cold object's surface and the moisture content in the air decreases. (Angelantoni Test Technologies Srl, 2019)

3.1.4 Temperature model of chamber

To explain how heating in the chamber works, a basic mathematical model was designed. The basic principle is presented in Chapter 2.6.1, and based on information from it, Equation 8 was constructed:

$$q_{Heater} + q_{Steam} - q_{Loss,Walls} - q_{Loss,other} = \frac{\Delta Q_{Air} + \Delta Q_{Structure}}{t} \tag{8}$$

Where:
q_{Heater} = heat transfer from the heater = heating power [W]
q_{Steam} = heat transfer from the hot steam = heating power [W]
$q_{Loss,Walls}$ = heat loss through the chamber walls [W]
$q_{Loss,Other}$ = heat loss through other structures than walls e.g. losses through ventilation duct when air flows in it [W]
ΔQ_{Air} = Heat energy needed to heat the air in the chamber [J]
$\Delta Q_{Structure}$ = Heat energy needed to heat the inner structure of the chamber [J]
t = time [s]

When using Equations 1-4, Equation 8 can be advanced. Results of this can be seen in Equation 9:

$$UA\Delta T + q_{Steam} - \frac{\Delta TA}{\left(\left(\frac{s_1}{k_1}\right) + \left(\frac{s_2}{k_2}\right) + \cdots + \left(\frac{s_n}{k_n}\right)\right)} - q_{Loss,other} = \frac{m_{Air}c_{Air}\Delta T + m_{Str}c_{Str}\Delta T}{t} \tag{9}$$

Now the unknown factors are the heat transfer from the hot steam q_{steam} and other heat transfer losses $q_{Loss,other}$. These factors are not easy to present any further, because of multiple unknown variables e.g. how much steam is added compared to air and what is the specific heat of all other structures.

3.2 Test procedure

Three different test procedures were deemed to be needed to verify how the environmental testing chamber works and to acquire enough information from it to make reliable conclusions. Most of the information was gained from Test 3, which was mostly done according to the standard IEC 60068-3-6.

3.2.1 Test 1. Temperature maximum set values

Testing a temperature range goes as follows: first, the temperature will be run down to -20 °C from 23 °C, at the set change rate. After that, the temperature is kept at the specified temperature for 30 minutes. Next, the temperature will be run up to the +100 °C, at the set change rate and the temperature is kept at the specified temperature for 30 minutes. This cycle is repeated six times with different change rates to study how accurate the set change rate of the temperature is compared to real change rate. In addition, minimum and maximum temperature and maximum change rates were studied in this test.

At first, this test was supposed to be tested at the maximum temperature of sensors (123,8 °C), but after a quick test of putting the sensor in this high of a temperature, regarding manufacturer's advice that there might be problems with the cable, the cables outside the surface got slightly stuck on the rack. So, keeping this in mind the test was modified so that the maximum temperature was 100 °C. To verify maximum temperature of the chamber, a separate test was conducted. This separate test was simply done in a way, that the chamber's temperature was run up to 120 °C as fast as the machine was able, and then kept there for 15 min.

Change rates:
a) 0,5 °C/min warming, 0,2 °C/min cooling
b) 1,0 °C/min warming, 0,4 °C/min cooling
c) 1,5 °C/min warming, 0,6 °C/min cooling
d) 2,5 °C/min warming, 0,8 °C/min cooling
e) 3,5 °C/min warming, 1,0 °C/min cooling
f) 60 °C/min warming, 21 °C/min cooling (for testing maximum change rates)

3.2.2 Test 2. Relative humidity maximum set values

Testing a RH range goes as follows: first, the RH will be run down to 20 % from 60 %, at the set change rate. Then, the RH is kept at a specified temperature for 30 min. Next, the RH will be run up to the 98%, at the set change rate, and the RH is kept at a specified temperature for 30 min. Testing temperature will be at 70 °C, because chamber's best accuracy control area is + 65 °C – (+85 °C) ac-cording to the manufacturer. Testing accessory will consist of 10 humidity sensors, positioned in the way presented in Figure 13 and one sensor outside the cabinet. This cycle is repeated six times with different change rates, to study how accurate set change rate of the temperature is compared to the real change rate. Also, minimum and maximum RH, and maximum change rates were studied in this test.

Change rates:
a) 1 %/min increasing RH, 1 %/min decreasing RH
b) 2 %/min increasing RH, 2 %/min decreasing RH
c) 3 %/min increasing RH, 3 %/min decreasing RH
d) 4 %/min increasing RH, 4 %/min decreasing RH
e) 5 %/min increasing RH, 5 %/min decreasing RH
f) 39 %/min increasing RH, 30 %/min decreasing RH (for testing maximum change rates)

3.2.3 Test 3. Cyclic test

This test was based on a test method instructed on the standard IEC 60068-3-6. In the standard, there is an example of climatogram, which shows what kind of a cycle gives necessary information from the climate chamber. This climatogram is very similar to the blue area presented in Figure 8, which is a working area of the chamber where manufacturer has promised that temperature and RH can be regulated accurately. So, this test was done with a step order presented in the standard but with the limits of the Figure 8. The information gained from this test was used to study how the temperature and RH readings deviated in different locations of the chamber, how accurately chamber was able to repeat test cycles, how the changing temperature effects RH readings and vice versa, what kind of static and dynamic accuracy the chamber has. This test cycle is presented in Figure 9.

The steps were as follows (there was a so called 30 minutes "set step" between every step, where the machine went to desired values and then started to measure the desired time of the steps a-h):

a) Temp. 20 °C, RH 40 %, 1 hour
b) Temp. 65 °C, RH 20 %, 1 hour
c) Temp. 85 °C, RH 20 %, 1 hour
d) Temp. 85 °C, RH 98 %, 1 hour
e) Temp. 25 °C, RH 98 %, 1 hour
f) Temp. 20 °C, RH 95 %, 1 hour
g) Temp. 50 °C, RH 60 %, 1 hour
h) Temp. 70 °C, RH 80 %, 1 hour
This cycle was repeated 5 times so the whole duration of the test was 60 h (2,5 days).

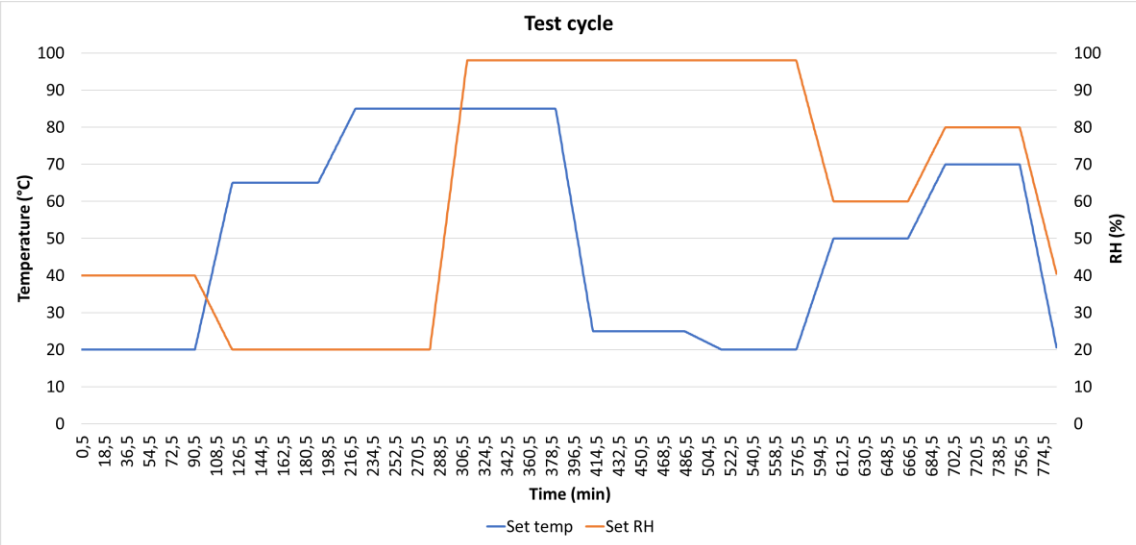

FIGURE 9. Test cycle used in the test 3

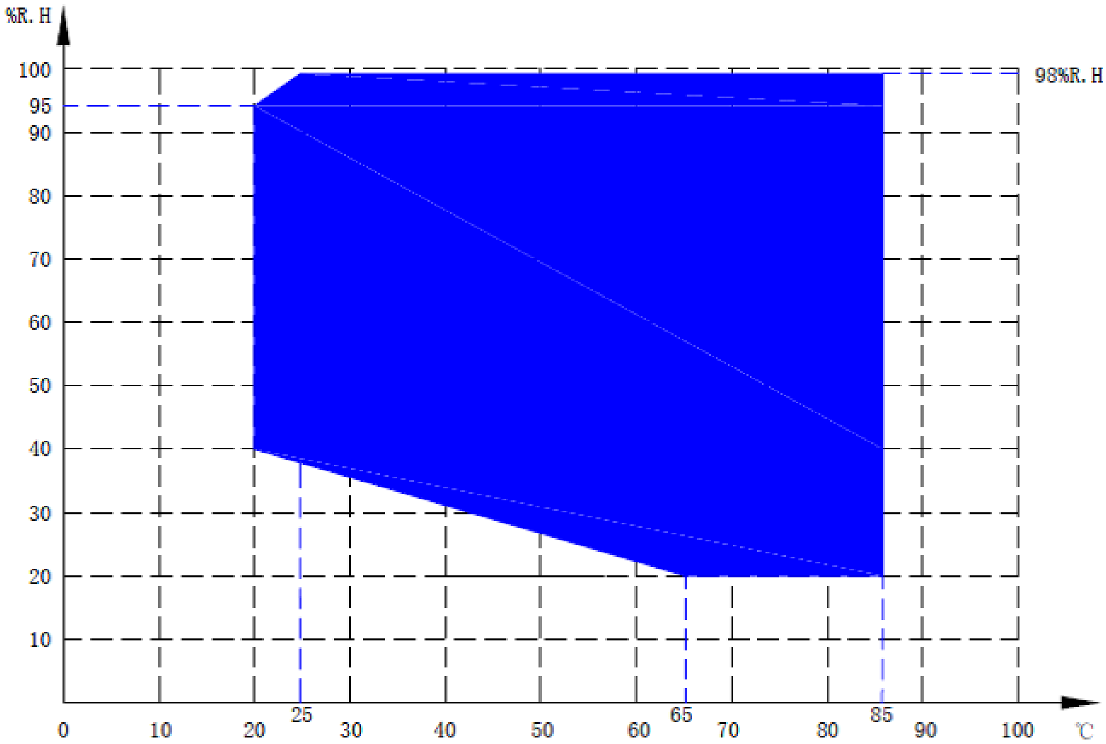

FIGURE 10. Working range of the chamber when values can be controlled accurately (Biuged Laboratory Instruments (Guangzhou) Co. Ltd, 2019)

3.3 RH/Temperature measurement equipment

The testing equipment used in the test was provided by LabJack. Their T7-datalogger with two extension boards, CB37 and CB15, were used ((LabJack, 2019 a), , (LabJack, 2019 b), (LabJack, 2019 d)). Extension boards were needed to fit all the sensors simultaneously into the datalogger. EI1050-sensor probes were used for both measuring of the temperature and RH and 10 of these kinds of sensors were used (LabJack, 2019 c).

The only problem with this probe was the cable. Although the sensor works at +123,8 °C , the cable is only rated to withstand +80 °C. But the manufacturer of the EI1050-probe had tested the cable at +150 °C and from their experience, the cable got softer in high temperatures, but it still worked fine. Furthermore, no degrading was observed when the cable was returned to room temperature. The manufacturer still reminds that because of the rating of the cable, the usage over 80 °C is at a user's own risk.

The sensor that is inside the EI1050-probe is made by Sensirion and its model is SHT11. A typical accuracy of these sensors is ± 3.0 % for RH and ± 0,4 °C for temperature. The operating range of these sensors is -40 -(+123,8) °C, so they're at a sufficient level when comparing to the working range of the chamber. There are actually two different sensor elements in the chip. One element is the capacitive sensor that measures the humidity and the other one is a silicon band-gap sensor, which measures temperature. (Sensirion, 2011, pp. 1-2)
The working principle of the humidity sensor element is, as the name suggests, based on measuring changes in an electrical property called capacitance. There are two electrodes and a hygroscopic dielectric between them. When the humidity in the space where the sensor is rises, the dielectric absorbs moisture. This can be seen as an increase of capacitance in the sensors and humidity reading can be taken from it. The working principle of the silicon band-gap sensor is totally different from humidity sensor's working principle and it is based on a forward voltage of a silicon diode (AZoSensors, 2014). (Rotronic, 2019 c)

3.4 Calibration of sensors

To get accurate test results, a calibration of the sensors was needed. No measurement equipment is perfect, so if the chamber's measurement equipment needs to be tested, so need the sensors themselves. For example, sensors can have different readings between each other even if they are basically identical according to the manufacturer and sensors subjected to high or low temperatures, humidity, or shock can alter the sensors' change rate. (Earl, 2019, p. 3)

3.4.1 Relative calibration

To verify that the sensors' readings don't vary between each other too much, a relative calibration study was needed. In this study the idea was to put all EI-1050 sensors simultaneously in a testing area where the environmental conditions would be stable and then take temperature and RH readings from them.

An acceptable solution was found for the testing area. A box made of EPS was found from the production line. It was deemed to be of the right size and its insulation level was enough. The box was modified in a way that an inlet was drilled in the front wall of the box for the sensors' cables. To make the box airtight after cables had been routed, an appropriately sized plug was made from PUR-foam and crack between lid and the box was insulated with tape. The inside of the box with sensors can be seen in Figure 11.

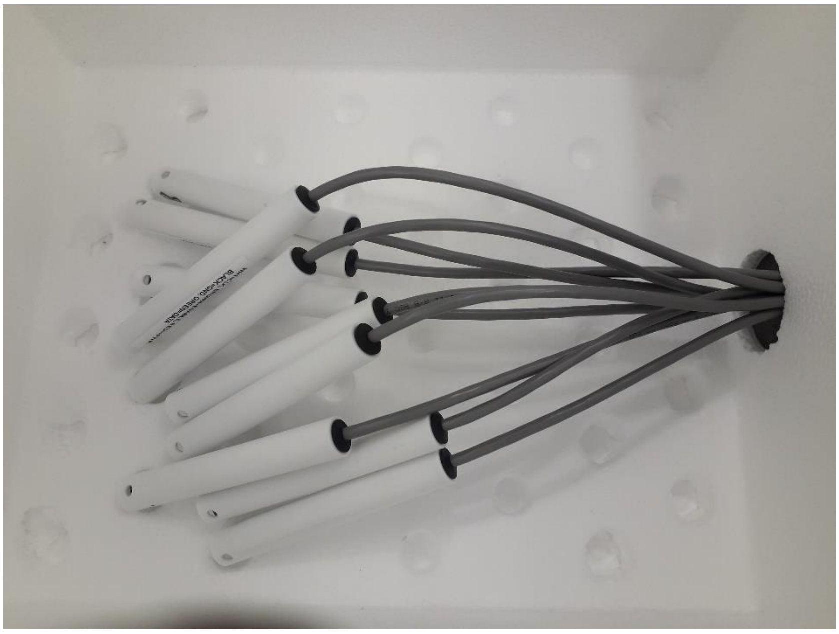

FIGURE 11. Sensors inside the EPS-box before relative calibration

The results of the calibration were very positive. The calibration lasted around 19 hours and the readings were taken every six seconds. For the whole duration of the test, readings did not vary much. The average maximum error where quantities' readings varied at a specific moment during the calibration were 0,016 °C for temperature and 0,023 % for RH. So, over all the sensors' readings were close enough to each other and no further calibration was needed considering relativity.

