

UNIVERSITY OF WEST BOHEMIA
FACULTY OF MECHANICAL ENGINEERING

**Study programme: N0715A270011 – Machining, Additive
Technology and Quality Assurance**

Study specialisation: None

DIPLOMA THESIS

Air enthalpy difference measurement method uncertainties

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Academic year 2023/2024

ZÁPADOČESKÁ UNIVERZITA V PLZNI

Fakulta strojní

Akademický rok: 2023/2024

ZADÁNÍ DIPLOMOVÉ PRÁCE

(projektu, uměleckého díla, uměleckého výkonu)

Jméno a příjmení: **Bc. Jan PRAŽÁK**
Osobní číslo: **S22N0004P**
Studijní program: **N0715A270011 Obrábění, aditivní technologie a zabezpečování kvality**
Téma práce: **Air enthalpy difference measurement method uncertainties**
Zadávající katedra: **Katedra technologie obrábění**

Zásady pro vypracování

1. Introduction and definition of goals
2. Research on the current state of the situation
3. Experimental description
4. Evaluation of the experiments and their assessment
5. Conclusion

Rozsah diplomové práce: **50 – 70 stran**
Rozsah grafických prací: **dle potřeby**
Forma zpracování diplomové práce: **tištěná/elektronická**
Jazyk zpracování: **Angličtina**

Seznam doporučené literatury:

- h-x diagram, Konstrukce a použití, Siemens Building Technologies, Landis & Staefa Division.
- Nejistoty v měření I: vyjadřování nejistot, Automa, Vol. 7-8, 2001.
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- DOSSAT, Roy J. a Thomas J. HORAN. Principles of refrigeration. 5th ed. Upper Saddle River, N.J.: Prentice Hall, 2002. ISBN 978-0130272706.

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Datum zadání diplomové práce: **16. října 2023**
Termín odevzdání diplomové práce: **24. května 2024**

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Prohlašuji, že jsem tuto diplomovou práci vypracoval samostatně, s použitím odborné literatury a pramenů, uvedených v seznamu, který je součástí této diplomové práce.

V Plzni dne:

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Acknowledgments

I would like to thank my supervisor Ing. Dana Kubátová Ph. D., for her constructive approach during the whole period of writing the thesis and for the consultations. I would also like to thank Ing. Jan Uher, Ph.D. and Ing. Vít Hubálek for consultations in the field of thermodynamics and communication with the management of Daikin Industries Czech Republic. Last but not least, I would like to thank Mr. Jeremy Marc King B.A. (Hons) for checking the English language.

ANOTAČNÍ LIST DIPLOMOVÉ PRÁCE

AUTOR	Příjmení Pražák	Jméno Jan	
STUDIJNÍ PROGRAM	N0715A270011 – Obrábění, aditivní technologie a zabezpečování kvality		
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PRACOVISŤE	ZČU - FST – KTO		
DRUH PRÁCE	DIPLOMOVÁ	BAKALÁŘSKÁ	Nehodící se škrtněte
NÁZEV PRÁCE	Stanovení nejistoty měření metodou rozdílu entalpie vzduchu		

FAKULTA	strojní	KATEDRA	KTO	ROK ODEVZD.	2024
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POČET STRAN (A4 a ekvivalentů A4)

CELKEM	77	TEXTOVÁ ČÁST	77	GRAFICKÁ ČÁST	0
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STRUČNÝ POPIS (MAX 10 ŘÁDEK) ZAMĚŘENÍ, TÉMA, CÍL POZNATKY A PŘÍNOSY	Obecným cílem této práce je provést analýzu systému měření při stanovování kapacitního výkonu vnitřní jednotky klimatizace nebo tepelného čerpadla pomocí metody rozdílu entalpií. Následně stanovit velikost nejistoty výsledků na základě dostupných dat.
KLÍČOVÁ SLOVA ZPRAVIDLA JEDNOSLOVNÉ POJMY, KTERÉ VYSTIHUJÍ PODSTATU PRÁCE	Nejistoty měření, klimatizace, vnitřní jednotka, výpočet, metoda rozdílu entalpie

SUMMARY OF DIPLOMA SHEET

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INSTITUTION	ZČU - FST - KTO		
TYPE OF WORK	DIPLOMA	BACHELOR	Delete when not applicable
TITLE OF THE WORK	Air enthalpy difference measurement method uncertainties		

FACULTY	Mechanical Engineering	DEPARTMENT	KTO	SUBMITTED IN	2024
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NUMBER OF PAGES (A4 and eq. A4)

TOTAL	77	TEXT PART	77	GRAPHICAL PART	0
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BRIEF DESCRIPTION TOPIC, GOAL, RESULTS AND CONTRIBUTIONS	The general target is to perform an analysis of the measurement system for capacity testing by using the air enthalpy method. After that the uncertainty will be calculated based on available data. The measurement and calculations are performed on the indoor side of the system
KEY WORDS	Uncertainties of measurement, air conditioning, calculation, air enthalpy method

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List of abbreviations and symbols

V – volume of the mass [m^3]

R – ideal gas constant [$\text{J}\cdot\text{mol}^{-1}\cdot\text{K}^{-1}$]

T – temperature of the system [K]

p_v – pressure of the vapour in a certain volume of moist air at a given temperature [Pa]

p_s – pressure of the water vapour in the same volume of saturated air at the same temperature [Pa]

x – amount of water vapour [kg/kg]

x_s – amount of water vapour for saturated air [kg/kg]

φ – relative humidity [%]

ACs – air conditioners

ϑ – dry bulb temperature [$^{\circ}\text{C}$]

h – specific enthalpy [kJ/kg dry air] or [J/kg dry air]

x – absolute humidity [g moisture/ kg of dry air]

$^{\circ}\text{C}$ - degree of Celsius

K – Kelvin

p – pressure [Pa]

Pa – pascals

hPa – hecto pascals

kg – kilogram

m^3 – cubic metres

J – joule

c_p – specific heat at a constant pressure [$\text{kJ}/\text{kg}\cdot\text{K}$]

c_v – specific heat at a constant volume [$\text{kJ}/\text{kg}\cdot\text{K}$]

Δh – difference of specific enthalpy [kJ/kg]

h – hour

s – seconds

T – absolute temperature [K]

p_d – partial pressure of the vapour at wet bulb temperature [Pa/kPa]

ϑ_L – dry bulb temperature [$^{\circ}\text{C}$]

p_s – saturated vapour pressure [Pa]

ϑ_S – dew point temperature [$^{\circ}\text{C}$]

ϑ_F – wet bulb temperature [$^{\circ}\text{C}$]

ρ – density [kg/m^3]

z – score

ε – absolute error of measurement

y – the result of measurement

x_0 – measurand

δ – relative error [%]

ε – absolute error

s – estimation of standard deviation

n – number of measurements

Δy_i – absolute deviation i^{th} element from the arithmetic mean

$s_{\bar{y}}$ – estimation of standard deviation of the chosen arithmetic mean

Δy – systematic error

y_m – the chosen arithmetic mean

x_s – conventional correct value (value of the standard)

\bar{q} – arithmetic mean or average

q_k – values of the individual measurements

$s(q_k)$ – experimental standard deviation

x_n – value which is suspected from the extreme

H_n – the standard value

H – limit value

q_j – results from partial measurements

u_A – standard A uncertainty

k_s – coefficient which depends on the number of measurement

z_{jmax} – deviation range

Δz_{jmax} – maximum deviation range of each source

k – parameter which can be seen in Figure 7

u_{Bzj} – standard B uncertainty of each source

X – quantity which is dependent on different sources

$u_{x,zj}$ – standard B uncertainty for X value

u_{zj} – type B standard uncertainty

$A_{x,zj}$ – coefficient of sensitivity

∂X – partial derivation of X value

∂Z_j – partial derivation of each source

$u_{b(x)}$ – relative standard uncertainty

$u(x)$ – value of standard uncertainty

$\bar{u}(x)$ – arithmetic mean of values

u_c – combined standard uncertainty

U – expanded standard uncertainty

k_u – coefficient of coverage factor (in the case which is mentioned above $k_u=2$)

$T_u = Au$ – nominal value of measured quantity

p_{cond} – pressure of condensation [Pa]

p_{evap} – pressure of evaporation [Pa]

\dot{Q}_{evap} – evaporation heat derivation

\dot{Q}_{cond} – condensation heat derivation

\dot{W}_{comp} – compression work derivation

Q_v – volumetric air flow [m^3/min]

A – flow area [m^2]

C – function of Reynolds number

dp – pressure difference [Pa]

H – enthalpy [J]

T_{DB} – dry bulb temperature [K]

q_{vi} – air volume flow rate, indoor-side [m^3/s]

h_{a1} – specific enthalpy of air entering indoor-side [J/kg of dry air]

h_{a2} – specific enthalpy of air leaving indoor-side [J/kg of dry air]

v'_n – specific volume of air-water vapour mixture at nozzle [m^3/kg]

W_n – specific humidity at nozzle inlet [kg/kg of dry air]

ϕ_{tci} – total cooling capacity [W]

C++ – programming language

HP – indication of maximum capacity

EMEA – Europe Middle East and Africa

DICz – Daikin Industries Czech Republic

PT-100 – thermometers used in DICz

T_{DB} – dry bulb temperature [K]

T_{WB} – wet bulb temperature [K]

q_{vi} – air volume flow [m^3/s]

p – static pressure difference [Pa]

mA – miliamps

V – volts

Ω – ohm – electric resistance

h_{a1} – Specific enthalpy of air entering the indoor side [J/kg of dry air]

h_{a2} – Specific enthalpy of air leaving the indoor side [J/kg of dry air]

T – air dry bulb temperature [K]

p_w – Water vapour partial pressure at wet-bulb temperature [Pa]

c_1 – indirect contribution [W]

T_{DBC} – cyclometric dry bulb temperature [K]

T_{WBC} – cyclometric wet bulb temperature [K]

WET – nozzle specific volume [–]

Hda – enthalpy [J/kg]

P_w – water vapour partial pressure [Pa]

$\bar{\phi}_{tci}$ – arithmetic mean of total cooling capacity [W]

\bar{q}_{vi} – arithmetic mean of air volume flow [m³/s]

z_1 – uncertainty for airflow uncertainty which is described by standard ISO 16491 [m³/s]

ub_{qvi} – standard B uncertainty of air volume flow [m³/s]

$ub(r)_{qvi}$ – value of relative standard B uncertainty of air volume flow [%]

\bar{h}_{a1} – arithmetic mean of specific enthalpy of air entering the indoor side [J/kg]

\bar{h}_{a2} – arithmetic mean of specific enthalpy of air leaving the indoor side [J/kg]

$\bar{h}_{a1+0.2^\circ C}$ – arithmetic mean of specific enthalpy of air entering the indoor side +0.2°C [J/kg dry air]

$\bar{h}_{a2+0.2^\circ C}$ – arithmetic mean of specific enthalpy of air leaving the indoor side +0.2°C [J/kg dry air]

z_2 – uncertainty for specific enthalpy of air entering the indoor side which is described by standard ISO 16491 [J/kg of dry air]

z_3 – uncertainty for specific enthalpy of air leaving the indoor side which is described by standard ISO 16491 [J/kg of dry air]

ub_{ha1} – standard B uncertainty specific enthalpy of air entering the indoor side [J/kg dry air]

ub_{ha2} – standard B uncertainty of specific enthalpy of air leaving the indoor side [J/kg dry air].