3.4.2 RH Calibration

The RH calibration was done in a way that environment conditions with sodium chloride (table salt) were established. First, the aim was to calibrate all the sensors simultaneously using the same box that was used in the relative calibration. But the box was noticed to not to be insulated enough for this test, so the test procedure needed to be modified. (Genovese, 2017)

An acceptable container for this test was found to be a simple bottle used to store food in a freezer. The cap of the bottle was modified by drilling a hole close to the size of the sensor's probe. Then, the probe was stuck through the hole and the opening between the probe and the cap was sealed with a mounting putty. This system can be seen in Figure 12.

FIGURE 12. Test container in RH calibration of the sensors

After the container was prepared, a mixture of sodium chloride and distilled water was made. Salt and water were added in relation of 5:1. The mixture's texture needed to be like that of wet sand, and this was achieved. After this, the sensors were put in the container with the solution, and they were kept there a minimum of six hours so that the air inside the container managed to reach the desired RH level. (Genovese, 2017)

The base of this test relies on empirical tests done for different salt solutions. For all temperatures saturated salt solutions always have the same concentration, and when these solutions, for example, in a metal or glass chamber, the air inside of the chamber will eventually achieve a certain RH. The desired values of RH that different salt solutions form with air, that are also used in this test, have been determined by comparing results from total of 1106 individual measurements. (Omega Engineering Inc., 2019 a)

The results of the calibration were positive. All the sensors managed to reach a wanted level with a margin of 1,3 %. This was acceptable level considering that the tolerance of the sensors was ± 3.0 %. There was the possibility to scale the RH readings of the sensors to match each other based on this test, but considering the results from relative calibration, it seemed unwise to do so. This is because there was no certainty that if the sensors are scaled to match each other at 75 %, they still might not show same results when the RH level is different. So, the sensors were let to be as they were.

3.4.3 Temperature calibration

A separate temperature calibration was skipped in this study because of the difficulty of it and because the results gained from relative calibration. Normally, temperature calibration is done by dipping sensors in water with temperature of 0 °C or 100 °C (Earl, 2019, p. 6). However, EI1050-sensors cannot endure straight contact with water, which made this calibration method challenging.

Another possible calibration method was to compare sensors' readings to even more accurate sensor (Earl, 2019, p. 6). This kind of a sensor was not available, and to acquire a sensor more accurate than EI1050, would it need to be a laboratory level sensor. Acquiring this kind of sensor would have been very expensive. Also, when looking at relative calibration results, maximum range of the temperature calibration results was 0,04 °C. Because of these two facts the sensors were deemed to be precise enough for this study when considering temperature accuracy.

3.5 Positions of sensors

When comparing our test equipment to the IEC 60068-3-6 standard, the basic principle was like in it, but there were some differences. The position of the sensors can be seen in Figure 13. One difference from the standard was that one sensor was outside of the chamber, so that a clear understanding of ambient temperature and RH of the room was acquired. If this is bypassed, test results might be invalidated because the exterior temperatures can sometimes significantly influence interior performance (Vaisala, 2011). (Finnish Standards Association SFS, 2018, p. 10)

After a couple of temperature change rate tests, Sensor 9 started to malfunction, so it was replaced with Sensor 4, which was outside the chamber originally. Analogue thermometer and analogue RH-meter were set outside to substitute Sensor 4.

Also, the standard suggested that RH would only be measured from the middle of the chamber, and using the 8 temp. sensors in the corners, RH could be calculated with wet and dry bulb method (Finnish Standards Association SFS, 2018, pp. 10,11). As our sensors measured both RH and temperature, so in this thesis study both RH and temperature were measured from all measurement points.

It is also wise to study irregularities of the mapping space. If the mapping space has heat sources, air inlets or outlets, or theoretical gradients for example temperature difference between top and bottom of the chamber, it would be wise to add sensors near these irregularities. These factors become more critical with big mapping areas like warehouses. (Rotronic, 2019 b)

In the case of this study, mapping area is relatively small, and the air inside is somewhat homogeneous because of the mechanical air circulation system. Of course, the air inside the cabinet circulates, so there is also inlet and outlet for air. But the sensors near the back wall of the chamber were near inlet and outlet, so no extra sensors were needed.

To get the placement of sensors as presented in Figure 13, the chamber's racks were utilized. Eight holes from the rack were selected to be enlargened so that the probes can fit through. The selected holes were the ones that were nearest when considering preferred dimensions on the standard IEC-60068-3-6. In our case, this meant to position sensors 60 mm from the side wall, 85 mm from the top or bottom of the wall, depending on the sensor's position in the chamber, and finally 80 mm from the front or back wall depending on the sensor's position in the chamber (Finnish Standards Association SFS, 2018, p. 10). To fix the sensors to a preferred height, cable ties were used. The sensor in the middle of the chamber was also fixed with a cable tie. Before fastening other sensors, they were numbered as Sensors 0-9, so they would be easier to track. The sensors' numbers are also presented in Figure 13.

FIGURE 13. Location of RH/temperature sensors in this thesis study

4 RESULTS AND DISCUSSION

4.1 Operating range

The minimums and maximums of temperature and RH were studied on Tests 1 and 2. During these tests, ambient temperature and RH in the room where the tests were conducted stayed relatively same (24-26 °C and 30-40 %), so environmental quantities of the testing room had relatively small effect to test results. Therefore, there is no compensation on test results regarding this fact.

4.1.1 Temperature

The test was conducted as presented in part one of the Chapter 3.2.1. The sensors' maximum measurement temperature was +123,8 °C and the maximum temperature of the chamber was +130 °C. This test's maximum temperature was +120 °C, because temperatures higher of this will most certainly never be used and the cables' promised maximum temperature of +80 °C was taken into consideration here. All the sensors got in the desired value. The sensors' average was 121,3 °C after 15 minutes from the start of the static step in the test (the desired value was 120 °C). So, it seems difficult for the chamber to hold a high temperature value at a static state, but a longer test would be needed to confirm this assumption. What can be said based on this test is that a chamber is capable to produce temperatures higher than 120 °C, which was to be expected based on the fact that the maximum temperature of the chamber was promised to be 130 °C.

The minimum temperature achieved in this test with all six cycles was about - 19,5 °C (desired value being - 20 °C). With an error of 0,5 °C at a static state and considering the sensors' tolerance of ± 0,4 °C, the promised minimum temperature of - 20 °C can be achieved relatively well. Although the error was the same in all cycles, it would be more likely that the chamber does not go as low in temperature as promised.

The maximum change rates that were achieved in the cycle f) of Test 1 were 7,0 °C/min when warming and 2,6 °C/min when cooling. These values, however, are momentary, and in reality, if we examine areas from the cycle where temperature changes linearly, average change rates are about 5,8 °C/min when warming and 1,8 °C/min when cooling. When the temperature changes, temperature change rate does not change linearly at the beginning and in the end of the change step, as can be seen in Figure 14. This happens because of the working principle of PID-controller in the end of the linear part and because of the warming system at the beginning. At the end, as the set temperature starts to be close, PID-controller starts to slow down the change rate to get to the desired level. In addition, in the beginning, the warming system has a 1-2 minutes long delay before the maximum heating capacity is reached.

4.1.2 Humidity

The Test was conducted as presented in part two of the Chapter 3.2.2. The maximum RH of 98 % was not achieved. The maximum RH that was achieved was 95,95 % and in all six cycles the maximum RH was between 95-96 % (average of the sensors' readings at certain time). Sensors have tolerance of ± 3.0 %, so it is possible that 98 % RH was really achieved. But this is certainly unlikely considering that the error was in all cycles 2-3 % and the error stayed the same for 15 minutes after chamber had achieved equilibrium. It is more likely that the chamber's maximum RH is 95-96 %, at least at 70 °C which was the testing temperature in this test.

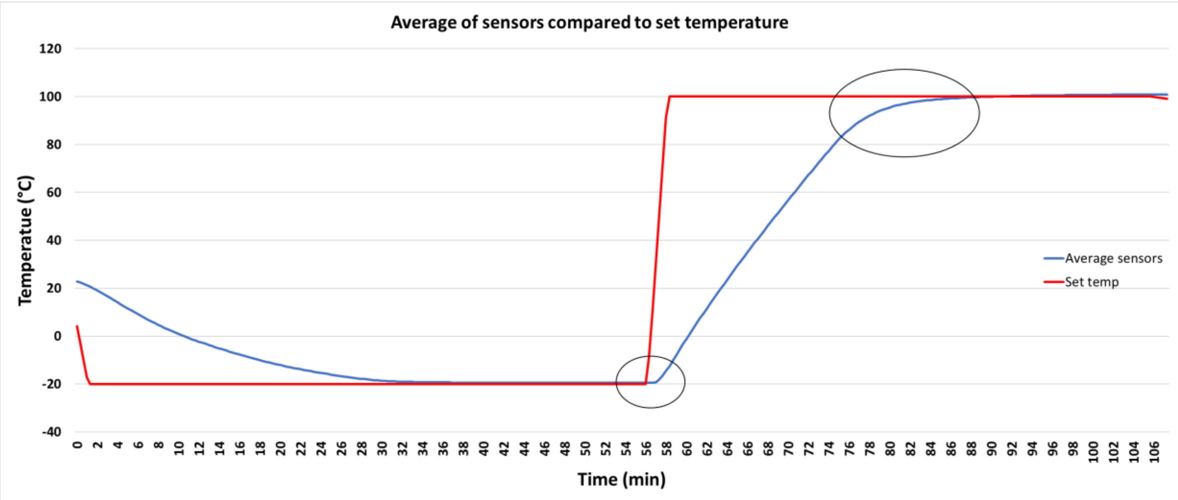

FIGURE 14. Average of sensors temperature compared to set temperature in cycle f) of test 1. Also, nonlinear parts of the dynamic increasing area of the cycle are circled.

The minimum RH that the manufacturer had promised to be accurately controllable was 20 %. During test cycles, it turned out that the chamber had difficulties keeping the desired 20 % of RH. In all cycles, first the testing chamber dropped the RH too low, as can be seen in Figure 15, and it had to do a correction to fix this error. The RH also seems to oscillate between 17 and 22 %. Promised stability for RH was 2 %, so the oscillation exceeds this promised value. But desired 20 % of RH was achieved even though there was oscillation. It seems that oscillation would happen again with the same time interval, but this doesn't appear in Figure 15 because a test step where RH rises to 98 % starts simultaneously with possible starting point of oscillation. In Test 3. more information from RH was achieved and this information is presented in Chapters 4.2 and 4.3.

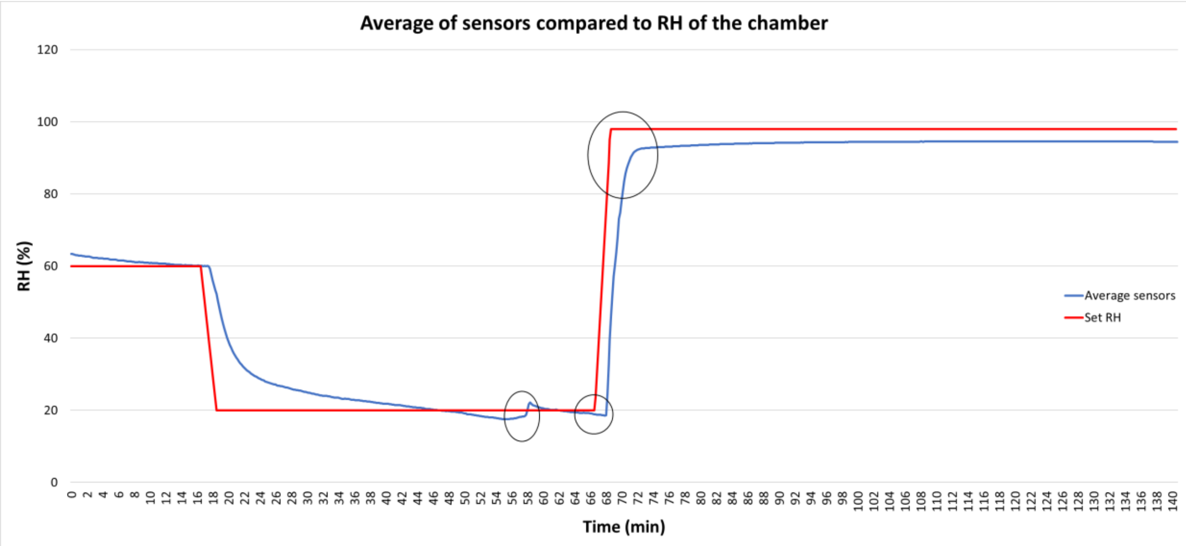

FIGURE 15. Average of sensors RH compared to set RH in cycle f) of test 2. Also, non-linear parts of the dynamic increasing area and oscillating area of the cycle are circled

The maximum change rates that were achieved in the cycle f) of Test 2 were 49 %/min during increasing step and 11,4 %/min during decreasing step. These values, however, are momentary, and in reality, if we examine areas from the cycle where RH changes linearly, average change rates were about 32,7 %/min during the increasing step and 7,6 %/min during the decreasing step. The change steps can be seen in Figure 15. At the beginning of the dynamic increasing step, RH behaves almost the same way as the temperature (change is sharper at the beginning) but at the end of this step, there really isn't as clear effect from the PID-controller as in the case of temperatures. The delay at the beginning is the same, 1-2 minutes, just like in the case of temperature.

4.1.3 Dew formation on Test 3.

In steps e) with set RH of 98 % and set temperature of 25 °C, and f) with set RH of 95 % and set temperature of 20 °C on Test 3., RH readings were over 100 %. Based on sensors' manufacturer, if RH readings are over 99 %, this means that air is fully saturated (Sensirion, 2011, p. 8). Of course, RH can't really be over 100 % because it is relative quantity. But because of the sensor's working principle, readings over 100 % are possible. These readings over 100 % are certainly interesting, and the question is: which one is wrong here, sensors or the chamber. RH readings over 100 % were acquired from all test cycles, so it would seem unlikely that the sensors would be the faulty one. And the fact that manufacturer of the chamber has stated that these tested temperature and RH combinations on test steps e) and f) are limit values of the chamber's accurate control area, could that mean that the chamber is indeed the faulty one here. If the RH indeed was 100 %, this would mean that dew point would have been reached and dew would have been formed in the chamber. To confirm this, a test where steps from d) to f) were run again and this time test period was shoot with Go-Pro Hero + -camera, so if dew would actually form, this should appear on photos.

The test results were like they were in the cycle tests and they can be seen in Figure 16. The RH and temperature had same kind of errors as previously. The thing that was needed to confirm in this test was if the RH really goes over 100 %. And according to sensors it did. This means that the chamber really can't keep the RH at 98 %, with certain combinations with temperature. In Figure 17 there is an example of how the dew has been formed to the chamber during the period when RH was over 100 % according to sensors. This example picture is from when the RH has been at over 100 % more than an hour. The chamber's inner structure should have been at the same temperature as the air inside. The dew formation shouldn't have happened because of the temperature difference, rather because of the air's RH has really been at 100 %.

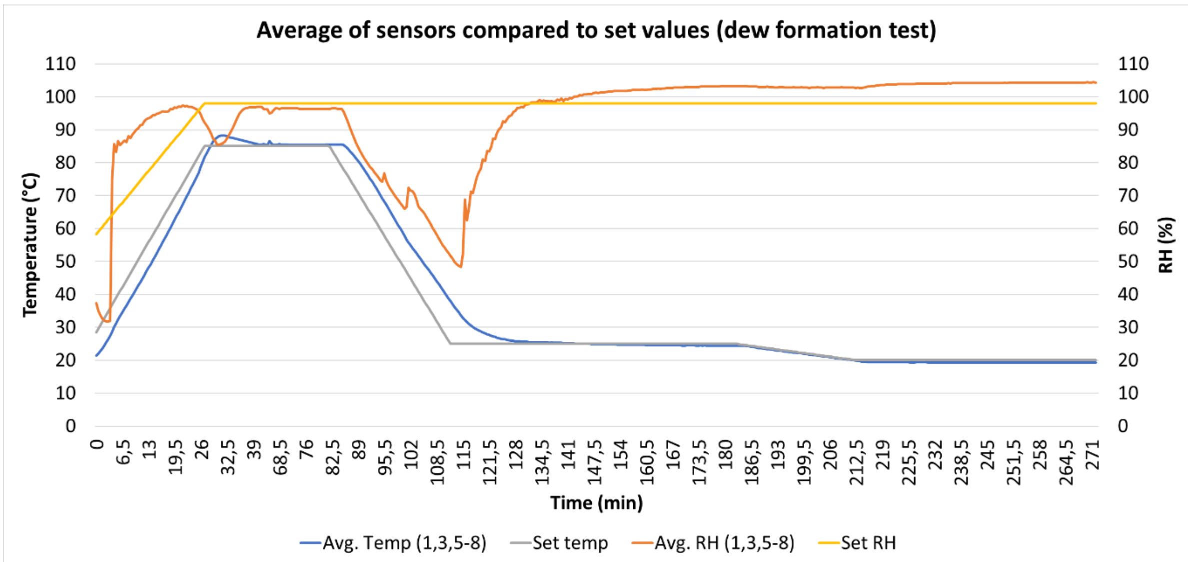

FIGURE 16. Results from dew formation test

FIGURE 17. Dew formed at the circled areas in the chamber's back wall and at the bottom of the chamber

4.2 Static accuracy

Setting accuracy was studied by scrutinising static temperature and RH steps in different parts of the test cycle in Test 3. The test cycle and parts wherefrom static values were studied can be seen in Figure 18. When the results of the Test 3 were processed, it appeared that a delay of 2,5-3 minutes had been formed during the cycle 2 of the test. This delay was deemed to be an error in the chamber's logging data, since the both set values and the chamber's own temperature sensor showed that there was nothing irregular. But still, the test sensors' readings started to change, which means that the chamber had started its next step too early. This delay was taken into consideration when the test results were analysed. Analysed time periods are from the end of the set steps, and their start point is at the area of the step when results have reached a somewhat static state. The Test 3 was conducted mistakenly at one point of the cycle. When temperature was set to 20 °C, RH should have been 95 % instead of the mistakenly used 98 %.

In Figure 19 there is an example from Test 3's results. The most notable deviations in the test results are the delays at the end of the dynamic steps, RH peaked at the first step of the cycle at 40 % RH and oscillation at 20 % RH and at 98 %.

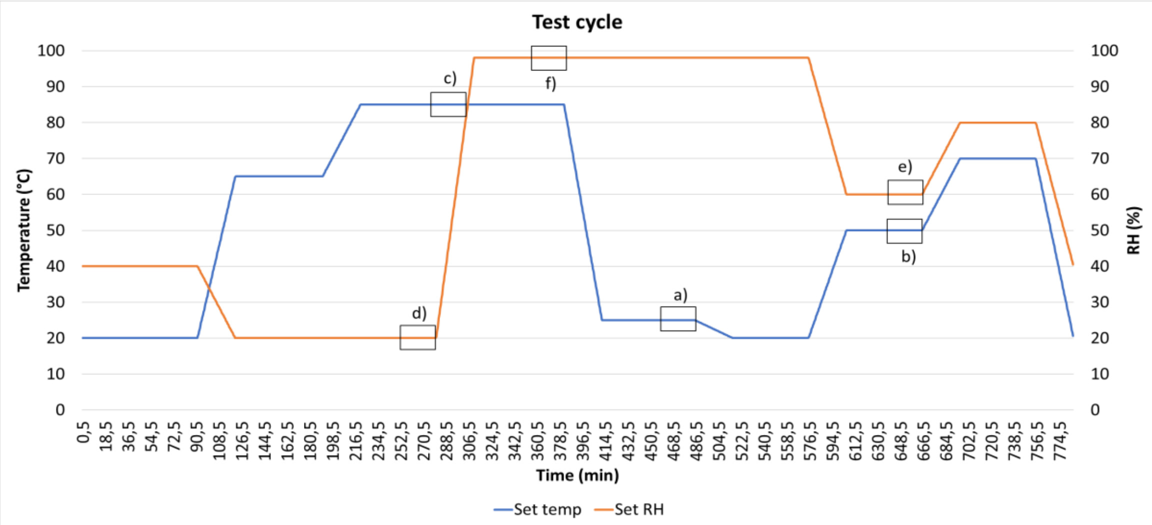

FIGURE 18. Test cycle used in test 3, and Cases a) – e) wherefrom static temperature and static RH were studied

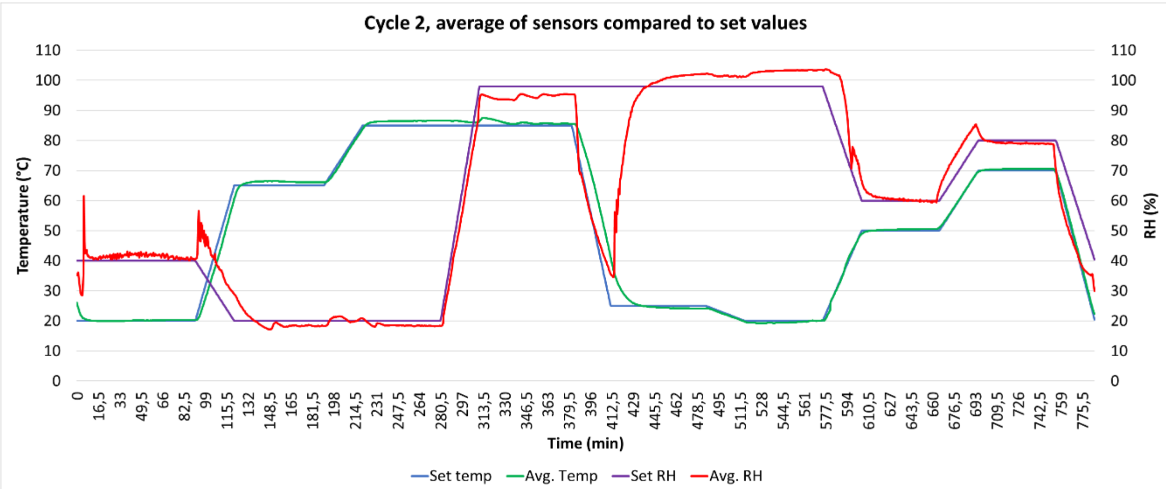

FIGURE 19. Example cycle from test 3 results

4.2.1 Temperature observations

The overall temperature error was at a very reasonable level. During all static steps in test 3, 91 % of the results were at a range of [0; 2,0]. A distribution of these static errors can be seen in Figure 20. In the following paragraphs, three temperature cases from Test 3 are studied more accurately. These cases were chosen so that one low, one high and one average temperature were studied.

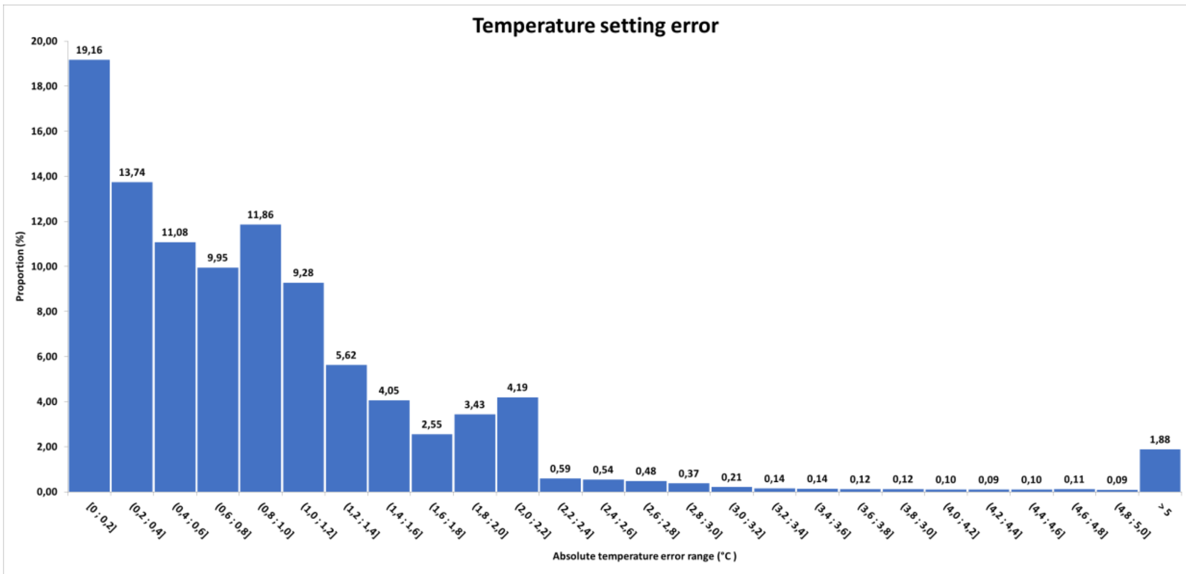

FIGURE 20. Absolute temperature setting error in test 3

The first part from where test results were studied was a period when temperature was 25 °C. The test results from this can be seen in Figure 21. This period is named Case a). One point presents average of a single sensor's values at the given time period at a specified cycle. Also, minimum and maximum values wherefrom averages are calculated are presented (this marking principle is also used at the rest of the static temperature and RH cases). An error between the set temperature and the sensors' cycle average was 0,86 °C. The biggest error was in Sensor 1 with an average error of 2,04 °C, and the minimum error was in Sensor 4 with an average error of 0,09 °C. It seems that the temperature has achieved a relatively static state since the maximum range between a single sensor's readings during stated period is 0,27 °C and most of the sensors have even a lower range. In addition, the cycles seem to be relatively identical since the range between readings averages in different cycles is 0,027 °C.

In Figure 22, all the errors between the set and measured temperature, when the set temperature was 25 °C, are presented. There is a relatively big variance in measured values. The largest number of results have an error of (-1,1; -0,9] with a proportion of 27,36 %. We can also see here that basically all measured values are smaller than the set value.

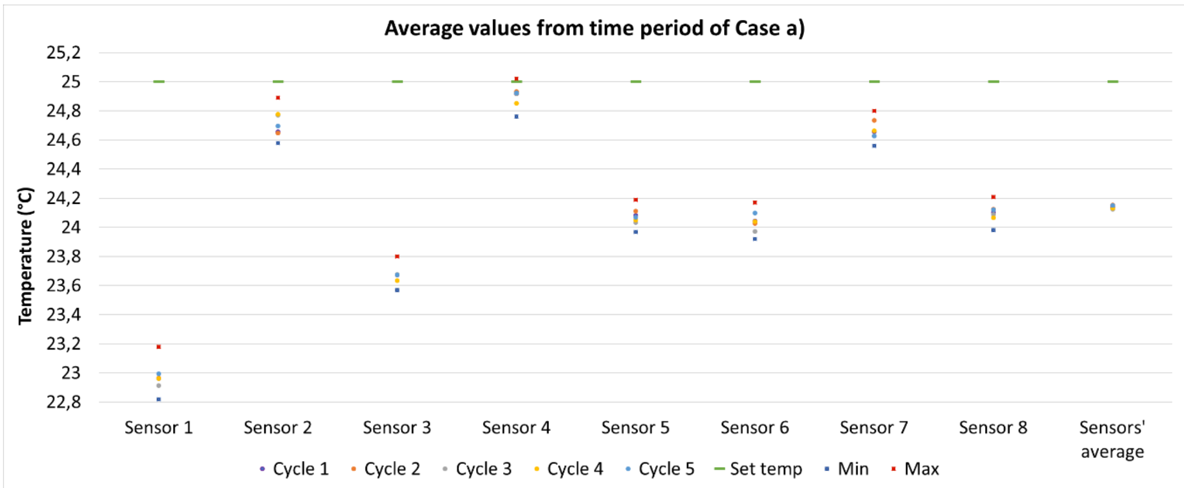

FIGURE 21. Averages from sensors' temperature readings in all cycles from time period of Case a)

The second scrutinised period was when temperature was at 50 °C, and it is called Case b). Its results are presented in Figure 23. An error between the set temperature and the sensors' cycle average was 0,51 °C. The maximum error was in Sensor 4 with an average error of 1,15 °C, and the smallest error was in Sensor 3 with an average error of 0,13 °C. The average error of sensors from the set value was 0,51 °C. The maximum range between single sensor's readings during the stated period is 0,19 °C, but again in most of the cases, the range is much smaller. Also, cycles seem to be relatively identical, since the range between readings' averages in different cycles is 0,067 °C. Based on this, the temperature on this time period is also relatively static.

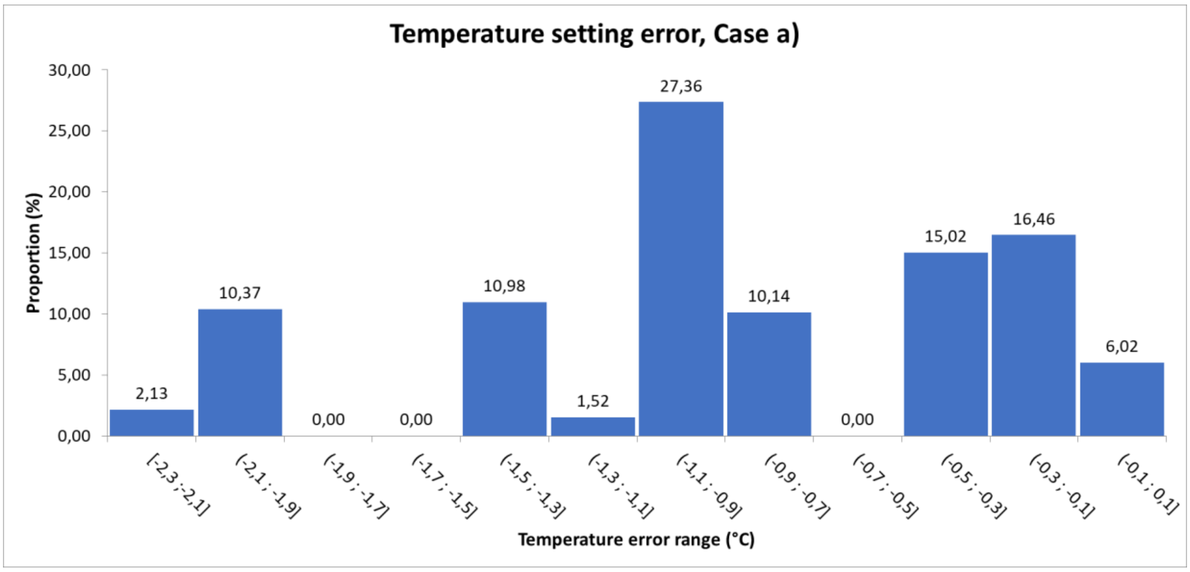

FIGURE 22. Temperature setting error at Case a)