$ub(r)_{ha1}$ – relative standard uncertainty of specific enthalpy of air entering the indoor side [%]

$ub(r)_{ha2}$ – relative standard uncertainty of specific enthalpy of air leaving the indoor side [%]

\bar{T}_{DB} – arithmetic mean of dry bulb temperature

z_4 – uncertainty for dry bulb temperature uncertainty which is described by standard ISO 16491 [K]

ub_{TDB} – standard B uncertainty for dry bulb temperatures [K]

$ub(r)_{TDB}$ – relative standard B uncertainty for dry bulb temperature [%]

\bar{p} – arithmetic mean of static pressure [Pa]

z_5 – uncertainty for static pressure which is described by standard ISO 16491 [Pa]

ub_p – standard B uncertainty for static pressure [Pa]

$ub(r)_p$ – relative standard B uncertainty for static pressure [%]

\bar{p}_w – arithmetic mean of water vapour partial pressure at wet bulb temperature [Pa]

z_6 – uncertainty for water vapour partial pressure at wet bulb which is described by standard ISO 16491 [Pa]

$ub(r)_{pw}$ – relative standard B uncertainty for water vapour partial pressure [%]

ub_{pw} – standard B uncertainty for water vapour partial pressure at wet bulb [Pa]

z_7 – uncertainty for indirect contribution which is described by standard ISO 16491 [W]

ub_{c_1} – standard B uncertainty for indirect contribution [W]

$ub(r)_{c_1}$ – relative standard B uncertainty for indirect contribution [%]

$ub(r)$ – relative standard B uncertainty [%]

s_{Tdb} – standard deviation of dry bulb temperature [K]

s_{Twb} – standard deviation of wet bulb temperature [K]

u_{CTdb} – combined uncertainty for dry bulb temperature

u_{CTwb} – combined uncertainty for wet bulb temperature

U_{Tdb} – expanded uncertainty for dry bulb temperature

U_{Twb} – expanded uncertainty for wet bulb temperature

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1 Introduction and definition of goals

In this chapter, basic information about the company and its history is given. Also, there is a chapter which describes the background of the issues which are evaluated during the thesis. Mainly it is necessary to combine the theory of metrology with the theory of heat transfer and the properties of the air.

1.1 The company

This diploma thesis has been created at Daikin Industries Czech Republic. The company belongs to worldwide network of corporations founded in Osaka, Japan 100 years ago. Last year it celebrated 50 years in Europe. From the beginning production was mainly air conditioners and heat pumps. Thanks to their high quality production and a wide product portfolio, Daikin has become one of the top three companies producing alternative heating and cooling devices all around the world. These days it operates in more than 150 countries.



Figure 1 – Daikin logo [28]

1.2 Background

Global warming is considered one of today's biggest problems. This kind of issue could and probably will affect future generations. There are people and companies all around the world trying to find solutions to reducing greenhouse gases as much as possible. This is leading to efforts to find alternative solutions for almost every case that could potentially cause global warming. One example of alternative solutions for heating and cooling devices are air conditioners and heat pumps. During their operation there is no leakage of greenhouse gases to the atmosphere so there is no risk of increasing global warming as is the case with coal heating. Also, inside heat pumps and ACs, there is refrigerant which is not burned out during the operation such as the case with coal heating. With the increasing demands for the quality of the production and the efficiency of products, the legislation is also changing. The main topics such as being harmless to the environment and reducing the cost of the products make requirements for designing these products tougher year by year.

If the company wants to show its capability of designing high quality products, its demands for production and design should comply with the latest demands of the technical standards which guarantee that final products will be of the highest level as possible. In the latest revisions of the standard, the uncertainty of measurement should be stated. This was the motivation for writing this master thesis. However, uncertainties are also new for the market itself, especially for the energy market which deals with heating and cooling operations.

Since all these topics are not so easy to understand, broad research of the current state needs to be performed to put the theory of cooling and the theory of uncertainties together and become familiar with these topics. After that, the evaluation of uncertainties can follow.

1.3 Target of diploma thesis

This diploma thesis is written based on the request of Daikin Industries Czech Republic. Specifically, the request was raised by the compliance group, which is part of the development centre which includes Europe, the Middle East and Africa, and the target is to comply with the standard EN 14 511-3(2022) which states the maximum value of the combined uncertainty of measurement for total cooling and heating capacity. Also, some additional standards such as ISO TS 16491 (2012), ISO 5151 (2017) and ISO 14825 (2022) are connected to the standard EN 14 511-3 (2022). Once the combined uncertainty has been evaluated according to the standard EN 14 511-3(2022), evaluation of the maximum expanded uncertainty according to the standard ISO 5151 (2017) is performed. This thesis deals with the determination of the uncertainty of measurement for total cooling capacity only according to the mentioned standards (EN 14 511-3 and ISO 5151 (2017)).

Another target of the thesis is to create a semi-automatic excel file which will serve to help testing engineers determine the uncertainty of measurement for every measurement which will be performed in the future.

2 Research on the current state of the situation

The theory is described in this chapter. It begins with the basics of thermodynamics and the properties of air. Then metrology terms are described and the uncertainty procedure is described.

2.1 Air conditioning

For a better understanding of how air conditioning works, it is important to describe the four main elements which affect the efficiency of air-conditioners. These are temperature, humidity, air purity and air distribution. These are the elements which affect the properties of air conditioners, starting with the quality of the air and ending with the air distribution, and they also impact customer satisfaction. In this thesis, the crucial elements of thermodynamics are described and explained. The main scope is not air-conditioners themselves, however, it is important to know the basics of heating or cooling circuits to better understand the issue as a whole.

2.2 Humidity and moisture

For a better understanding of humidity, below is described the relationship between temperature and humidity. In order to measure humidity, one way is to use the dry and wet bulb temperatures. It is possible to find the exact value from their differences. Humidity can be understood in the context of weather and climate, while moisture is connected with the amount of water in the air or inside some objects.

Another parameter which is connected to temperature, humidity and atmospheric pressure is relative humidity, which is expressed as the actual amount of water vapour in the air compared to the total amount of vapour that can exist in the air at its current temperature.

[1]

2.3 Temperature

Temperature is divided into two types. The first is dry bulb temperature, which is measured using a basic thermometer with no modifications. The dry bulb thermometer is not affected by the moisture of the air. The second one is called wet bulb temperature and is measured by the same type of thermometer which is used for dry bulb temperature measurements but it is wrapped in wet gauze. Wet bulb temperature is very closely connected to humidity and it measures it. It is also defined as the temperature of adiabatic saturation. When the adiabatic evaporation of water from the thermometer starts, the wet bulb temperature is lower than the dry bulb temperature in the air. The adiabatic process is defined as the process where there is no heat exchange between the thermodynamic system and its environment. The psychrometer is a device which measures both of these quantities. For a better understanding, a combination of the dry bulb and wet bulb temperature can be seen in the psychrometric chart or Mollier diagram and this gives the state of the humid air. The difference between the two diagrams is that the Mollier diagram is widely used all around Europe and the psychrometric chart is mainly used in America. For the purposes of this thesis the Mollier diagram will be used. The only

difference between these two charts is that the axes are mirrored and rotated. Figure 2 shows the Mollier diagram and Figure 3 psychrometric chart.

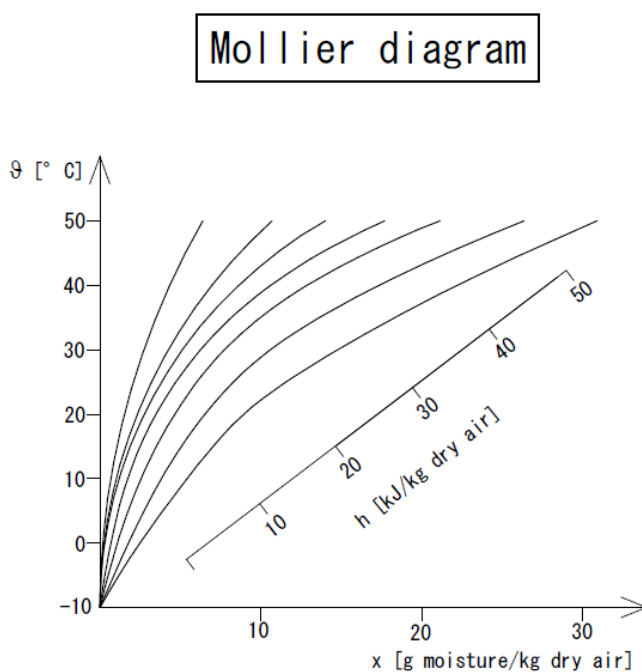


Figure 2 – Mollier diagram

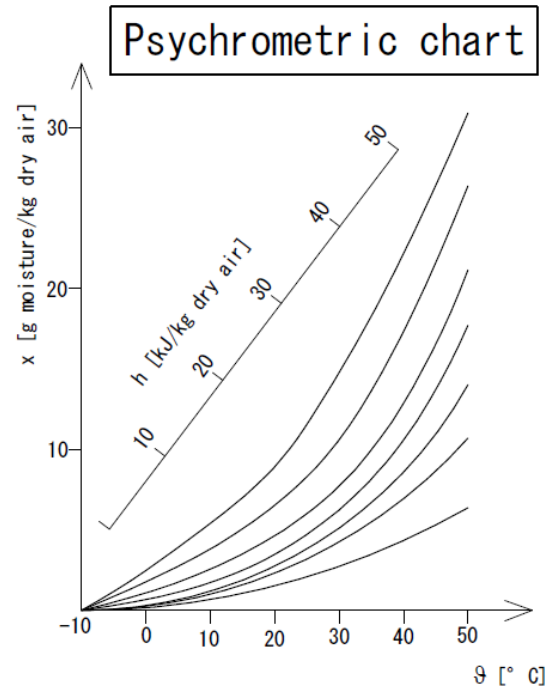


Figure 3 – Psychrometric chart

If the relative humidity equals 100%, there will be no evaporation of the water and the dry bulb temperature will be equal to the wet bulb temperature. Thus the wet bulb depression will be zero. This is why the wet bulb temperature is used as way to indirectly measure the dryness of the air.

[1] [2] [3]

2.4 Air purity

Air purity represents how clean the air really is. Basically, the air in a room is contaminated by people, machines etc. It is very risky to have polluted air with regard to human health. Polluted air can be divided into air which contains dust, air which contains viruses and air which contains both. So it is important to clean the air as much as possible by using air conditioners. Apart from the risk to health, there can be some other risks. For example, very precise manufacturing such as assembling electronic devices, engines or assembling microscopically small electronic devices can be affected when the air is polluted. The typical ways of maintaining air cleanliness are the removal of air contaminants with filters and ventilation by which contaminated room air is replaced by clean outdoor air. [1]

2.5 Air distribution

Air distribution in a room depends on combination of temperature, humidity and air motion. The difference of the temperature should not be bigger than 1°C in one room. Any drafts which can influence the comfort of the people in a room must also be taken into account. A draft is defined as any feeling of coolness or warmth in any corner of the room due to air movement and air temperature. It is very important to mention that the most desirable direction of the air flow is from the front side towards the face of a person. Warm air directed towards the legs is

comfortable but directed to the face is undesirable. Residential AC's have an outlet air flow up to 10-20 m³/min. The performance of an air conditioner also affects the air flow and the air distribution all around the room. [1]

2.6 Humid air

In the context of air conditioning and its capacity calculations, it is necessary to mention the properties of humid air. These properties can be determined by using the Mollier diagram. The construction of a Mollier diagram is described in chapter 2.16.

2.7 Mollier diagram

The Mollier diagram is widely used by engineers all around the world to predict a system's performance and efficiency. An example of a Mollier diagram is shown in Figure 2. Basically, it is a p-h chart. In this kind of chart, the relationship between enthalpy, air temperature and moisture is described. When two thermodynamic quantities are given, it is possible to find out other quantities. For example, when the dry bulb temperature and relative humidity is known, a Mollier chart can be used to obtain values such as enthalpy, wet bulb temperature and specific humidity. The saturated liquid line and saturated vapour line are shown a Mollier diagram. For a better understanding of refrigeration cycles, several characteristic variables are defined below. [3]

2.8 Absolute humidity

Absolute humidity is expressed as the amount of water in grams per kilogram of air. Absolute humidity represents the amount of water vapour contained in humid air. [3]

2.9 Relative humidity

Air can only hold a certain amount of water vapour at a given temperature. The higher the temperature and pressure, the higher the maximum possible water content. When the saturation points at each air temperature are connected into a line, it is called the saturation line. The relative humidity shows how big the ratio of the current amount of water in the air is relative to the maximum amount of water in the saturation condition at a certain temperature. The relative humidity can be expressed by the following formula (1),

$$\Phi = \frac{m_v}{m_{vs}} = \frac{\frac{p_v V}{RT}}{\frac{p_s V}{RT}} = \frac{p_v}{p_s} = \frac{x}{xs} \quad (1),$$

where

m_v – mass of vapour in a certain volume of moist air at a given temperature [kg]

m_{vs} – mass of water vapour in the same volume of saturated air at the same temperature [kg]

V – volume of the mass [m³]

R – ideal gas constant [J.mol⁻¹.K⁻¹]

T – temperature of the system [K]

p_v – pressure of the vapour in a certain volume of moist air at a given temperature [Pa]

p_s – pressure of the water vapour in the same volume of saturated air at the same temperature [Pa]

x – amount of water vapour [kg/kg]

x_s – amount of water vapour for saturated air [kg/kg]

Based on the formula above, the relative humidity can be described as the ratio of the pressure of the water vapour and certain unsaturated moist air at a given temperature T to the saturation pressure of water vapour at the same temperature.

[3] [1]

2.10 Density

Density is defined as a substance's mass per unit of volume. Some values of density are shown in Table 1. [3]

Table 1 – Example of density at 0°C [3]

Temperature at sea level [°C]	Density of dry air [kg/m ³]	Density of water vapour [kg/m ³]
0	1.293	0.804

2.11 Specific heat

Specific heat is defined as the amount of heat required to heat 1 kg of a material by 1 K. Thus, there is a division of specific heat to specific heat at a constant volume marked as c_v and specific heat at a constant pressure marked as c_p . For example c_v for dry air is 1.01 [kJ/kg.K] and for water vapour is 1.86 [kJ/kg.K] [3]

2.12 Heat content or enthalpy

One of the most important thermodynamic calculations is how much heat is necessary to change the humidity and the temperature in a room by a specific value. In thermodynamics, the heat content in a substance weighing 1 kilogram is known as specific enthalpy. The difference between the starting and the ending point can be seen in a Mollier diagram. If the mass of modified air is multiplied by the difference of specific enthalpies Δh [kJ/kg], the amount of heat required for this modification is calculated. [3]

2.13 Pressure

Pressure is force distributed across a surface. The weight of the air on the surface of the earth is called atmospheric pressure. At sea level, it is about 1.013 bar. Previously, the pressure for air and thermic calculations was commonly specified by the height of a column of fluid, for example a water column. [3]

2.14 Flow

When it comes to material flow, there are two very similar quantities that differ by the density in the equation only. The first is called volumetric flow in [m³/s] or [m³/h]. The second is mass flow in [kg/s] or [kg/h]. The amount of homogeneous or gaseous medium with a specified volume and mass and which flows through a certain cross section evenly in 1 s, is called the volume or mass flow. [3]

2.15 Structure of Mollier diagram

The main field of focus will now become the structure of the Mollier diagram. Generally, Mollier diagrams serve to make the calculations of the air state easier. The most frequently used charts are h-x charts where h represents enthalpy [kJ/kg] and x stands for absolute water content of the air [g/kg]. T-x diagrams also exist but they are not so widely used as h-x ones. T represents absolute temperature [°C]. The Mollier diagram, as can be seen in Figure 2 is a combination of both cases because the T axis represented by the letter ϑ is used. Also, there can be seen the specific enthalpy axis described by letter h and finally, there is also the x axis which represents the absolute water content. [3]

- ϑ – air temperature [°C]
- φ – relative humidity [%]
- x – absolute water content [g/kg]
- h – specific enthalpy [kJ/kg]

The values of these characteristics and the behaviour of humid air depend on the barometric pressure. Thus, a Mollier diagram can be drawn for one specific barometric pressure only. [3]

2.16 Diagram construction

The following chapter describes and shows how the Mollier diagram is constructed.

2.16.1 Temperature scale

The temperature scale is marked on the vertical axis. Horizontal auxiliary lines drawn from the right side to the left side are called isotherms, which are curves with the same temperature. The higher the temperature, the higher the slope of these lines. [3]

2.16.2 The absolute water content scale

The absolute water content is the second important state quantity. It is plotted on the horizontal axis. The vertical auxiliary lines are called curves with constant absolute humidity. If the temperature, absolute humidity and atmospheric pressure is known, it is possible to determine the position of the point which represents the specific air. [3]

2.16.3 The scale of vapour pressure

Overheated water vapour which is mixed with air has a specific pressure p_D . This pressure represents part of the total air pressure, so it is called partial pressure of water vapour. Its value depends on the ratio of the mixture of water vapour and dry air. The higher the proportion of the steam, the higher the partial pressure of the vapour p_D . [3]

The pressure of saturated vapour

Partial pressure and the concentration of water vapour can be increased up to the moment when the pressure of the saturated vapour is reached. Then it is no longer able to receive the water steam. If the partial pressure is increased by adding more water steam into a system and the value of pressure goes above the pressure of saturated steam, the added steam condenses into small drops of water and creates a visible fog. When the points of saturation during different temperatures are connected, the line of saturation is created. The air is completely saturated on this boundary and it is no longer able to receive further water steam without condensation. [3]

2.16.4 Temperature of the dew point

The intersection of the vertical line representing air temperature and the saturation line is called the dew point and the corresponding temperature is called the dew point temperature. The dew point expresses the state when the liquid cannot be cooled down further without condensing. Water vapour condenses on surfaces which have a lower temperature than the dew point temperature, creating drops of water. The air temperature has to be lower than its dew point temperature to dehumidify it. [3]

2.16.5 Curves with constant relative humidity

Along the curve of saturation, the air is completely saturated by water vapour – relative humidity is 100%. If the air contains for example only 50% water, the saturation level is marked as $\varphi = 50\%$. [3]

2.16.6 Lines with constant enthalpy

Enthalpy consists of the enthalpy of dry air and the enthalpy of water vapour. The enthalpy of water vapour is significantly bigger than the enthalpy of dry air. It means that an overwhelming amount of wet air enthalpy is contained in the water vapour. If the water is sprayed in the air or the air touches a wet surface, the water is vaporised and during this process the evaporative heat is taken away. During this process there is no energy exchange between the air and the environment. Thus, there is also no change of enthalpy. Assuming that during the creation of isotherms the different specific heat of dry and wet temperatures must be respected, isoenthalpies (lines with constant enthalpy) are very close to parallel lines. [3]

2.16.7 Influence of wet bulb temperature

The principles of how the wet bulb temperature is measured have already been described in chapter 2.3. When the evaporated water has the same temperature as the air, only latent heat is necessary for providing the evaporation. When there is no condensation, it can be said that absolute humidity stays the same. By releasing enthalpy for humid air the latent and sensible is decreased. The heat is transferred to latent evaporation of water to water steam. In this situation the change during constant enthalpies exists until the saturated state is reached. The lines of wet bulb temperature (adiabatic lines) have the same slope as isoenthalpies. [3]

2.16.8 Density

Density depends mainly on three factors. The first one is the pressure of the air. The Mollier diagram applies for a certain constant value of air pressure. It is important to use the diagram only for a specific altitude. Secondly, the density depends on temperature. The higher the temperature, the bigger the expansion of the air and its density decreases. Finally, the water vapour content is mentioned in the context of density. Water vapour has lower specific mass than air. Thus, when the water vapour content increases, the density of the air – steam mixture decreases. [3].

The values described and shown above are used to create the Mollier diagram. The following chapter shows which values can be determined by using the diagram. Below in Figure 4 numbers from 1 to 10 are assigned to the diagram. Each number represents a physical quantity which is described in Table 2.