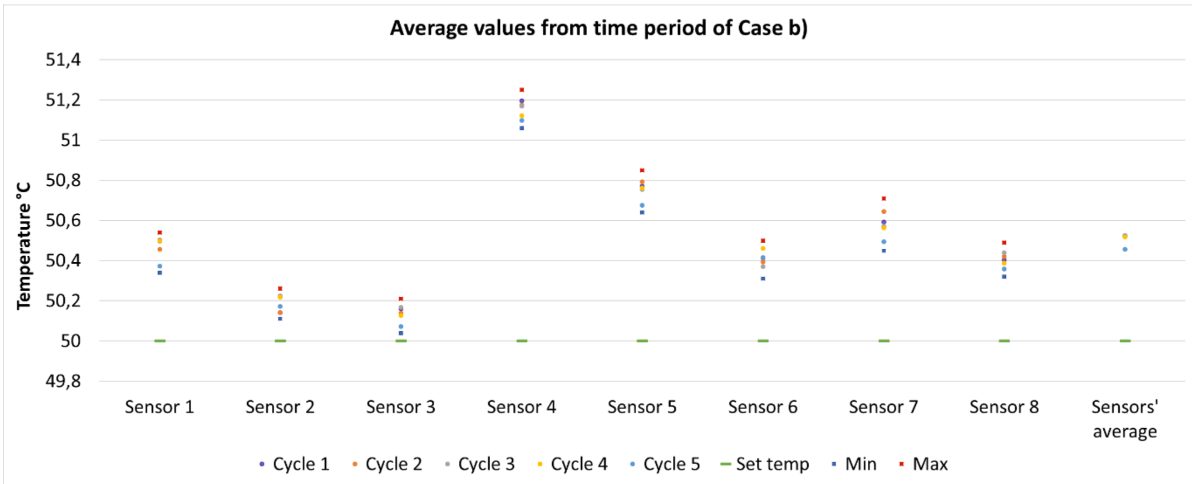

FIGURE 23. Averages from sensors' temperature readings in all cycles from time period of Case b)

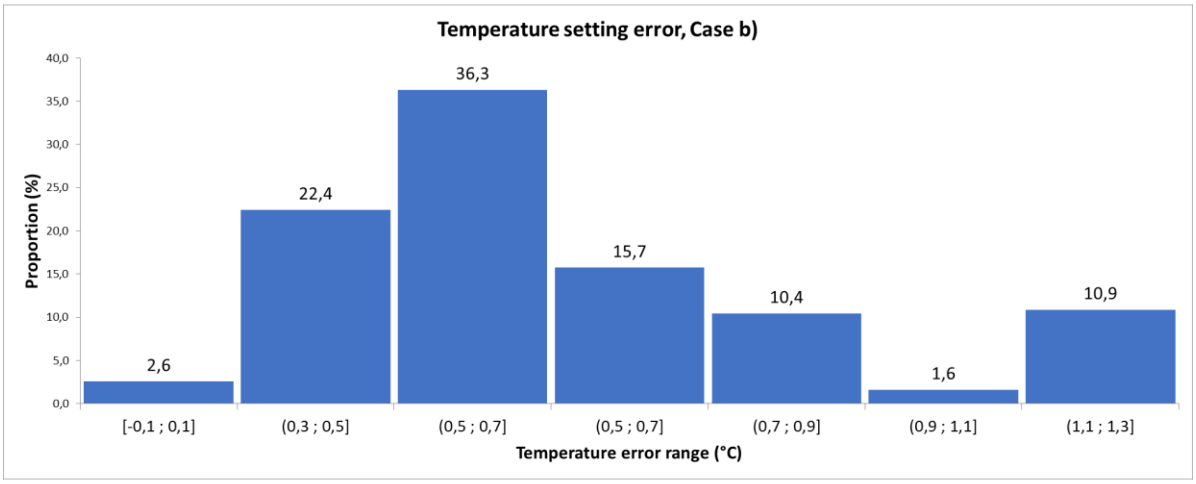

FIGURE 24. Temperature setting error at Case b)

Setting error is relatively small since 87,5 % of the results have an error of 0,9 °C or smaller and all results have a maximum error of 1,3 °C, as can be seen in Figure 24. The error range with most measurement results was (0,5; 0,7] with a proportion of 36,3 %.

The last period from where the temperature was studied was at 85 °C. The test results of this can be seen in Figure 25. This period is called Case c). An error between the set temperature and the sensors' cycle average was 1,54 °C. The biggest error was in the Sensor 5 with an average error of 2,09 °C and the minimum error was in Sensor 2 with an average error of 0,89 °C. The maximum range between a single sensor's readings during the stated period is 0,20 °C but still in most of the cases the range is even smaller. Also, the cycles seem to be relatively identical since the range between readings' averages in different cycles is 0,032 °C. Based on this, the temperature on this time period is also relatively static.

All the measurement results were in this case larger than the set temperature. The measurement results were at a range of [0,7; 2,3], and the results have scattered quite a lot in this range. The results from this test period can be seen in Figure 26. The largest single range of error was at (1,9; 2,1] with a portion of 26,08 %.

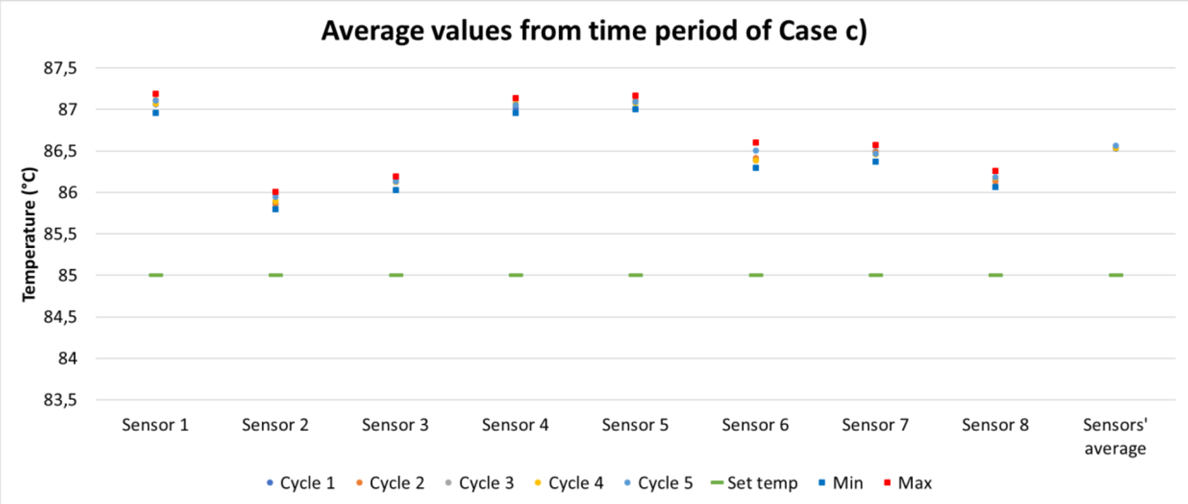

FIGURE 25. Averages from sensors' temperature readings in all cycles from time period of Case c)

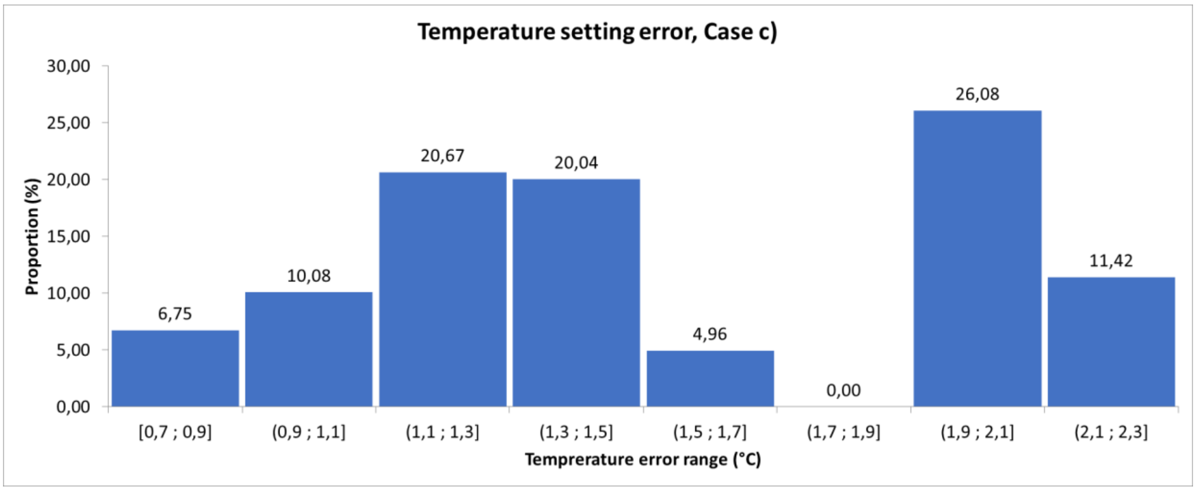

FIGURE 26. Temperature setting error at Case c)

4.2.2 Humidity observations

The overall RH setting error is presented in Figure 27. RH error with respect to the temperature's setting error is much larger and it is distributed at a wider range since 5,3 % of the RH results have an error 10 or higher. Still 93 % of the results are in the range of [0;6,5]. In the following paragraphs, three RH cases are studied more accurately in the same way as the temperature.

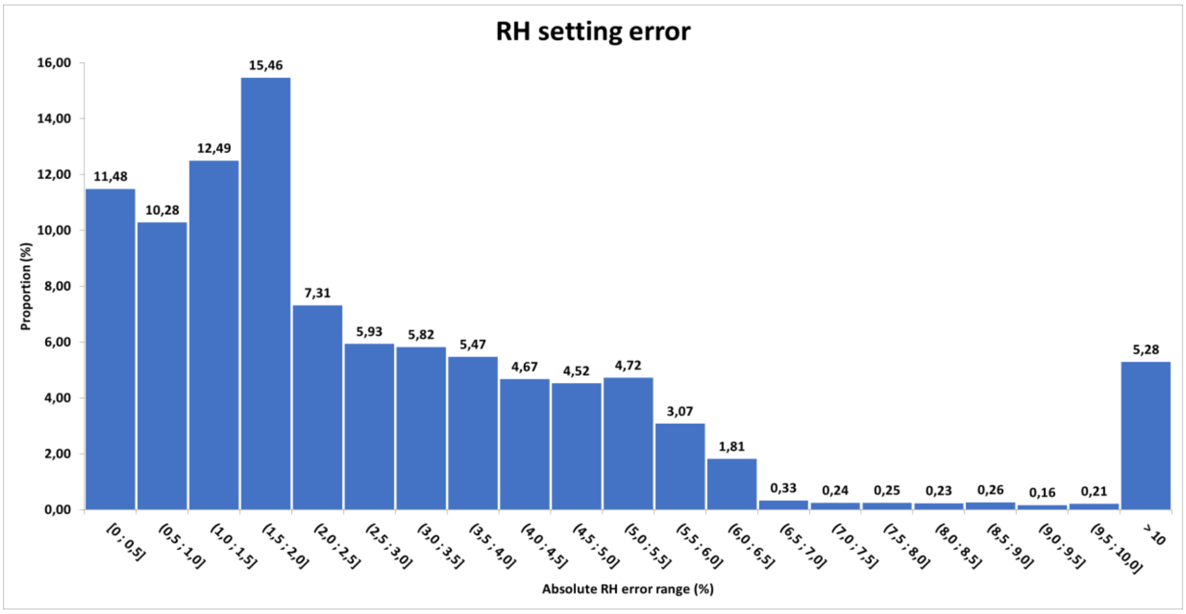

FIGURE 27. Absolute RH setting error in test 3.

The first period wherefrom the RH was studied was when the set RH was 20 %. The Results from this can be seen in Figure 28. This period is called Case d). This period's results are relatively similar, but if the largest and the smallest error from sensors is taken, Sensor 4 has the largest average error of 1,92 % and Sensor 7 has the smallest average error of 0,60 %. The average error of sensors from the set value was 1,57 %. The range between cycle averages is 0,71 %, so there is a much larger difference between cycles than in the temperature cycles. Furthermore, the maximum range between single sensors readings at a specified time period was 0,73 %, which is also much larger than in the temperature cases. The range between readings' averages in different cycles is 0,12 %, which tells us that the cycles have been relatively similar.

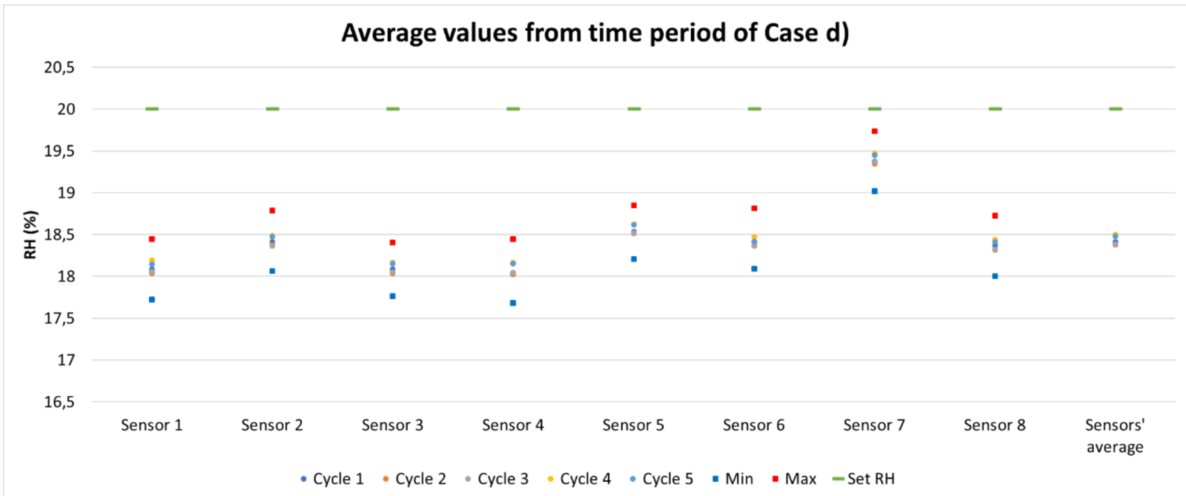

FIGURE 28. Averages from sensors' temperature readings in all cycles from time period of Case d)

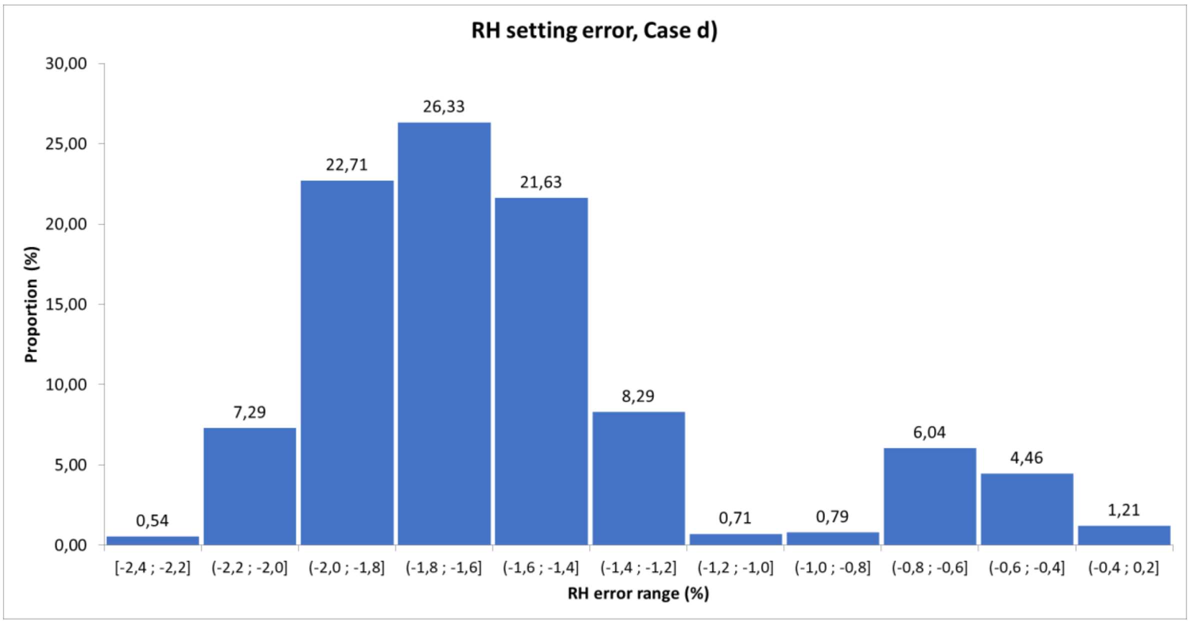

FIGURE 29. RH setting error at Case d)

The setting error can be seen in Figure 29, and the errors divided at the range of [-2,4; 0,2]. So, almost all results were under the set value. 86,25 % of these results were at the range of (-2,2; -1,2]. This means there has been a relatively large setting error during this period. The single largest error range was (-1,8; -1,6] with a proportion of 26,33 %.