Table 2 – State variables [3]

No.	Physical quantity	Symbol	Value	Unit
1	Dry bulb temperature	ϑ_L	17	°C
2	Absolute humidity	x	6.2	g/kg
3	Water vapour partial pressure	p_D	1.0	kPa
4	Saturated vapour pressure	p_s	2.0	kPa
5	Dew point temperature	ϑ_ζ	7	°C
6	Relative humidity	φ	50	%rH
7	Enthalpy	h	33.0	kJ/kg
8	Wet bulb temperature	ϑ_F	11.5	°C
9	Density	ρ	1.175	kg/m ³
10	Absolute humidity	x	12.4	g/kg

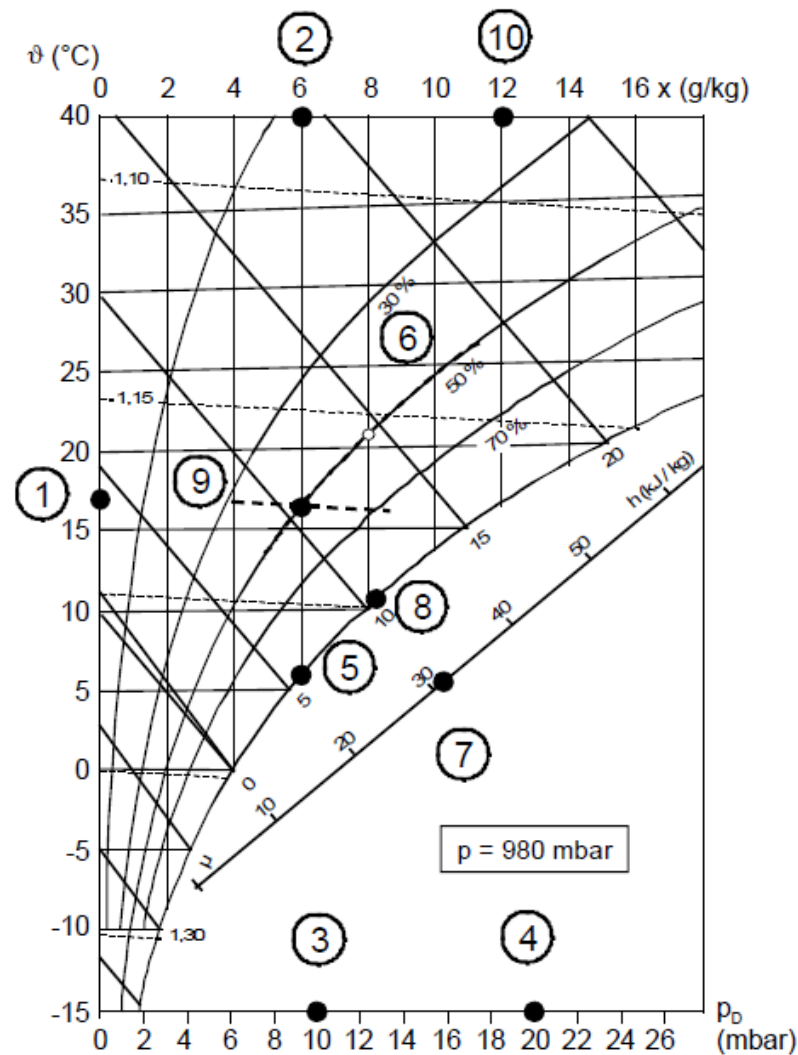


Figure 4 – States variables defining the air state [3]

2.17 Refrigerant properties

The pressure enthalpy diagram shows how enthalpy influences the pressure of a specific refrigerant. The principle of the p-h diagram is explained below. The diagram consists of two variables. The first is specific absolute pressure which is on the y axis. All the lines which are situated horizontally are called isobars. The second variable is specific enthalpy which is on the x axis. The definition of enthalpy has already been given in chapter 2.12. When the liquefied refrigerant reaches its boiling point, it is called a saturated liquid. The high heat amount between saturated states is called latent heat. Latent heat is defined as the heat which is necessary for an object to change its phase (melt, boil, freeze, etc.). Once the refrigerant starts to evaporate there is no increasing of the temperature in the system. To understand the properties of a substance it is necessary to know the saturation state of any liquid. It is possible to say that saturated liquid is ready for vaporising without any change of temperature or pressure. It means that when the liquid evaporates it will not increase the temperature of the substance and it will stay the same for the whole process of the phase change. Similarly, when gas touches the boiling point, it is called a saturated vapour. This state is very similar to the saturated liquid which was described above. When the saturated vapour starts to condense, there is no temperature change, and the pressure stays the same as well. This is valid for a single refrigerant and an azeotropic mixture.

When a zeotropic mixture starts to evaporate, the most volatile component will boil off first and the least volatile component will boil off last. In practice the saturation temperature at the inlet of the evaporator will be lower than at the outlet. The specific volume increases in response to heating a liquid refrigerant of a given pressure. A line which connects all the boiling points is called the saturated vapour and saturated liquid line. In the context of saturated liquid and saturated vapour the critical point is defined. It is defined as the highest pressure and temperature value when the liquid phase still exists. A visible difference can be seen between the liquid and the gas. Figure 5 shows a basic p-h diagram without the refrigeration cycle. [4]

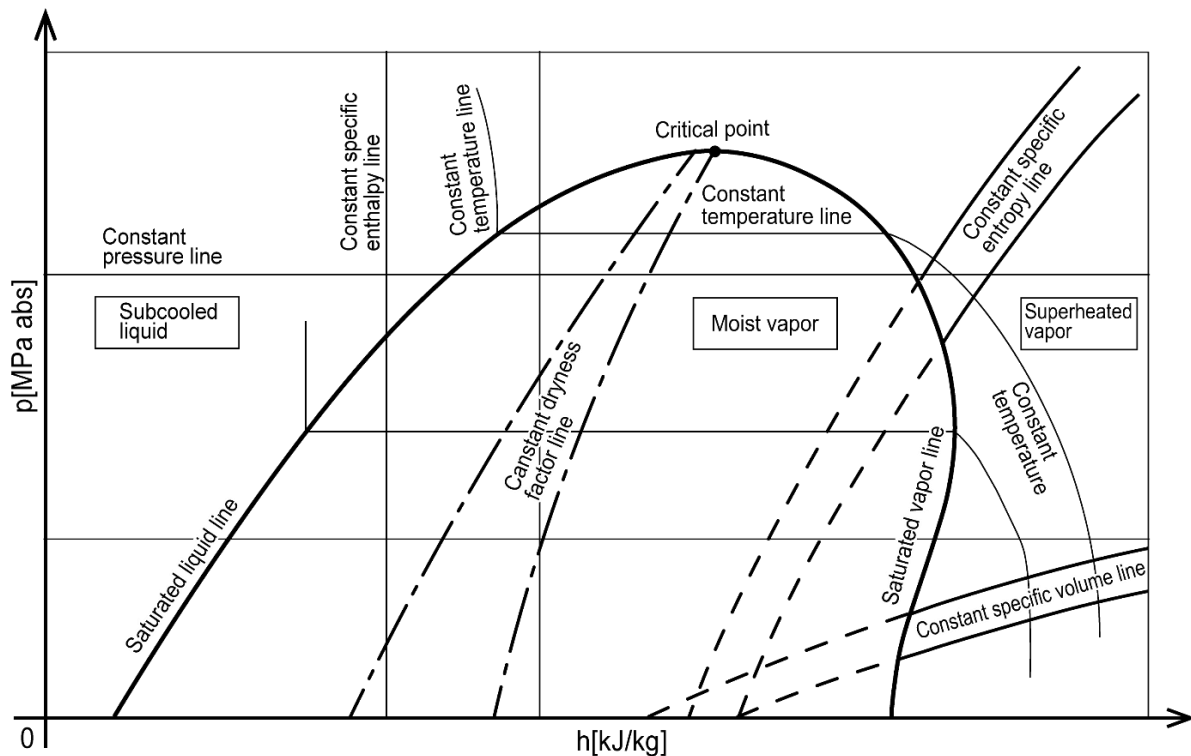


Figure 5 – p-h diagram

The point of this thesis is to calculate the uncertainty of the capacity measurement. The uncertainty of measurement belongs to the field of metrology and it is closely connected with the errors of measurement. The following paragraphs describe some basics of metrology, errors of measurement and finally the uncertainty of metrology.

2.18 Metrology in general

Metrology is an activity which has a big impact on industry from the point of view of quality and technological development. Measurements which are connected to metrology itself and the calibration of gauges is a significant requirement for increasing the quality of production.

Metrology itself is a scientific and technical discipline dealing with all knowledge and activities. It is based on uniform and accurate measurement in all fields of science. Quality management is understood as the set of activities related to the maintenance, recording, calibration and verification of measuring instruments. Its importance is due to the need to know a certain state of phenomena, whether it is in a production process, experiment or research.

Metrology can be divided into four main groups. The first is fundamental metrology. This is the basis of the metrological system. It deals with the system of measuring units, fabrication of

standards, and methods of measurement. Fundamental metrology is on the level of scientific research. The second group is called industrial metrology. This ensures the unity and accuracy of measurement in production. Industrial metrology deals with activities which are connected to the calibration of standards and working gauges. Industrial metrology is followed by legal metrology. Its target is to protect private individuals against the consequences of incorrect measurement when it comes to official and commercial business transactions, working conditions, health and safety. The final branch of metrology is scientific metrology. This involves the organisation and development of standards and their storage. [5]

2.19 Definitions of basic terms in metrology

For a better understanding of measurement and the issues associated with its evaluation, it is necessary to explain some basic terminology. The following chapters aim to introduce the essential terms and define them. Metrology is a set of experimental tasks whose target is to determine the value of a specific quantity.