The second part where the RH static step results were studied was the period called Case e). RH was 60 % during this period. The results can be seen in Figure 30. An error between the set temperature and the sensors' cycle average was only 0,14 %, which is mostly a result of both negative and positive errors between the measured and the set values. The maximum error over the set value was on Sensor 2, with an average error of 1,77 %. The maximum error under the set value was on sensor 4 with an average error of 1,16 %. The minimum error was in Sensor 8 with an average error of 0,09 %. Also, when looking at the test results in Figure 30, there are bigger differences between results in different cycles than in the temperature cases. This was also the case in the first analysed period. Especially Sensor 2 has a big difference in its results with a maximum error of 1,06 % between cycles 2 and 5. The maximum range between a single sensor's readings during the stated period is 1,09 %. The difference between cycles is a little bigger than in the first period since the range between readings averages is 0,55 %.

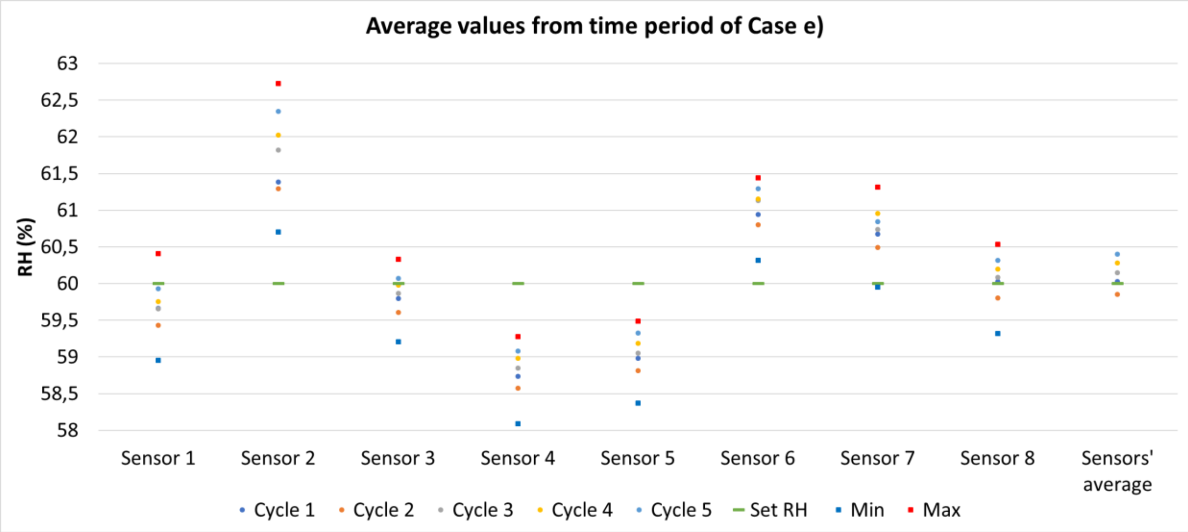

FIGURE 30. Averages from sensors' temperature readings in all cycles from time period of Case e)

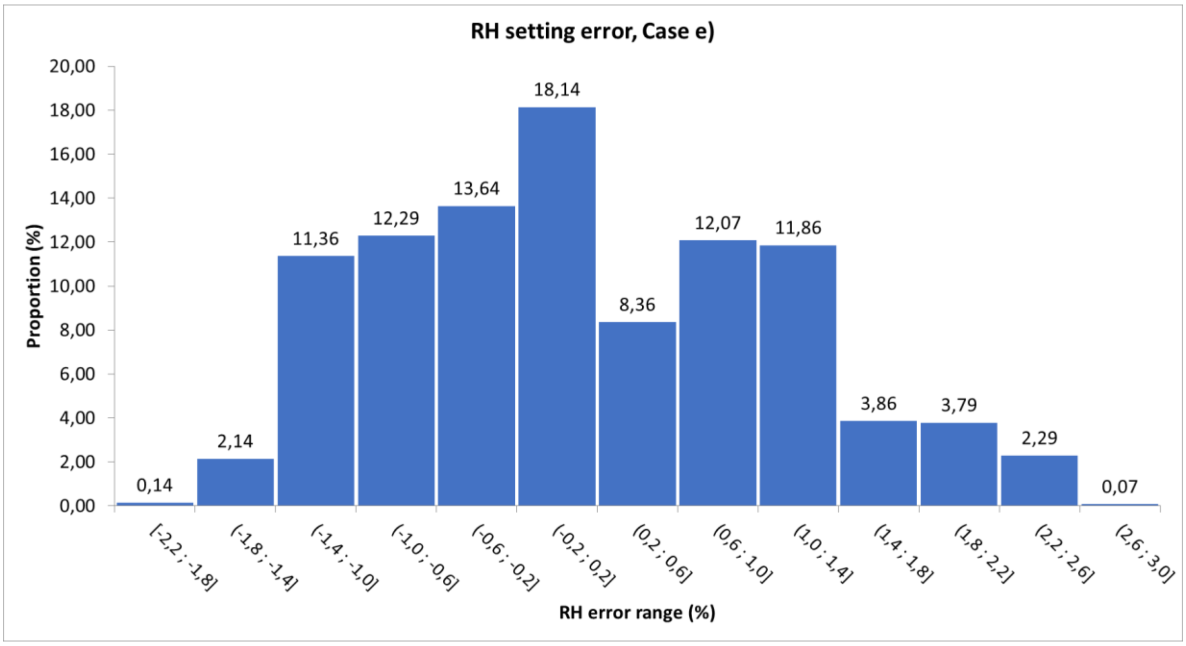

FIGURE 31. RH setting error at Case e)

The setting error can be seen in Figure 31. Some of the RH readings are over and some are under the set RH in this case. This is the only period when the RH has divided relatively evenly around the set point. But the error range is also the biggest one here, as it is at [-2,2; 3,0]. Even still 87,7 % of the results are in a range of (-1,4; 1,4] and the range with most results was (-0,2; 0,2] with a proportion of 18,14 %. This tells us that the setting accuracy has been at the right level, but the RH has oscillated relatively much.

The final time period from where RH readings were scrutinised was when RH was 98 %. This period was called Case f). The results are shown in Figure 32. All readings are under the set RH in this case. Again, Sensor 2 seems to have the biggest error between cycles as in the second analysed part with an error of 1,20 % between cycle 1 and 5. The average error of sensors from the set values was 2,58 %. The maximum error from the set value was in Sensor 4, with an average error of 3,68 %. The minimum error was on Sensor 2, with an average error of 1,27 %. The maximum range between a single sensor's readings during the stated period is only 0,41 %. The similarity of the cycles is fine compared to the other two periods, as the range between the readings' averages is 0,33 %.

The setting error can be seen in Figure 33. A single largest range of measurements' errors is in a range of (-2,6; -2,4] with a proportion of 15,24 %. The results are very scattered during this test period since an overall range is [-4,0; -0,4]. Even though 90,48 % of the results are at a range of (-3,8; -1,4].

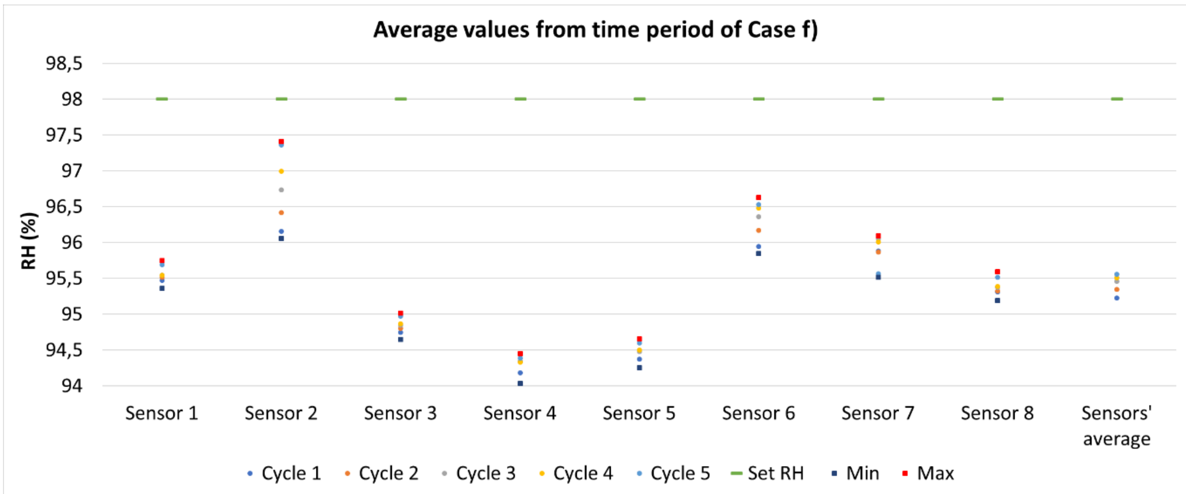

FIGURE 32. Averages from sensors' temperature readings in all cycles from time period of Case f)

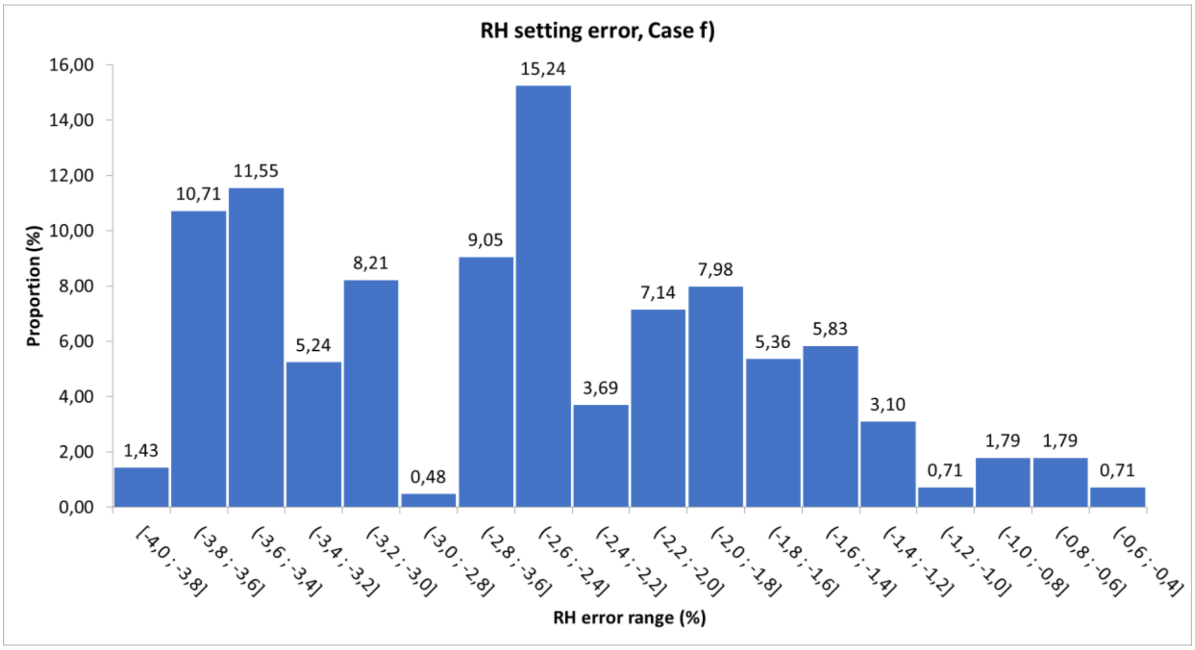

FIGURE 33. RH setting error at 98 %

4.2.3 Conclusions

The results gained from static accuracy tests are collected into the Table 3.

TABLE 3. Static accuracy results

	Case a)	Case b)	Case c)	Case d)	Case e)	Case f)
Max average error in a single sensor from the set value (°C or %)	-2,04 (Sensor 1)	1,15 (Sensor 4)	-2,09 (Sensor 5)	1,92 (Sensor 4)	1,77 (Sensor 2)	-3,68 (Sensor 4)
Min average error in a single sensor from the set value (°C or %)	-0,09 (Sensor 4)	0,13 (Sensor 3)	-0,89 (Sensor 2)	0,6 (Sensor 7)	0,09 (Sensor 8)	-1,27 (Sensor 2)
Difference between Min and Max average error (°C or %)	1,95	1,02	1,2	1,83	1,68	2,41
Average error of sensors from the set value (°C or %)	-0,86	0,51	1,54	-1,57	0,14	-2,58
Range between readings averages in different cycles (°C or %)	0,027	0,067	0,032	0,12	0,55	0,33
Max range between a single sensor's readings (°C or %)	0,27	0,19	0,20	0,73	1,09	0,41
Error range with the most measurement results (°C or %)	(-1,1; -0,9]	(0,5; 0,7]	(1,9; 2,1]	(-1,8; -1,6]	(-0,2; 0,2]	(-2,6; -2,4]

When looking how temperature and RH vary in the different locations of the chamber, there really is not a clear pattern. All the results are from the end of the static steps, so the climate conditions inside the chamber should have been relatively close to that of an equilibrium. In the case of the temperature, the best and the worst sensor varies. But the best positions seem to be where sensors 2 and 3 are in the test setup. As can be seen in Figure 13, these locations are in the right top back corner and the left top front corner. Sensor 2 is right next to the chamber's own temperature sensor so this could be one explanation why its readings are so close to the set values. But this does not explain why position of the Sensor 3 is one of the best locations considering temperature.

In addition, when looking at the worst places regarding temperature, spots where Sensors 1, 4 and 5 are, seem to be the worst. One reason for why an error is so big in Sensor 1 might be that it is very close to the inlet vent. Then again, so is Sensor 2, which is one of the best spots when regarding temperature. Also, the fact that the position of Sensor 5 in the middle of the chamber is one of the worst, is really bizarre. This is due to the fact that there should be the least irregular temperature factors in the middle. For example, there are no air inlets or outlets near this spot and the walls of the chamber are at the farthest distance from this spot, so they should not affect the middle sensor. Overall, it would seem based on the test results that the temperature is closer to the set values at the top of the chamber than in the bottom.

The average of the sensors from the set value are: 0,86 °C in Cases a) and c), and 0,51 °C in Case b). The given tolerance, for the stability of the chamber temperature, was ± 0,5 °C by the manufacturer. This means that the test results should have been in a range of ± 0,5 °C from the set value. An average of Case b) is relatively close to the tolerance but the averages of Cases a) and c) are much higher than the set value. Also, as the largest temperature error group of the results is (1,9; 2,1], could this also implicate that the stability tolerance is too low. Based on these facts, the setting error for the temperature in the chamber is more than the manufacturer has promised.

The temperature uniformity tolerance was 2 °C by the manufacturer, which means that the temperature readings from the sensors should have been inside the range of 2 °C. When looking at the differences between the minimum and the maximum average errors, all of them are under this uniformity tolerance. Also, the cycles seem to be relatively identical, since the ranges between the readings averages in different cycles are all smaller than 0,067 °C. In addition, the static step has indeed been relatively static, based on the maximum range between a single sensor's readings, which all are smaller than 0,27 °C.

When compared to specifications of MIL-STD 810 shown in Table 1, temperature is easily under its temperature tolerance of ± 2 °C. In addition, when compared to static temperature tolerances in the IEC 60068-2-30 standard, which is presented in Figure 1, the averages of the measurements are easily under the tolerances ± 2 °C and ± 3 °C in all static Cases. In Cases a) and c) the maximum single errors slightly exceed the tolerance but as the averages are easily under the tolerance, it can be stated that the environmental testing chamber BGD 897/408B fulfils temperature tolerances of the standards MIL-STD 810 and IEC 60068-2-30.

Now, the RH case is somewhat similar regarding the sensor's position in the chamber. The best positions seem to be where Sensors 2, 7 and 8 are located. These locations can be seen again in Figure 13. Sensors 7 and 8 are at the bottom of the chamber, and in this regard, RH is different than temperature since in temperature cases top of the chamber had the smaller error. The readings of Sensor 2 are also interesting since it was one of the worst in the temperature cases. Also, the position of the Sensor 2 is the worst in RH Case e), which makes all this even more bizarre. Another worst spot seems to be the location of Sensor 4. Because this sensor is at the bottom with the best Sensors 7 and 8, a question arises: is there something wrong with Sensor 4 itself? Actually, when dew formation was retested, as explained in Chapter 4.1.3, Sensor 4 started to behave peculiarly and it was left with a static error in its readings. So, based on this fact, there might have been problems in it also during the Test 3 but this cannot be proofed from the logging data.

The RH stability tolerance was ± 2 % by the manufacturer. In all RH Cases, the average error of the sensors from the set value are inside this tolerance. Also, the largest error group in Cases d) and e) are below the tolerance. In Case f) the largest error group is over the tolerance with a range of (-2,6; -2,4]. But overall, the RH stability seems to be relatively good. The uniformity tolerance is 2-3 % when RH is below 75 % and 5 % when RH is over 75 %. When looking at the differences between the minimum and the maximum average errors, all of them are under this uniformity tolerance. The cycle difference is bigger than in temperature cases but as the readings all are smaller than 0,55 %, the level is still acceptable. The RH also seems to oscillate somewhat during a static step, since the maximum range between a single sensor's readings are smaller than 1,09 %.

The RH tolerance is ± 5 % according to the MIL-STD 810, as can be seen in the Table 1. So, even though there was an average error of -2,58 % in Case f) and the maximum error was -3,68 %, these errors still easily remain under this tolerance. In the IEC 60068-2-30 standard, the RH tolerances are stricter as can be seen in Figure 1. Set RH at static parts in the cycle of the standard is 95 % and readings are allowed to be at range of 90-96 %. So, if this tolerance is adapted into results of Test 3, all of the average errors fit this range. And if looking into the max errors of Cases d) and e), results do not fit this range. Making conclusions based on the tolerances of IEC 60068-2-30 standard is tricky since the set RH is not the same, and there is no clear explanation why the tolerance is so that the RH can be 5 % under the set value but only 1 % over the set value. But based on MIL-STD 810, RH is easily in the tolerance, and the overall operation of the environmental testing chamber BGD 897/408B is also fine when compared to IEC 60068-2-30 standard.

From Case f), we can again confirm the same result that was found in Test 2. The manufacturer's maximum promised RH of 98 % seems to be unreachable (at least at temperatures 50 and 70 °C) and the average maximum RH of the chamber seems to be close to that of 95,5 %. There were two periods in Test 3, when higher RH readings were reached. More information of this can be found in Chapter 4.1.3.

Few weeks after the tests were conducted, a check for the sensors was done. In this check, the sensors were tested the same way as in the relative calibration in Chapter 3.4.1. The results of the check were that the average maximum error of the temperature readings was 0,52 °C between Sensors 1 and 7. The average maximum error of the RH was 0,35 % and this error was between Sensors 4 and 6. Based on these check results, it can be said that the sensors were relatively identical but the errors had grown from the original calibration. So, the sensors may have added a little error factor to the results, especially for the Test 3. But since the readings still remained relatively identical, the results of the tests can be deemed to be accurate enough.

4.3 Dynamic accuracy

The rate of change accuracy was studied by looking at four dynamic parts in the Test 3. There were two RH and two temperature cases. Both the temperature and the RH were studied from two points of the cycle: first at the decreasing area and second at the increasing area. These areas can be seen in Figure 34.

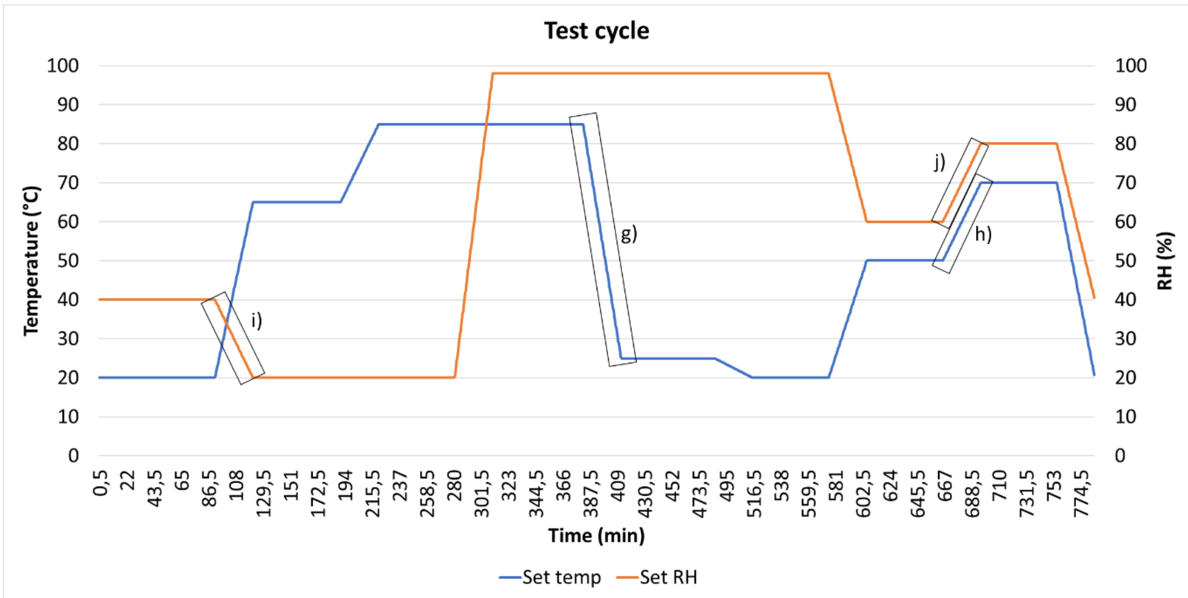

FIGURE 34. Test cycle used in test 3, and Cases g) – j) wherefrom dynamic temperature and dynamic RH were studied

4.3.1 Temperature observations

Temperature was studied in two periods in Cases g) and j). These cycles are presented in Figures 35 and 36. The delay was decided to be studied from three spots of the curve: from the middle of the dynamic part of the set value, from the point where measured values have reached 95 % of the static set value and from the point where measured values have reached 99 % of the static set value. This way, a comprehensive impression of the delay in the dynamic temperature could be achieved.

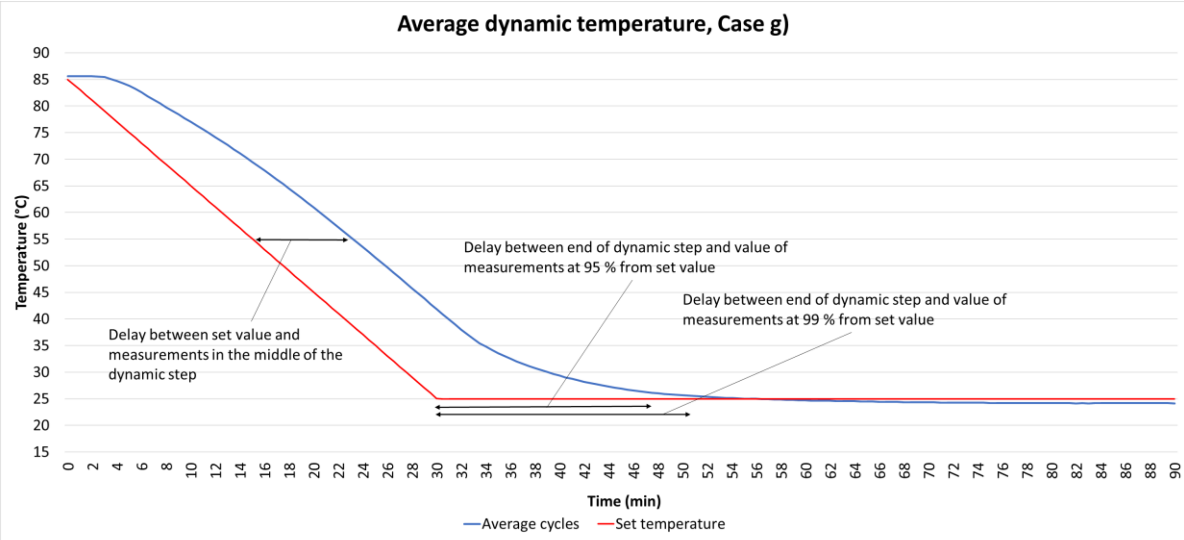

FIGURE 35. Average dynamic temperature at case g), wherefrom delays were studied

In both temperature cases there is a clear delay before the temperature starts to change in the chamber. This delay seems to be almost the same in both cases. The temperature seems to change very linearly for most of its dynamic part, but as the set values starts to approach, the change rate of the temperature seems to slow down. During end of the dynamic part, the delay seems to be larger in Case g). All the delays of these cycles are presented in the Table 4.

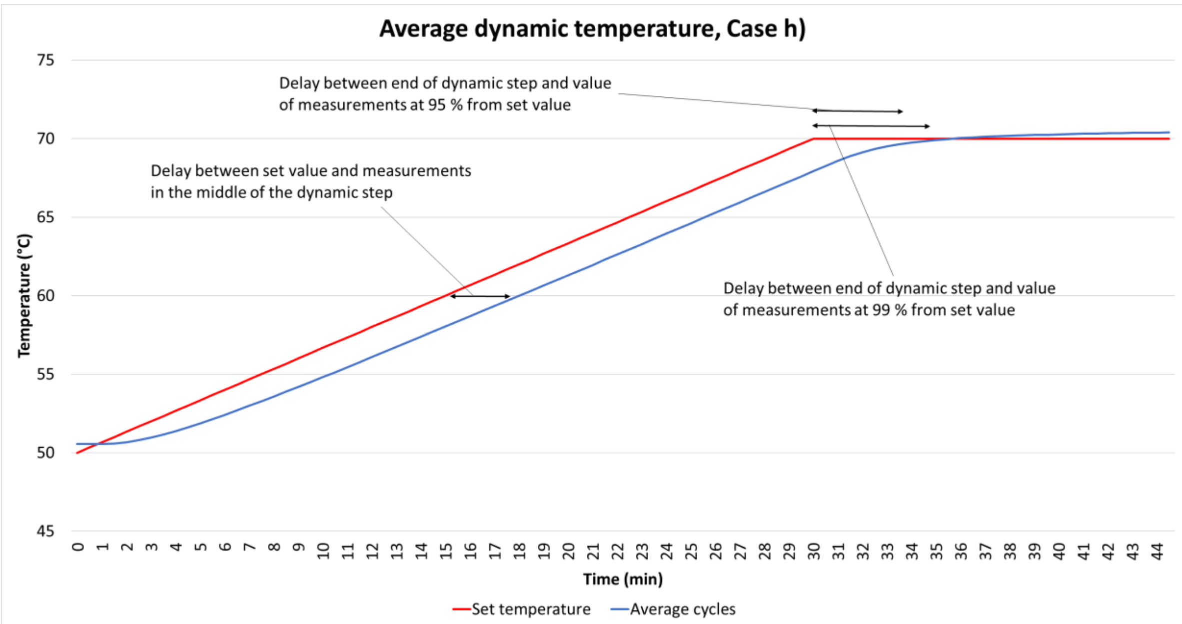

FIGURE 36. Average dynamic temperature at case h), wherefrom delays were studied

TABLE 4. Delays in minutes in Cases g) and h)

Sensor	Case g) mid delay	Case g) 95 % delay	Case g) 99 % delay	Case h) mid delay	Case h) 95 % delay	Case h) 99 % delay
Cycle 1 sensor 1	6,1	11,5	14,3	1,2	-4,2	0
Cycle 1 sensor 2	6,6	13,2	17,4	2,2	-2,9	1,4
Cycle 1 sensor 3	6,9	13,3	16,7	2,7	-2,5	1,9
Cycle 1 sensor 4	8,2	21,4	35,3	1,2	-3,5	0,7
Cycle 1 sensor 5	9,2	18,5	24,6	3,4	-1,8	2,8
Cycle 1 sensor 6	9,1	18,6	24,5	4,1	-1,1	4,3
Cycle 1 sensor 7	9,6	21,3	32,7	4,2	-1	4,2
Cycle 1 sensor 8	7,9	16,9	22,8	3,2	-2	2,7
Cycle 2 sensor 1	6,3	11,6	14,4	1,4	-3,8	0,4
Cycle 2 sensor 2	6,8	13,5	17,3	2,4	-2,7	1,7
Cycle 2 sensor 3	7,2	13,5	16,7	3	-2,2	2,5
Cycle 2 sensor 4	8,4	21,4	38	1,8	-3,2	1,1
Cycle 2 sensor 5	9,4	18,6	24,6	3,7	-1,5	3,1
Cycle 2 sensor 6	9,3	18,6	24,1	4,4	-0,7	4,8
Cycle 2 sensor 7	9,8	21,7	34,2	4,4	-0,7	4,3
Cycle 2 sensor 8	8,2	17	22,9	3,5	-1,6	3,1
Cycle 3 sensor 1	6,2	11,7	14,5	1,6	-3,8	0,5
Cycle 3 sensor 2	6,5	13,9	19,1	2,4	-2,7	1,7
Cycle 3 sensor 3	7,1	13,7	17	3,1	-2	2,5
Cycle 3 sensor 4	8,4	22,2	38,3	2,1	-3	1,2
Cycle 3 sensor 5	9,3	18,5	24,8	3,8	-1,4	3,3
Cycle 3 sensor 6	9,2	18,8	24,8	4,6	-0,6	4,8
Cycle 3 sensor 7	9,7	21,5	30,4	4,7	-0,5	4,7
Cycle 3 sensor 8	8,1	17,1	23,6	3,6	-2,7	3,2
Cycle 4 sensor 1	6,5	12,6	15,8	1,2	-4,3	0,1
Cycle 4 sensor 2	7	14,8	19,6	2,1	-3	1,3
Cycle 4 sensor 3	7,3	14,3	17,8	2,8	-2,5	2,2
Cycle 4 sensor 4	8,6	22,4	36,6	1,2	-3,4	0,9
Cycle 4 sensor 5	9,6	19,8	26,2	3,4	-1,8	2,9
Cycle 4 sensor 6	9,5	20	26	4,1	-1,1	4,3
Cycle 4 sensor 7	10	22,5	32,7	4,2	-0,9	4,3
Cycle 4 sensor 8	8,3	18,2	24,1	3,3	-2	2,9
Cycle 5 sensor 1	6,5	12,5	15,6	1,6	-3,8	0,4
Cycle 5 sensor 2	7	14,8	19,8	2,3	-2,8	1,4
Cycle 5 sensor 3	7,3	14,4	17,9	3,2	-2,2	2,5
Cycle 5 sensor 4	8,6	22,5	37,5	2,1	-3,1	1,2
Cycle 5 sensor 5	9,6	19,6	25,8	3,8	-1,4	3,4
Cycle 5 sensor 6	9,5	20	26,3	4,4	-0,8	4,5
Cycle 5 sensor 7	10,1	22,2	31,7	4,6	-0,6	4,8
Cycle 5 sensor 8	8,4	18,2	24,2	3,1	-1,6	3,2
Average	8,2	17,4	24,3	3,0	-2	2,5
Min	6,1	11,5	14,3	1,2	-4,3	0
Max	10,1	22,5	38,3	4,7	-0,5	4,8

4.3.2 RH observations

RH was also studied from two parts of the cycle of Test 3: one decreasing part and one increasing part. These parts were named as Cases i) and j), and they are presented in Figures 37 and 38. All the markings and the analysed areas in Figures are the same as in the temperature cases. However, there is an exception in Case j). The part where measurements would have achieved 99 % of the set value never happened, due to a static error of 2-3 % during the whole static step in this case.