2.19.1 Measurable quantity

An attribute of a phenomenon, body or substance which can be distinguished qualitatively and determined quantitatively. For example, quantity can be considered as length, time, mass, or concentration of a substance. [6]

2.19.2 Measurand

A measurand is a particular quantity subject to measurement. For example, it can be water vapour pressure of a given sample of water at 20°C. [6]

2.19.3 Influence quantity

This is a quantity which is not measured at the time, but it affects the result of the measured quantity. [6]

2.19.4 Result of measurement

This is the value attributed to the measurand and obtained by measurement. [6]

2.19.5 Repeatability of results of measurement

This is the closeness of the agreement between consecutive results from the same quantity under the same conditions. With the term repeatability there are also some conditions which have to be fulfilled to achieve the correct result. These conditions include the same measurement procedure, the same observer, the same measuring device which is used under the same conditions, the same location and repetition over a short period of time. The repeatability can be quantitatively expressed by the dispersion characteristics of the results. [6] [7]

2.19.6 Reproducibility of results of measurements

This is defined as closeness of the agreement between the results of the measurement of the same quantity under different conditions. The conditions which can be modified during the measurement are the same as described in the previous chapter. [6]

2.20 Error of measurement

When the measurement is repeated under the same conditions it is found that the measured values have some differences. This can be caused by multiple factors, for example the wrong measurement procedure, error of the measurement system or failure to observe constant conditions. When it comes to the measurement itself, only one correct value exists, so every deviation from the real value is called the error of measurement. The errors are divided mainly into two groups. The first is called absolute error and it is calculated as the difference between the result of the measurement and the true value of the measurand which is shown by formula (2). It is also important to mention that every measurement is subject to error. Basically, the appearance of the measured values is according to the Gaussian distribution which can be seen in Figure 6. More recently, the error of measurements has been expanded to the term which is called uncertainty of measurement, which is a statistical method for evaluating errors of measurement and measured data.

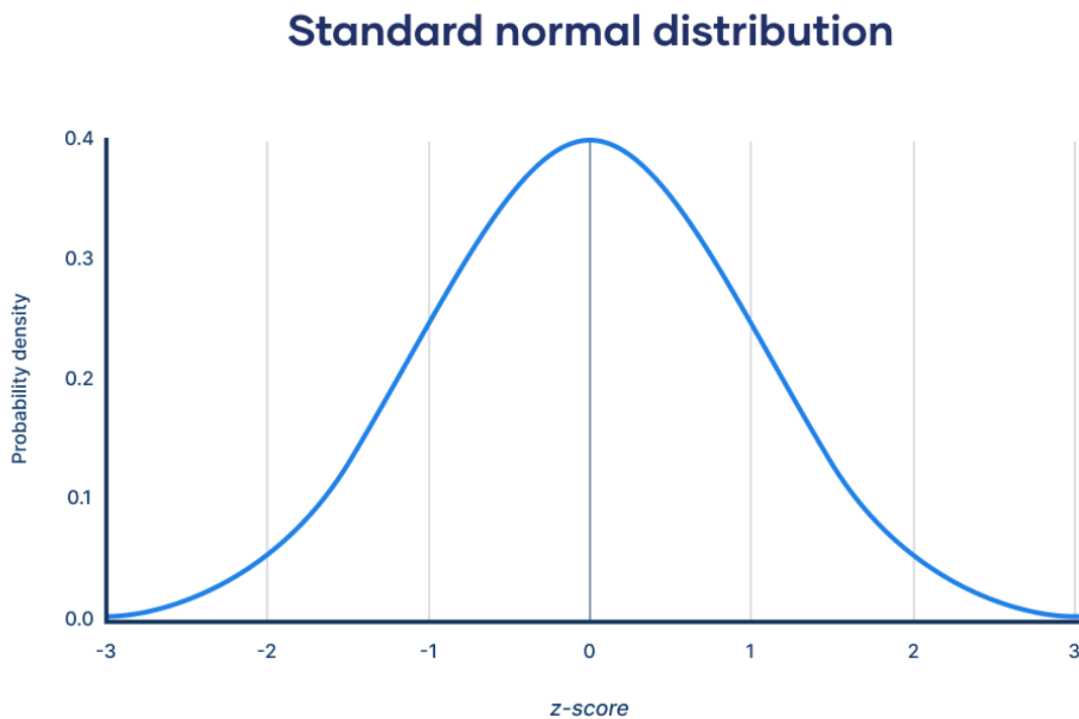


Figure 6 – Gaussian distribution [9]

$$\varepsilon = y - x_0 \quad (2),$$

where

ε – absolute error of measurement

y – the result of measurement

x_0 – measurand

The second error is called relative error and it is calculated by the following formula (3).

$$\delta = \frac{\varepsilon}{x_0} \cdot 100 \quad (3),$$

where

δ – relative error [%]

ε – absolute error

x_0 – measurand

For the estimation of the error, which is stated in formula (3), only one value is not optimal, but the error can still be determined.

First the errors of the individual components have to be determined so that the whole error of measurement can be determined. In practice this means that the whole system of measurement has to be described and determined. This is why an Ishikawa diagram was drawn as shown in Figure 23. This was done to determine which are the most significant factors affecting the results of the measurements, and the whole process of measurement was analysed. The number of measurements should be greater than 10. If this is impossible, and there are less than 10 measurements, the measured data cannot be evaluated, and it has to be evaluated as a type B uncertainty.

It is important to mention that if the result of a measurement is dependent on the values of some other quantities, the error of these quantities contributes to the error of the result of the measurement itself. In general, the measurement contains the source of the imperfections which cause the errors. Traditionally, there are three types of errors during the measuring process. These are random, systematic and rough errors. [6] [7] [5]

2.21 Random error

Random error is due to unpredictable or random temporary and spatial variations of influence quantities. When the measurement is repeated the size of the error and its sign (plus or minus) can change. Statistical methods are used to calculate the random error. Gaussian distribution (Figure 6) is the most common one. It is calculated as the difference between the result of the measurement and the middle value which results from an infinite number of measurements of the same measurand performed under the condition of repeatability. The results are represented by arithmetic mean, which depends on the number of measurements. The random error in the classical theory of mistakes is represented by standard deviation. The estimation of standard deviation and the estimation of standard deviation of a chosen arithmetic mean are described by formulas (4) and (5). The random error values are used for statistical evaluation of the data.

$$s = \sqrt{\frac{\sum_{i=1}^n \Delta y_i^2}{n-1}} = \sqrt{\frac{\sum_{i=1}^n (y_i - \bar{y})^2}{n-1}} \quad (4),$$

where

s – estimation of standard deviation

n – number of measurements

Δy_i – absolute deviation i^{th} element from the arithmetic mean

y – measured quantity

\bar{y} – arithmetic mean

$$s_{\bar{y}} = \frac{s}{\sqrt{n}} = \sqrt{\frac{\sum_{i=1}^n (y_i - \bar{y})^2}{n(n-1)}} \quad (5),$$

where

$s_{\bar{y}}$ – estimation of standard deviation of the chosen arithmetic mean

n – number of measurements

s – estimation of standard deviation

Both deviations which are expressed in formulas (4) and (5) are widely used for the characteristics of random errors. These errors are involved in the uncertainties of measurement.

[7] [6]

2.22 Systematic error

Systematic errors are revealed when one measurement is compared to another one. The other measurement is gained by another method, person or some other measuring device. This group also includes errors caused by temperature differences between the measured part and the measuring device. Systematic errors have a constant size and sign (plus or minus) under the same conditions and systematically influence the results of measurement. Formula (6) shows how the systematic error can be expressed.

$$\Delta y = y_m - x_s \quad (6),$$

where

Δy – systematic error

y_m – the chosen arithmetic mean

x_s – conventional correct value (value of the standard)

In terms of the measuring device, the benefit of systematic errors is that they can be determined and their influence can be reduced by using compensation and correction. This is how to remove a significant negative influence for the measurement. A systematic error is defined as follows. If there is an infinite number of measurements of the same quantity under the condition of repeatability, it is the middle value minus the right value of the measured quantity. For evaluation of the data, the values which are part of the systematic error need to be deleted or a correction has to be performed. [6]

2.23 Rough error

Rough error can be recognized very easily because its value is significantly different from the other values. It is caused by some kind of error, incorrect reading from the scale, a damaged machine or an incorrect procedure during the measurement. The process of measurement is stopped until the causes of these errors are eliminated. In some cases, there is no one hundred percent certainty that the measured value is actually a rough error, so the suspected values are tested. This testing is performed under the assumption that the measured values have a standard distribution of probability. The first step of testing is to calculate the value of the chosen arithmetic mean by formula (7). Before the data processing starts, there is a test which eliminates the values which are suspected of being a part of the rough error. The calculation is given below.

$$\bar{q} = \frac{1}{n} \sum_{k=1}^n q_k \quad (7),$$

where

\bar{q} – arithmetic mean or average

n – number of measurements

q_k – values of the individual measurements

[6]

When the parameter \bar{q} is known, the deviation $s(q_k)$ needs to be calculated. The calculation of $s(q_k)$ is shown in the formula (8).

$$s(q_k) = \sqrt{\frac{\sum_{j=1}^n (q_j - \bar{q})^2}{n-1}} \quad (8),$$

where

$s(q_k)$ – experimental standard deviation

\bar{q} – arithmetic mean or average

n – number of measurements

q_j – results from partly measurements

When the parameter \bar{q} is calculated, the outlying extreme values have to be found. It is expressed by formula (9).

$$H_n = \frac{x_n - \bar{q}}{s(q_k)} \quad (9),$$

$s(q_k)$ – experimental standard deviation

x_n – value which is suspected from the extreme

\bar{q} – arithmetic mean or average

H_n – the standard value

The tolerance limit value is marked as H and it is gained from Table 3 below.

Table 3 – Limit values H for probability p and range of selection n [8]

Range of selection n	Limit value H for the probability p			
	0.90	0.925	0.95	0.975
3	1.15	1.15	1.15	1.15
4	1.12	1.44	1.46	1.48
5	1.60	1.64	1.67	1.72
6	1.73	1.77	1.82	1.89
7	1.83	1.88	1.94	2.02
8	1.91	1.96	2.03	2.13
9	1.98	2.04	2.11	2.21
10	2.03	2.10	2.18	2.29
11	2.09	2.14	2.23	2.36
12	2.13	2.20	2.29	2.41
13	2.17	2.24	2.33	2.47
14	2.21	2.28	2.37	2.50
15	2.25	2.32	2.41	2.55
16	2.28	2.35	2.44	2.58
17	2.31	2.38	2.48	2.62
18	2.34	2.41	2.50	2.66
19	2.36	2.44	2.53	2.68
20	2.38	2.46	2.56	2.71
25	2.635	2.87	3.351	3.944
30	2.696	2.928	3.402	3.988
40	2.792	3.015	3.48	4.054
50	2.86	3.082	3.541	4.108
100	3.076	3.285	3.723	4.263

When the value H_n is reached it has to be compared to the value H from the Table 3 above. If $H_n < H$, it can be said that the value is not a rough error. Otherwise, it is considered as a rough error, and it has to be deleted from the datasheet or it can be measured again. Both options are possible. It depends mainly on the measurement process. [8]

2.24 Uncertainty of measurement

In the context of error of the measurement, a new term is used. This is the uncertainty of measurement and it is connected closely to the errors. Generally speaking, uncertainty of measurement is some kind of parameter which is related to the results of measurement. It is represented by the interval where the measured quantity can be found. Previously the error of measurement was used because there were no such options to calculate or define the uncertainty of measurement. That comes with the higher demands on the quality and precision of determining the results. The whole issue of uncertainty consists of several sublevels. There are two ways to calculate the uncertainty. They are the evaluation of standard uncertainty by method A and method B. They are described below. [7]

2.25 Evaluating standard uncertainty

The following section describes how to evaluate the uncertainties of measurement.