There is a notable fluctuation in the beginning of the Case i)'s curve and the RH value climbs up to almost 55 % before it starts to decrease as the set value has instructed. There seems to be fluctuation at the static part also. The RH also dives lower than the set value has instructed and it newer truly reaches the set value. The delay in Case i) is very similar to what it was with temperature. Results from Cases i) and j) can be found in Table 5.

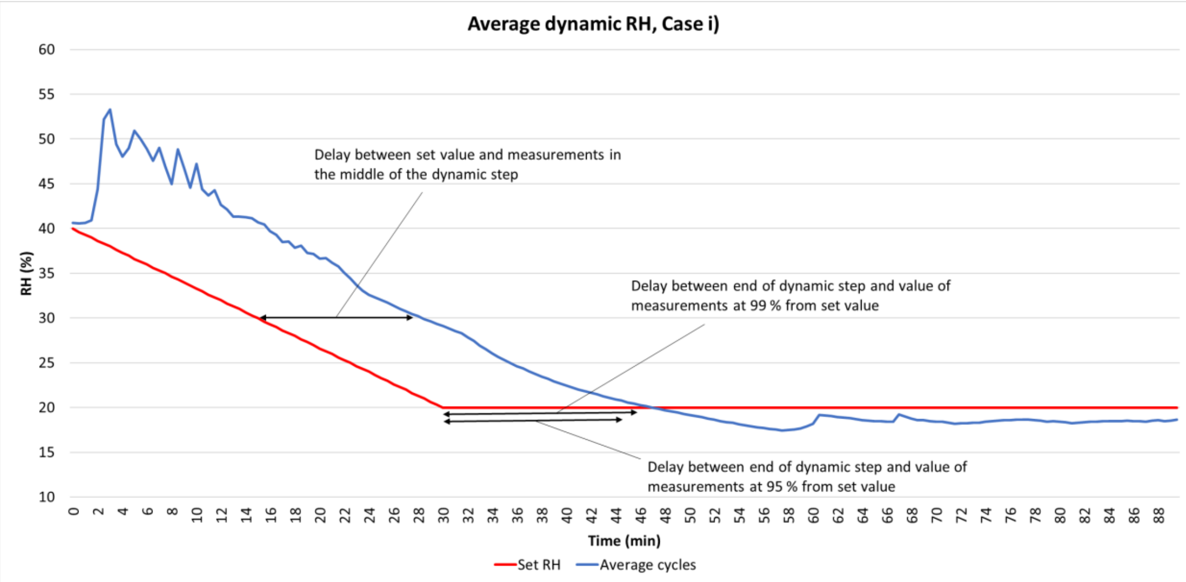

FIGURE 37. Average dynamic RH at case i), wherefrom delays were studied

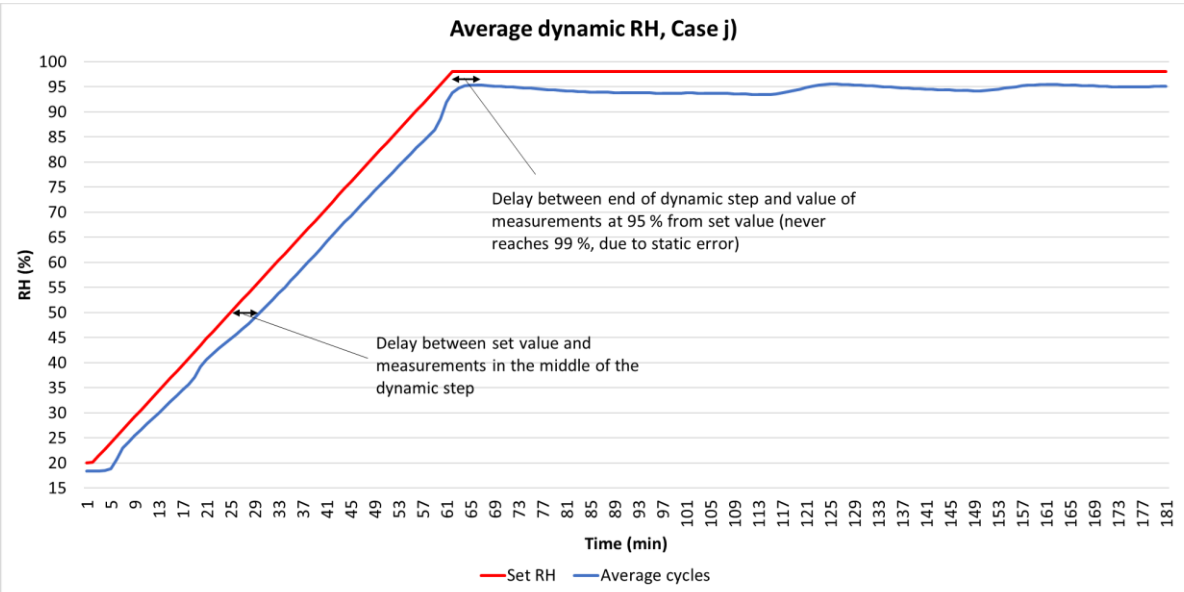

FIGURE 38. Average dynamic RH at Case j), wherefrom delays were studied

TABLE 5. Delays in minutes in cases i) and j)

Sensor	Case i) mid delay	Case i) 95 % delay	Case i) 99 % delay	Case j) mid delay	Case j) 95 % delay	Case j) 99 % delay
Cycle 1 sensor 1	7,9	14,3	18,4	3,2	0,5	Never *
Cycle 1 sensor 2	8,4	15,5	18,5	2,4	0,3	Never *
Cycle 1 sensor 3	9,5	14,3	17,9	3,2	0,8	Never *
Cycle 1 sensor 4	10	14,1	18,8	3,1	0,7	Never *
Cycle 1 sensor 5	15,2	16,7	20,2	3,3	0,8	Never *
Cycle 1 sensor 6	17,4	18,3	22,2	2,7	0,4	Never *
Cycle 1 sensor 7	18	20,3	23,9	2,1	0,5	Never *
Cycle 1 sensor 8	12,7	18,3	20,3	2,9	0,5	Never *
Cycle 2 sensor 1	7,3	10,4	13,1	2,7	0	Never *
Cycle 2 sensor 2	9,7	13,3	15,7	1,9	-0,2	Never *
Cycle 2 sensor 3	9,8	11,6	14	2,7	0,4	Never *
Cycle 2 sensor 4	11,2	12,3	14,3	2,6	0,3	Never *
Cycle 2 sensor 5	16,5	13,7	16,2	2,7	0,4	Never *
Cycle 2 sensor 6	17,7	14,8	17,4	2,2	-0,1	Never *
Cycle 2 sensor 7	18,5	16,5	19	2,1	0	Never *
Cycle 2 sensor 8	13,5	13,3	15,2	2,5	0	Never *
Cycle 3 sensor 1	7,5	10	12,4	2,9	0,4	Never *
Cycle 3 sensor 2	9,4	12,7	15,3	2	0	Never *
Cycle 3 sensor 3	9,7	10,8	13,5	3	0,6	Never *
Cycle 3 sensor 4	11,2	11,2	13,7	2,9	0,5	Never *
Cycle 3 sensor 5	16,2	13	15,5	3	0,6	Never *
Cycle 3 sensor 6	17,5	14,5	16,6	2,4	0,1	Never *
Cycle 3 sensor 7	18,3	15,8	18,4	2,3	0,4	Never *
Cycle 3 sensor 8	13,5	12,6	15,1	2,6	0,4	Never *
Cycle 4 sensor 1	7,5	9,6	11,5	2,6	0	Never *
Cycle 4 sensor 2	10,2	12,5	15,2	1,7	-0,3	Never *
Cycle 4 sensor 3	10	10,5	13	2,6	0,4	Never *
Cycle 4 sensor 4	11,2	11,1	13,4	2,5	0,3	Never *
Cycle 4 sensor 5	16,5	12,9	15,2	2,7	0,4	Never *
Cycle 4 sensor 6	17,7	14,2	16,8	2,1	-0,1	Never *
Cycle 4 sensor 7	18,4	15,8	18,3	2,1	0	Never *
Cycle 4 sensor 8	13,6	12,1	14,5	2,4	0	Never *
Cycle 5 sensor 1	7,7	10,5	12,8	2,7	0,4	Never *
Cycle 5 sensor 2	11,2	13,5	15,9	1,9	0	Never *
Cycle 5 sensor 3	10,6	11,8	13,9	2,8	0,6	Never *
Cycle 5 sensor 4	11,8	12,3	14,2	2,7	0,5	Never *
Cycle 5 sensor 5	16,8	13,5	15,7	2,8	0,7	Never *
Cycle 5 sensor 6	18	14,8	16,6	2,3	0,2	Never *
Cycle 5 sensor 7	18,7	16	18,2	2,3	0,4	Never *
Cycle 5 sensor 8	14	13	15	2,6	0,4	Never *
Average	13,0	13,6	16,1	2,6	0	Never *
Min	7,3	9,6	11,5	1,7	-0,3	Never *
Max	18,7	20,3	23,9	3,3	0,8	Never *

* RH never reaches 99 % during Case j), due to static error

4.3.3 Conclusions

The temperature delay in Case g) was relatively big and it continued to grow for the whole duration of the test. Of course, this is how the PID-controlled system is supposed to work. As the set value approaches, P-term starts to grow smaller to get the temperature to the right range. Then the I-term tries to get the temperature to right level and then the D-term kills the oscillation. I- and D-term are the ones that make the temperature levelling delay longer, but the curve is much smoother due to them. In Case h) the delays are small. 95 % of the set value is even reached before the end of the dynamic part of the cycle, meaning that the measurements follow the set value relatively well. Of course, the temperature change rate was really slow during Case h), being only 0,67 °C/min and in Case g) change rate was 2,0 °C/min. On top of this, a bigger change rate occurs when temperature drops, and a smaller change rate is when temperature rises. This is tricky because the manufacturer has promised only 1,0 °C/min for cooling and 3,5 °C/min for heating. This leads to the fact that the Test 3 has been designed faulty, in this regard. So, the bigger change rate is one reason why in Case g) the delay is bigger than in Case h). And as the manufacturer has promised a better change rate for heating, this fact would implicate that the temperature is also easier to control during heating.

The position of the Sensor 1 seems to have the overall best temperature accuracy during dynamic temperature steps, as it has the smallest delay in both cases. As for the worst position, there really is not clearly "a winner", but the worst ones are positions of Sensors 4,6 and 7. As can be seen in Figure 13, these sensors are all in the bottom of the chamber. This makes sense since an air inlet is on the top, so it is logical that the temperature changes slower in the bottom of the chamber. This also explains why the Sensor 1 has the lowest delay, since it is right next to the air inlet. The Sensor 4 is although irregular in a sense, since it is the best one in some cycles of Case h).

Both RH Cases i) and j) had their own problems. Case i) had a rise in the beginning of the dynamic cycle contrary to what the set value instructed. This is most likely caused by the dynamic temperature step, which started at the same time as the RH dynamic step in Case i). As previously concluded, the chamber has a priority in temperature control, so it abandons RH control when temperature control starts, and only in a little while, it also starts to control RH. It is also possible that the chamber deliberately rises the RH in the beginning of the dynamic step, so it could get the temperature into set value faster. The oscillation in the static part of Case i) is most likely caused by the fact that the chamber cannot control the RH statically at 20 % RH. This was also found to be true in the Test 2, as was previously mentioned in Chapter 4.1.2. The static error at 98 % RH in case j) is already covered in Chapters 4.1.3 and 4.2.3.

Now, the best positions for the dynamic RH control seem to be where Sensors 1 and 2 are, as can be seen in results in Table 5. This fact is explained the same way as with the temperature. These sensors are right next to the air inlet, so humidity changes the fastest there. As for the worst position, there is again some variation. The worst positions seem to be where Sensors 5 and 7 are. Sensor 7 is again in the bottom, but Sensor 5 is in the middle of the chamber as can be seen in Figure 13. But errors of Sensor 5 are all from the case j) where the difference between the minimum and the maximum is only 1,6 minutes. In conclusion, measured values of Case j) follow set value remarkable well compared to Case i) if the static error during static step is ignored.

4.4 Interaction of humidity and temperature

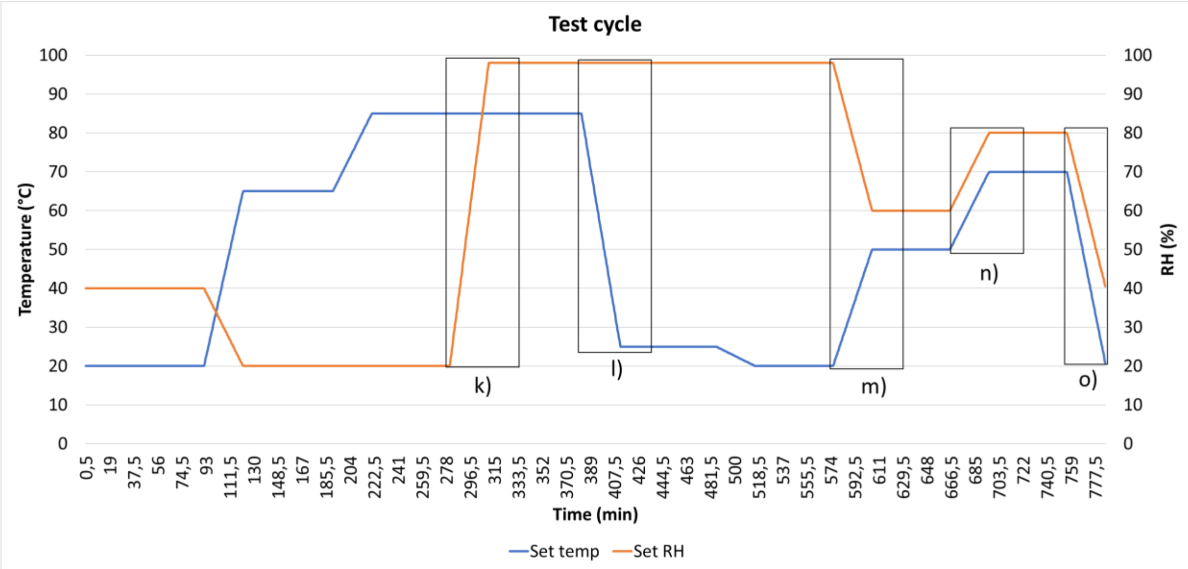

FIGURE 39. Circled areas k) – o) wherefrom humidity's and temperature's interactions were studied

To study how the RH effects the temperature and vice versa, five areas from the cycle of Test 3 were chosen. The areas were chosen in a way that there would be one area where the RH changes and the temperature doesn't, one where the temperature changes but the RH doesn't, one where both the temperature and the RH rise simultaneously, one where both the temperature and the RH decrease simultaneously and finally one where the temperature rises and the RH decreases. It would have been ideal to also have one area, where temperature decreases and RH rises, but this was not considered when the test cycle was designed. The studied areas can be seen in Figure 39 and the different parts are named as Cases k) – o). These cases are presented in Figures 40-44.

4.4.1 Observations

In all test cases there is a delay in the beginning of the dynamic part for both the temperature and the RH. The change rate of the temperature is relatively close to that of the set values, but the RH does not seem to change linearly. These facts were observed when dynamic parts of Test 3 were studied in Chapter 4.3.

In Case k) presented in Figure 40, it can be seen that the measured RH has been lower than the set value for both the static and the dynamic part of the test period. There is also a little bend in the temperature curve right after the linear part of the RH dynamic period has ended, even though temperature has set to be static for the whole duration of the Case k). The RH also remains under the set RH of 98 % at the static part. Reason for this is stated in the Chapter 4.1.2.