2.25.1 Type A evaluation of standard uncertainty

Type A evaluation of standard uncertainty comes from statistical analysis while the measurement is repeated. An estimate of the inputs which are not evaluated from repeated observations must be obtained by some other methods which are not important to mention here. The individual observations can obtain different values because of random fluctuation of influence quantities or due to some other random influences. The definition of influence quantity is given in chapter 2.19.3. The calculation of the arithmetic mean or average is expressed in the previous chapter by formula (7). If the number of measurements is greater than 10, formulas (10) and (5) can be used. They are basically the same formulas, and that is why type A uncertainty is very similar to random error. If the number of measurements is less than 10, the value is not as reliable as it should be, and evaluation method B should be used instead of type A.

$$u_A = s_{\bar{y}} = \sqrt{\frac{\sum_{j=1}^n (q_j - \bar{q})^2}{n(n-1)}} \quad (10),$$

where

$s_{\bar{y}}$ – experimental standard deviation

\bar{q} – arithmetic mean or average

n – number of measurements

q_j – results from partial measurements

u_A – standard A uncertainty

Formula (10) represents the calculation of type A uncertainty when the number of measurements is greater than 10. If the number of measurements is less than 10, the following formula (11) is used. The coefficient k_s is used for the calculation, which depends on the number of measurements. Its values are shown in Table 4.

$$u_A = k_s s(q_k) \quad (11),$$

where

$s(q_k)$ – experimental standard deviation

k_s – coefficient which depends on the number of measurement

Table 4 – Values of coefficient k_s which depends on number of measurements n

n	9	8	7	6	5	4	3	2
k_s	1.2	1.2	1.3	1.3	1.4	1.7	2.3	7

Table 4 shows that reducing the number of measurements leads to a disproportionate increase of uncertainty. When the number of measurements goes below 5, the measured data has only an informative character.

[6] [7]

2.25.2 Type B evaluation of standard uncertainty

Standard uncertainty type B is not connected to the number of measurements. It is estimated based on experience, skills and some information. The pre-measurement, information from the producer, information gained from calibration and certificates can be used. If both uncertainties are known, combined uncertainty can be determined. The calculation procedure for evaluating type B standard uncertainty is shown below. The first step is to identify the factors which can be a source of the uncertainty. In this thesis the Ishikawa diagram has been constructed with the help of a specialist in capacity measurement. The uncertainty of each source is determined by using available documents or by estimation which is described further below and can be seen in Figure 7.

Approximation by standard (Gaussian) distribution is used when small deviations from the nominal value are expected. For example, if the source of uncertainty is the measuring gauge which has been produced by a reliable producer, it can be expected that the errors will not be high. Rectangular distribution is used if there is the same probability of appearance of any deviation in the whole interval $\pm z_{j\max}$. This approximation is the most common in practice. The reason is that the enough facts about a distribution of probability appearance of deviations are not mostly available. So, rectangular division is the same for all deviations. Triangular division is used for modelling situations in cases which are very similar to standard division. Bimodal division is used for approximating uncertainties for example for measuring gauges which are not as precise as gauges which are inside standard division.

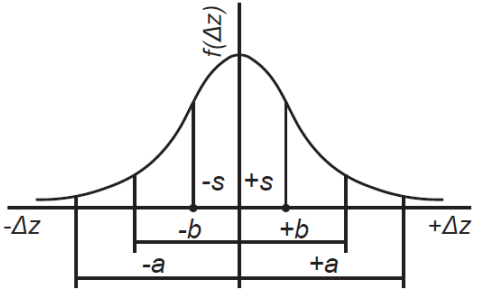
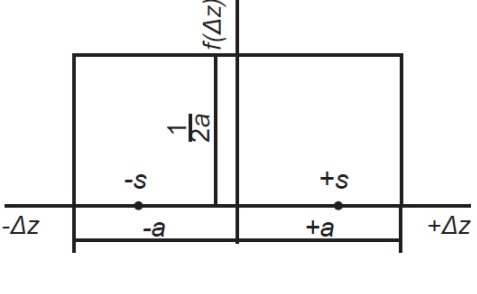
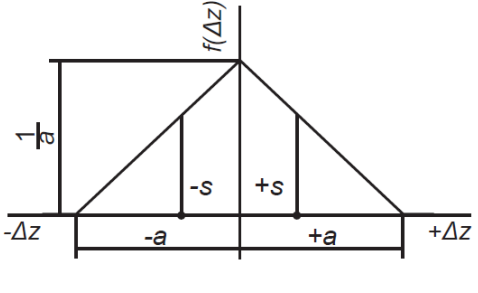
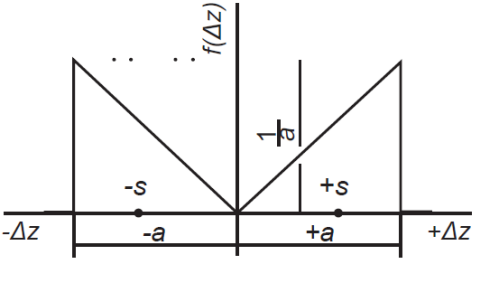
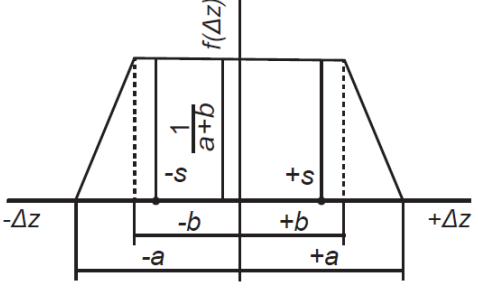
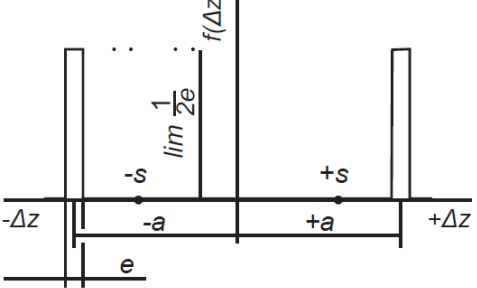
Division	Z_{\max}	k	Division	Z_{\max}	k
	a	3		a	$\frac{\sqrt{3}}{1.73}$
	a	$\frac{\sqrt{6}}{2.45}$		a	$\frac{\sqrt{2}}{1.41}$
	a	2.32 for $b = \frac{a}{3}$		a	1
	a	-2.19 for $b = \frac{a}{2}$			
	a	-2.04 for $b = \frac{2a}{3}$			

Figure 7 – Division of measured values [6]

Following this, the values of $\pm\Delta z_{\max}$ are estimated. This has to be done to prevent exceeding the value of Z_{\max} .

Type B uncertainty of each source Z_j is determined by formula (12)

$$u_{Bz_j} = \frac{\Delta z_{j\max}}{k} \tag{12},$$

where

$\Delta z_{j\max}$ – maximum deviation range of each source

k – parameter which can be seen in Figure 7 (divisor)

The fourth step is the assessment of correlation between each source. Finally, the formula which describes the relation between quantity X and every single source is determined. This is shown in formula (13).

$$X = f(Z_1, Z_2, \dots, Z_j, \dots, Z_p) \tag{13},$$

The measured value X has its type B uncertainty determined by formula (14).

$$\mathbf{u}_{x,z_j} = \mathbf{A}_{x,z_j} \mathbf{u}_{z_j} \quad (14),$$

where

u_{z_j} – type B standard uncertainty

A_{x,z_j} – coefficient of sensitivity

Quantity A_{x,z_j} is calculated by formula (15).

$$\mathbf{A}_{x,z_j} = \frac{\partial X}{\partial z_j} \quad (15),$$

Standard ISO TS 16491 (2012) determines that for calculations of each factor uncertainty, the relative standard uncertainty should be used. It is calculated as follows by formula (16)

$$\mathbf{u}_{b(x)} = \frac{u(x)}{\bar{u}(x)} \quad (16),$$

where

$u_{b(x)}$ – relative standard uncertainty

$u(x)$ – value of standard uncertainty

$\bar{u}(x)$ – arithmetic mean of values

[9] [7] [10]

2.25.3 Determination of combined uncertainty

When uncertainty type A and uncertainty type B are quadratically summarized, the combined standard uncertainty is determined. Combined standard uncertainty gives the interval where the actual value of the measurand exists with high probability. It is expressed by formula (17).

$$\mathbf{u}_c = \sqrt{\mathbf{u}_A^2 + \mathbf{u}_B^2} \quad (17),$$

Where

u_c – combined standard uncertainty

u_A – type A standard uncertainty

u_B – type B standard uncertainty

2.25.4 Expanded standard uncertainty

If the standard uncertainty is not enough, the expanded standard uncertainty has to be used. The standard uncertainty gives the probability of standard distribution correctness of about 68%. If the requirement is that the probability should be close to 100%, then the expanded uncertainty has to be calculated. This is done by using coefficient k_u which is called the coefficient of expansion. This coefficient can be equal to 2 which ensures a probability of 95% or can be equal to 3 which ensures a probability of 99.7%. The calculation of expanded uncertainty is shown in formula (18).

$$\mathbf{U} = \mathbf{u}_c k_u \quad (18),$$

where

U – expanded standard uncertainty

u_c – combined standard uncertainty

k_u – coefficient (in the case mentioned above, $k_u=2$)

The values of coefficients are rounded up to three decimal places. The final uncertainty is rounded to two decimal places. How the result of measurement using uncertainty is shown can be seen as follows. For example, the capacity of an indoor unit could be expressed as $4.60\text{kW}\pm 10\%$. In the examples, the uncertainties are written as follows:

$\varnothing (20.00 \pm 0.25) \text{ mm}$

$\varnothing 20.00 \text{ mm} \pm 0.25 \text{ mm}$

$\varnothing 20.00 \text{ mm} \pm 250 \mu\text{m} P=95\%$

In the examples above it can be seen that it is necessary to have equal numbers of decimal places. This means that the number of decimal places for uncertainty have to be the same as the number of decimal places for the measured dimension.

In relation to uncertainty, it is also important to mention false acceptance and false rejection. This situation is shown in Figure 8 and is described below.

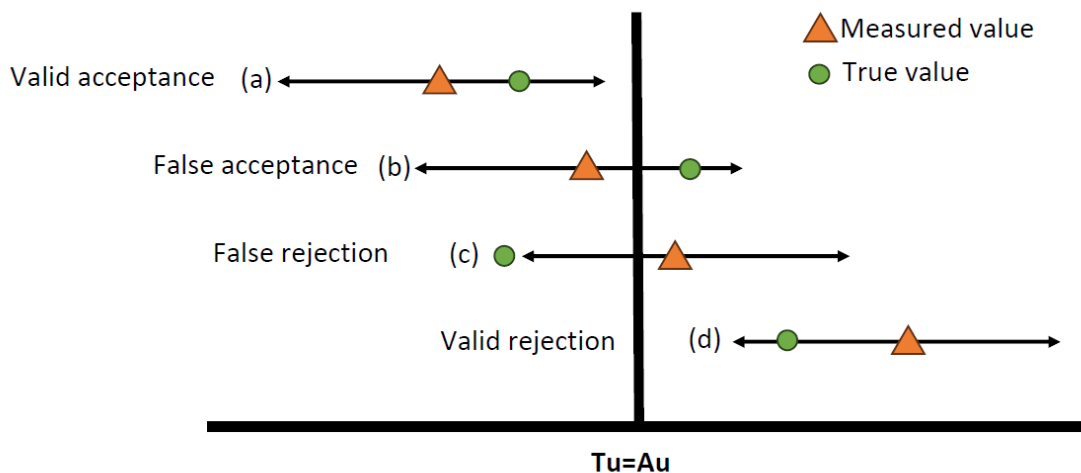


Figure 8 – False and valid rejection

$T_u=A_u$ means the nominal value of the measured quantity. The green circle represents the true value and the orange triangle represents the measured value. When the tolerance field is not narrowed by the value of uncertainty, according to the figure above, four states can be reached. Valid acceptance and valid rejection do not have to be explained, they are clear from the figure. False acceptance can happen when the uncertainty of the measuring chain is not calculated, so it seems that the true value is in the interval which represents the parts which are calculated according to the tolerance. In fact, when the value of uncertainty is used for narrowing the tolerance field, the result of the evaluation will not be correct. A similar situation happens during false rejection. Valid acceptance is marked as (a) and valid rejection is marked as (d) in Figure 8.

For analysis and evaluation of uncertainty during capacity measurement using the air enthalpy method, the following standards EN 14511-3 (2022), EN 14825 (2022), ISO TS 16491 (2012), ISO 5151 (2017) are used.

2.26 Ishikawa diagram

The diagram is also known as the fish bone diagram, herringbone diagram, cause and effect diagram or Fishikawa. It shows the connections between cause and effect in more detail. Basically, causes are divided into multiple main groups and these are subsequently described and finally the root effect is determined. The steps which need to be taken to construct the diagram are as follows. Firstly, the problem has to be determined as simply as possible. Secondly, the effect is written down. This is the problem which needs to be analysed. After that, the main categories which could cause the problem need to be identified. This is followed by brainstorming where all the causes are written down according to the previous steps. Finally, all the factors need to be evaluated and the most probable causes determined. All the steps described above can be seen in Figure 9. [11] [12]

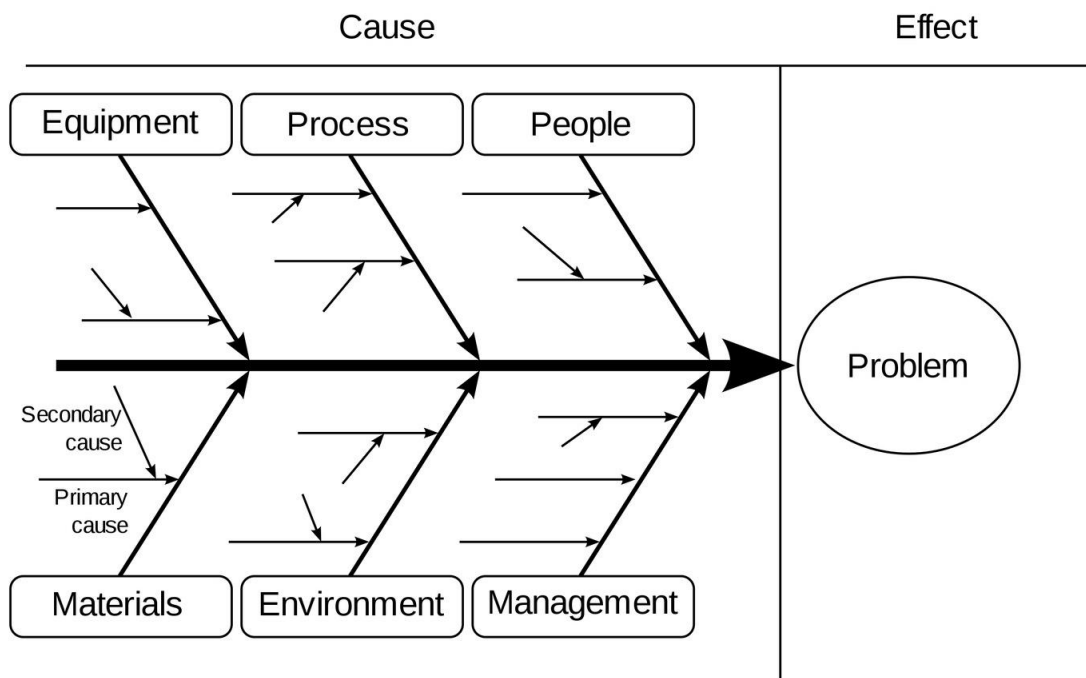


Figure 9 – Draft of Ishikawa diagram [13]

3 Experimental description

In this chapter there is an explanation of the principles of a heat pump, the layout of the chamber is shown and the essential calculation mainly of the total cooling capacity is described.

3.1 Four components of the refrigeration cycle

To understand the refrigeration cycle properly it is necessary to describe how the ideal refrigeration cycle is drawn into a p-h diagram. The conditioner consists of four basic components. The first is a compressor, the second is a condenser followed by expansion and finally an evaporator. The whole process starts with compression. The compressor sucks in gases which are generated in the evaporation process and change the pressure and temperature of the refrigerant from low values to higher ones. This is called superheated vapour in the compressor. Refrigerant is superheated on the input side and on the output side too. This action takes place during the adiabatic process. After this it continues to the condensation phase. The superheated, high-temperature, high-pressure gas is transformed into condensed subcooled liquid. After this the whole process is followed by expansion when the pressure of the condensed liquid refrigerant is reduced through an expansion valve. In an ideal case, there is no heat transmission between the refrigerant and the surroundings. Thus, this phase occurs during constant specific enthalpy. The final phase is comes evaporation. During this the low-temperature and low-pressure subcooled liquid refrigerant evaporates and removes heat from the air or the moisture. In the p-h diagram this change is marked by a horizontal line which represents the constant pressure line. The whole process is shown in Figure 10.

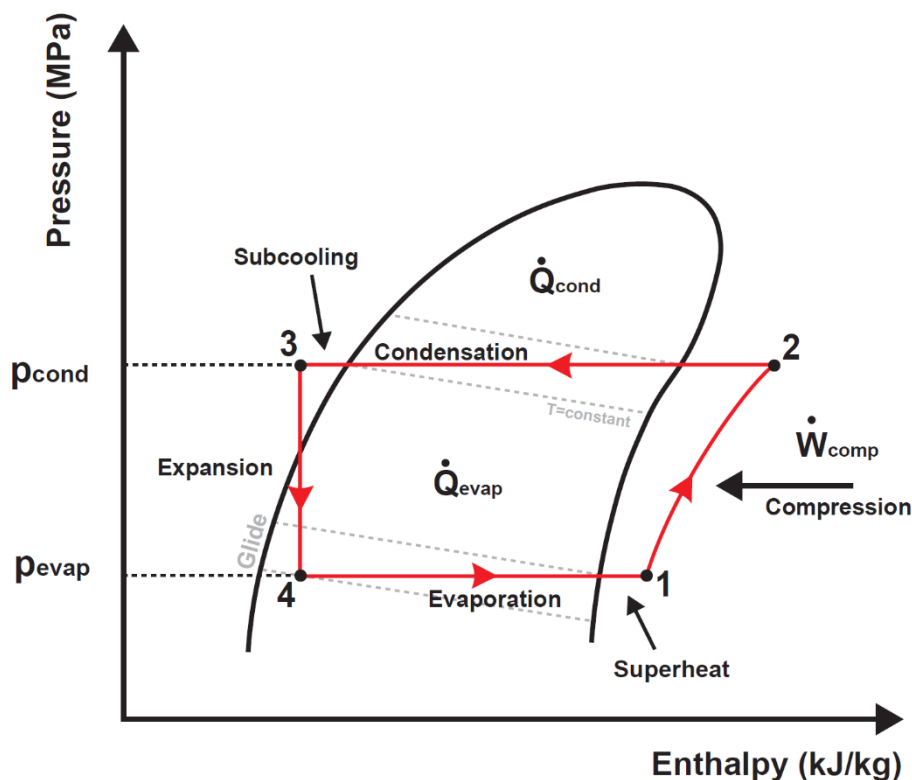


Figure 10 – Refrigeration cycle [21]

In Figure 11 the refrigeration cycle is depicted showing the actions of the four main components.