In Case l), which is presented in Figure 41, there is a remarkable error in the RH control, because the RH has peaked during the dynamic part of the temperature, even though the RH has been set to be static for the whole duration of the Case l). There is also a static error in RH in a point where both the RH and the temperature are static, and on top of this the RH readings over 100 % should be theoretically impossible. This static error is explained in the Chapter 4.1.4.

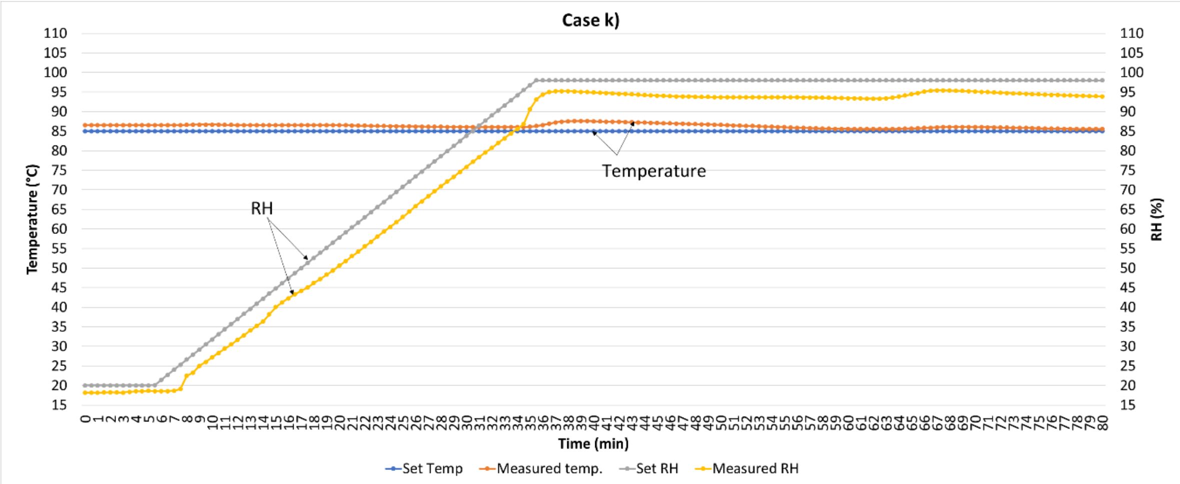

FIGURE 40. Interaction of temperature and RH in Case k), when the set RH increases and the set temperature is static

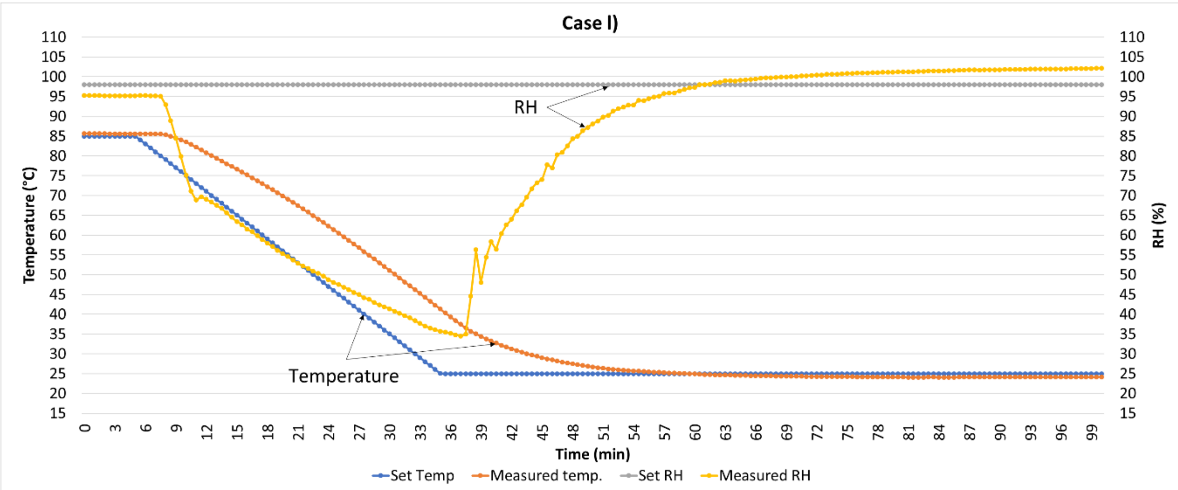

FIGURE 41. Interaction of temperature and RH in Case l), when the set RH is static and the set temperature decreases

In Case m), when RH has been set to decrease and temperature has been set to increase, the RH has a long delay after it starts to decrease, and its change is not linear. In both Cases m) and n), which are presented in Figures 42 and 43, the temperature is lower than the set value for whole the duration of the dynamic step and the RH is over the set value in both cases. In case o), which is presented in Figure 44, the RH drops way lower the set value and it doesn't change linearly. It also peaks high compared to the set value in a point where temperature has reached static state. The RH also has oscillation in its static step in case o).

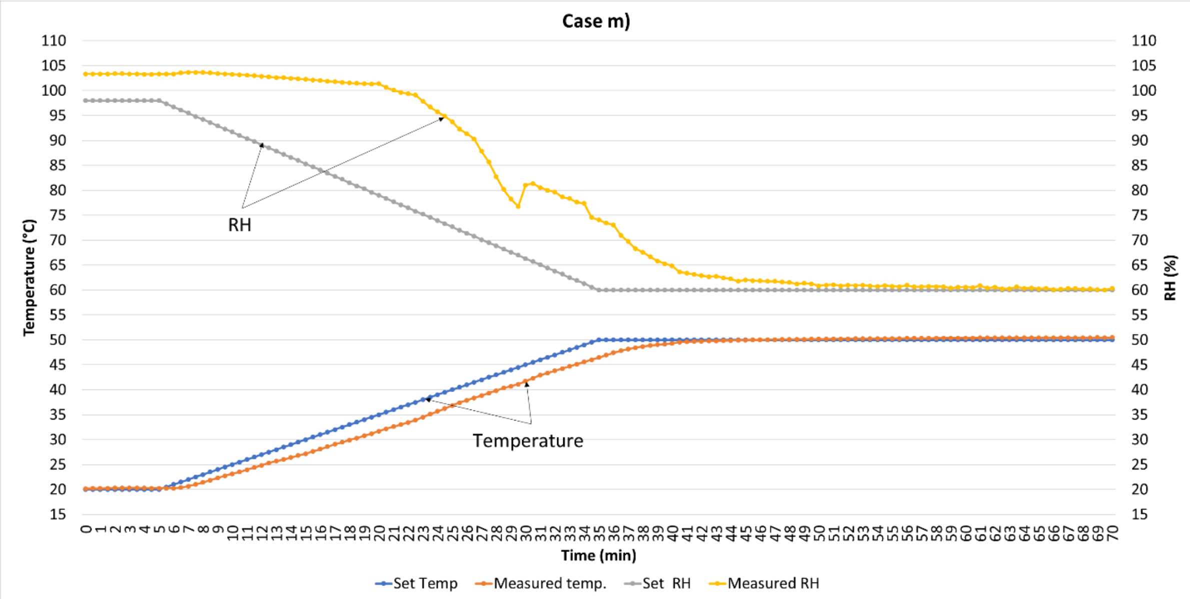

FIGURE 42. Interaction of temperature and RH in Case m), when the set RH is decreases and set temperature increases

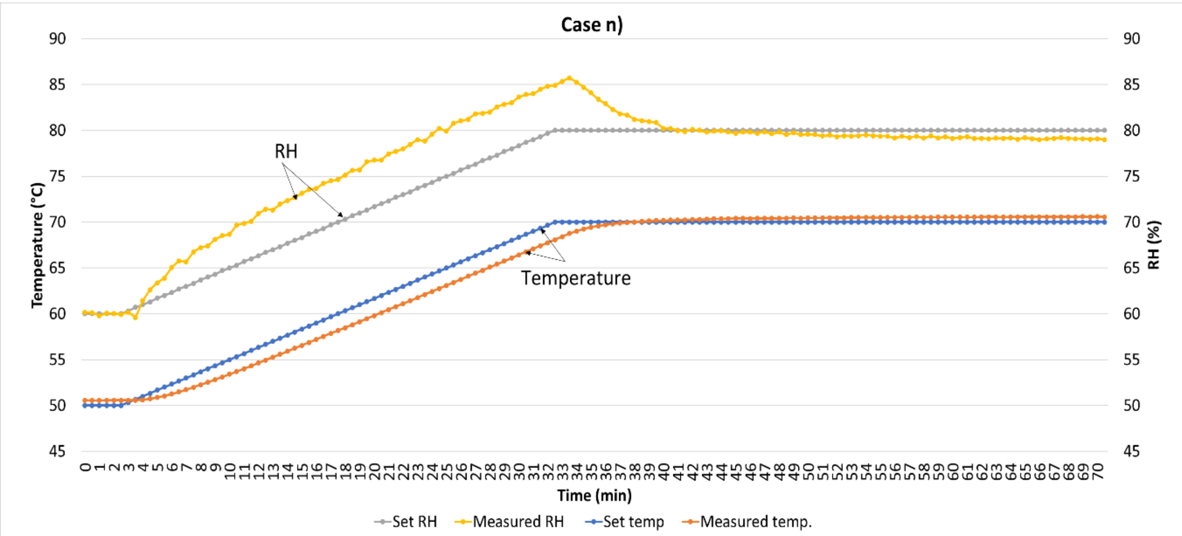

FIGURE 43. Interaction of temperature and RH at Case n), when both the set temperature and RH increase

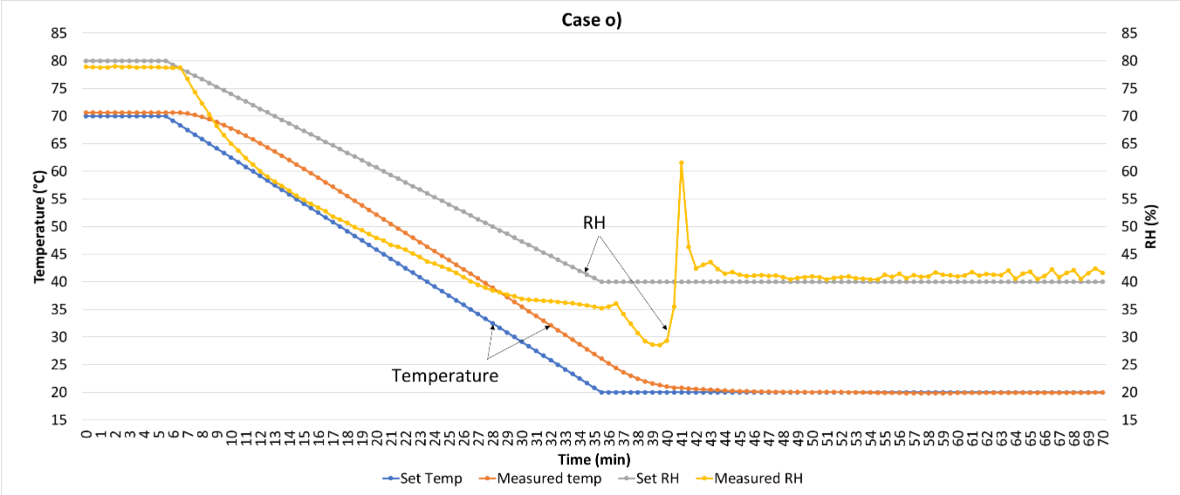

FIGURE 44. Interaction of temperature and RH at Case o), when both the set temperature and RH decrease

4.4.2 Conclusions

The delay in the start of the dynamic cycles are caused by control system's slowness, and physical capabilities of the system. E.g. heating element first needs some time to start and then it also needs some time to heat itself, before it can start to warm the air. Then this warm air needs to flow to the chamber itself. The RH control and the cooling also have similar slowness factors, and these cause the delays in the beginning of the dynamic parts of the curves. These delays cause the curves to be higher or lower than the set value during dynamic steps.

It also seems that the chamber prioritizes temperature control over the control of RH. One reason for this, is that the measured change rate of the temperature seems to be relatively close to that of the set change rate, but when the RH change rate is analysed, it fluctuates, and its change rate is nowhere close to that of a linear. RH curves also have many peaks. Also results from the Case l) support this theory, since even though the RH has been set to be static, there seems to be no control in its behaviour during the linear part of the dynamic period.

In addition, when comparing the curve in the case l) to the tolerance stated in the method 507.6 of the MIL-STD 810, the RH tolerance is [+4; -10] instead of its normal ± 4 %, when temperature is decreasing. Also, as shown in Figure 1, when the temperature is decreasing in the test cycle of IEC 60068-2-30, RH is allowed to drop to 80 % from 95 set RH. Based on these tolerances in different standards, the behaviour seen in the Case l) seems to be usual for RH control. Still the RH drops over 50 %, which is way too much compared to standards' 10 % and 15 % tolerances. In Case o), the RH also drops lower than the set value, as can be seen in Figure 44. This drop, however, is smaller than in the Case i) being at an error range of 10-15 % during the dynamic part of the curve. So, it fits the IEC standard's tolerance but not the one in the MIL-STD 810.

The long delay after RH starts to decrease in Case m) might be caused by dew. As was observed in the Chapter 4.1.4 dew started to form in the chamber. If dew has been formed on the sensing elements of the sensors, this would explain why readings won't change until the sensors have dried enough to measure real readings.

5 CONCLUSIONS

The aim of this thesis study was to get all the useful information from the BGD 897/408B environmental testing chamber by doing different tests. When all this information was processed and analysed, by comparing test results to standards and specifications of the manufacturer, solid conclusions could be made. In the future, this information can be used for optimizing test cycles to be as fast as possible, taking all the errors into account in the working principle of the chamber, and gathering proper results from tests.

The errors in temperature were relatively well inside the tolerances and specifications that the manufacturer had set, and inside the tolerances of the standards IEC 60068-2-30 and MIL-STD 810. 91 % of the temperature readings had an absolute setting error of [0; 2,0] °C during static temperature steps, depending of the set temperature. Overall, the readings were relatively static. The minimum and maximum temperatures that the chamber was able to produce were as the manufacturer had specified. From the dynamic parts, a lot was learned from the delay between a set and measured temperature, and there was a clear delay between measured and set values in the beginning of the dynamic parts. This was deemed to be due to the physical capabilities of the system. Delay in the end of the dynamic parts was deemed to be caused by the working principle of the PID-controller, which makes the temperature curve smoother but at the same times makes the dynamic part longer. From all the information gained from the test results of the temperature, a conclusion that the chamber prioritizes temperature control over RH control was made. When results from the sensors were compared to the position of sensors, it was found that the temperature levels and changes faster in the top of the chamber than in the bottom. This was deemed to be due to the location of the air inlet in the top of the back wall.

Compared to the specifications of the manufacturer and the tolerances of the standards IEC 60068-2-30 and MIL-STD 810, a conclusion is that the RH control in the chamber is at an acceptable level. 93 % of the RH readings had an absolute setting error of [0; 6,5] %, which indicates that RH oscillated more than temperature and the RH also remained farther from the set values than the temperature. Even still, the RH was on average inside the tolerances of both the manufacturer and the standards. Dynamic parts of the RH behaved very similarly with the temperature but a priority in the temperature control was clear. The RH peaked occasionally and developed some interesting set error in the beginning of the dynamic parts. The position of the sensors revealed that the RH changes and levels in a same way as the temperature and because of the same reason. There were problems with high and low RHs. At a low RH level, the measurement results showed that the RH oscillates during the static steps and never becomes stable. In addition, at the set RH of 98 % combined with high temperatures, it was deemed to be impossible for the chamber to produce and the maximum RH was about 95,5 %. With the set RH of 98 % combined with low temperatures, dew was formed to the chamber and the RH was then at 100 %.

Based on the results acquired from the tests, RH levels higher than 95,5 % should be avoided due to difficulties of the chamber to control RH in the specified area. Other very important thing to remember when new environmental tests are designed is that dynamic steps need to be chosen in a way that there is enough time for temperature and RH to change before the static steps begin.

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