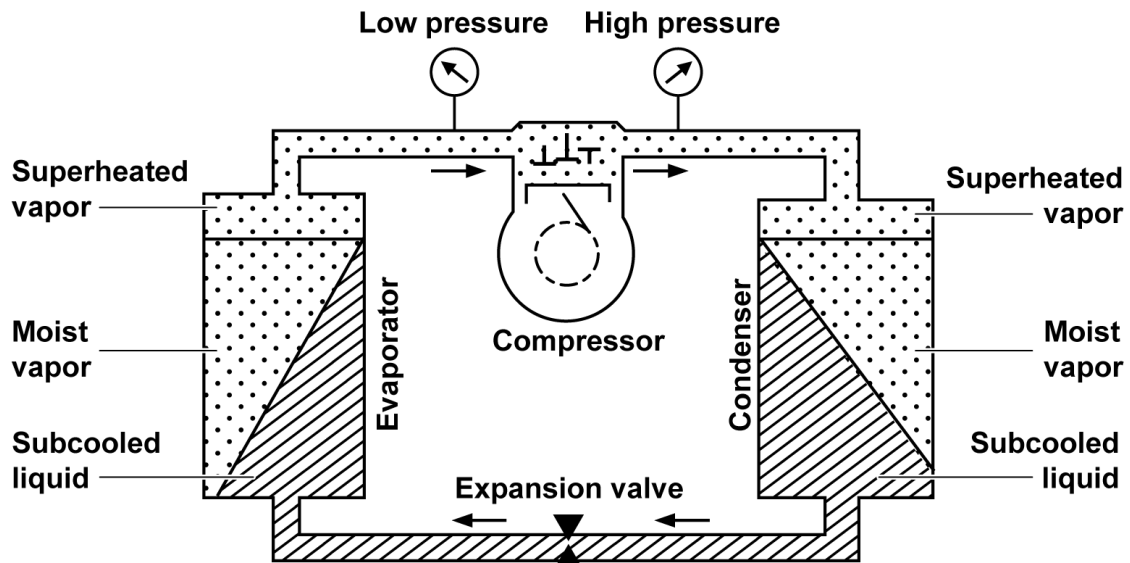


Figure 11 – Refrigerant cycle [21]

3.2 Cooling, heating, defrost operation

It is important to mention that, unlike heat pumps, air conditioners can only perform cooling operations. Both heat pumps and air conditioners are able to operate in cooling and also heating mode thanks to the reversing valve in the outdoor unit. Cooling happens when an indoor unit produces cold air and an outdoor unit blows warm air into the surroundings. Basically, it means that the temperature of the suction air is higher than temperature of the discharge air. In this case the heat exchanger of the indoor unit is called an evaporator and the outdoor unit's heat exchanger is called a condenser. In the opposite case, heating occurs.

At very low ambient temperatures, there is a risk of ice building up on the evaporator. In this case it is a heat exchanger of an outdoor unit. To prevent this risk, there is an operation which is called defrost. This means that the refrigeration cycle is performed in the outdoor unit. This has the effect of warming up the heat exchanger and melting the ice which has built up.

3.3 Installation of an indoor unit for measuring the capacity by using the air enthalpy method

In this chapter the principle of the installation of an indoor unit for testing the capacity using the air enthalpy method is described. The measurement itself is based on measuring the entering and the leaving air temperatures and associated air flow rate. It is therefore necessary to connect the indoor air outlet section of the unit to an air flow measuring device.

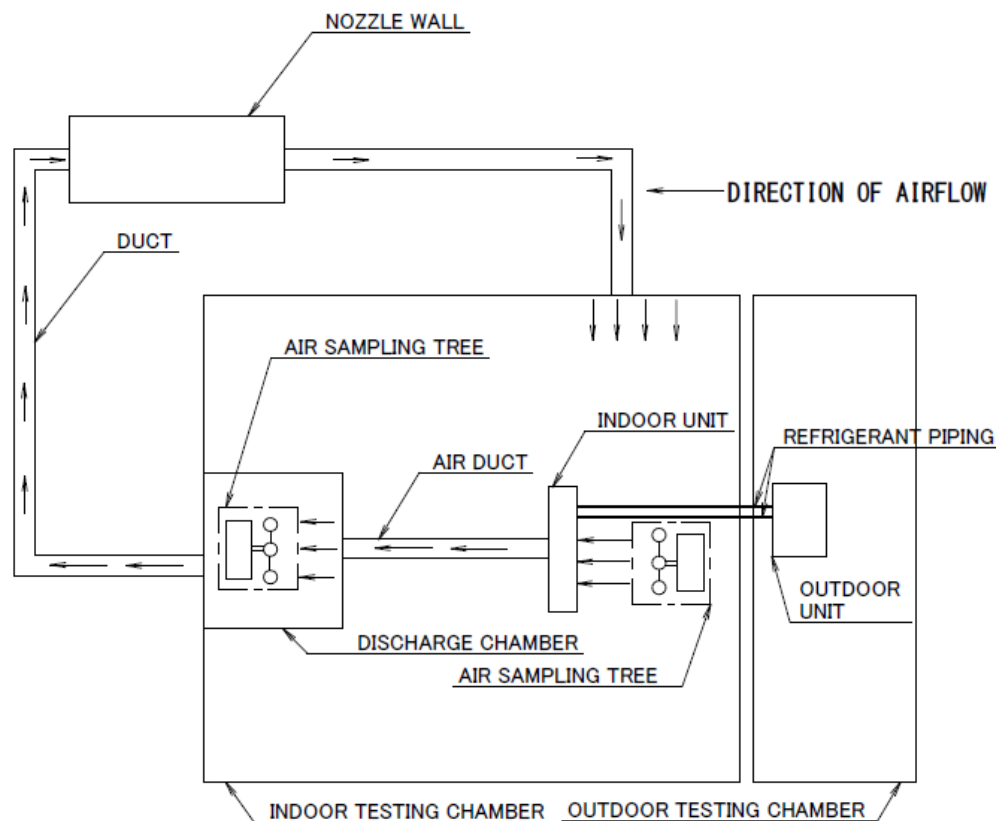


Figure 12 – Testing chamber layout

How to install the unit itself is described in the internal standards. The way it is done is not important for the purposes of this thesis. What is more important is the installation of the layout of the measurement circuit. This layout can be seen in Figure 12.

The outdoor and indoor units are connected by field piping. A short duct is used for connecting the discharge chamber to the air outlet section. It serves to prevent blocking air from the unit and it is adapted to its air outlet section size. This leads to the design of the discharge chamber. It should be at least the same size as the air outlet section of the unit. It has to be constructed to not prevent the leaving air from expanding. A rough draft of a chamber layout can be seen in Figure 12. After that the air goes through the duct to the nozzle wall and back to the chamber. A more detailed description of the chamber can be seen in chapter 4.2 including the draft which is described in greater depth. The sampling tree serves for measuring the air parameters. Details of this tree are shown in more detail in Figure 15.

3.4 Capacity calculation

When the unit is installed and tested as described in chapter 3.3, the evaluation of the measurement process begins. Results are achieved by the system itself where the calculations are performed. This means that the testing engineers do not interfere with this process. The final data are available in real time in an excel file. For a better understanding of how the whole process works, the basics of the calculations are described below. For the calculation it is necessary to know the volumetric air flow which is described by formula (19).

$$Q_v = AC \sqrt{\frac{2dp}{\rho}} \quad (19),$$

where

Q_v – volumetric air flow [m³/min]

A – flow area [m²]

C – function of Reynolds number

dp – pressure difference [Pa]

ρ – air density [kg/m³]

Enthalpy is described in chapter 2.12 and it is another necessary quantity for the capacity calculation. To the determine enthalpy, formula (20) applies.

$$H = 1004.16T_{DB} + (2499.1 + 1845.14T_{DB})x \quad (20),$$

where

H – enthalpy [J]

T_{DB} – dry bulb temperature [K]

x – absolute humidity [g/kg]

Also, the absolute humidity has to be determined. Formula (21) describes how it is expressed.

$$x = \frac{m_v}{V} \quad (21),$$

where

m_v – mass of the water vapour [g]

V – volume of the air [m³]

Also the standard EN 14511-3(2022) determines the calculation of total cooling capacity which is necessary to evaluate the uncertainty of measurement. This is described by formula (22).

$$\phi_{tci} = \frac{q_{vi}(h_{a1} - h_{a2})}{v'_n(1 + W_n)} \quad (22),$$

where

q_{vi} – air volume flow rate, indoor-side [m³/s]

h_{a1} – specific enthalpy of air entering indoor-side [J/kg of dry air]

h_{a2} – specific enthalpy of air leaving indoor-side [J/kg of dry air]

v'_n – specific volume of air-water vapour mixture at nozzle [m³/kg]

W_n – specific humidity at nozzle inlet [kg/kg of dry air]

ϕ_{tci} – total cooling capacity [W]

3.5 CoolProp software

Very complex formulas are used to calculate the properties of the humid air or refrigerant. For the purposes of this thesis the way of calculating all the physical quantities is not so relevant. More important are the results themselves. That is why CoolProp is used for calculating all the necessary values. It is a C++ library that implements the properties of the humid air and refrigerant.

All the equations which are inside CoolProp logic are based on the results of the ASHRAE research project ASHREA-RP1485. The code which is used for CoolProp has high accuracy and all the tests which were performed to verify its results ended successfully. The software is applicable for a range of pressures from 10 Pa up to 10 MPa and a temperature range from -143.15 °C up to 350 °C with a humidity ratio from 0 kg of water up to 10 kg of water per kg of dry air. Water vapour and air mixture can be used for modelling humid air. In the simplest situation, air and water should be considered as ideal gases but in fact there is an interaction between the air and water molecules that must be included when the interaction parameters are used. Since humid air is a mixture of dry air and water vapour, three variables are required to fix the state by state postulate. [14]

4 Evaluation of the experiments and their assessment

The practical part of this thesis was performed at Daikin Industries Czech Republic (DICz) in the EMEA development centre. The motivation for this thesis was provided by the compliance group due to new legislation which declares that the uncertainty of capacity measurement should be determined. The chamber is called 20HP, which indicates the maximum reachable capacity. The calculation process and its evaluation is described in the chapters below. As described in chapter 3.2, heat pumps can operate in two conditions – cooling or heating. For the practical part of this thesis, the cooling operation is evaluated.

4.1 Confirmation of compliance with standard EN 14511-3 (2022)

Before the calculation is done it is necessary to determine if the measuring device uncertainties comply with the actual demands for applying the standard EN 14511-3 (2022) for evaluation. The standard states the maximum allowed values for these uncertainties and also the value for the combined uncertainty, which has to be lower than 5%. This can be seen in the table below. Originally, the table was larger because it also included values for the refrigerant itself. Since this thesis is only concerned with air parameters, these are chosen for further evaluation. The first demand is the static pressure difference. Its value of uncertainty is $\pm 5\%$ when the pressure difference is greater than 100 Pa which is this case. The second demand is to state the air flow volume. An uncertainty of $\pm 5\%$ is given for this. The third demand is the uncertainty of the wet bulb temperature which is described as ± 0.4 K. The last factor, dry bulb temperature uncertainty, is given as ± 0.2 K. For better orientation these values are listed in Table 5. [15]

Table 5 – Maximum allowed uncertainty of measurement [15]

Measured quantity for air parameters	Marking	Units	Maximum allowed uncertainty of measurement
Dry bulb temperature	T_{DB}	K	$\pm 0.2K$
Wet bulb temperature	T_{WB}	K	$\pm 0.4K$
Air volume flow	q_{vi}	m^3/s	$\pm 5\%$
Static pressure difference	p	Pa	$\pm 5\%$

These values are stated by the standard as the maximum allowed uncertainties. To confirm that the measuring system for the total cooling capacity is compliant with the standard EN 14 511-3 (2022), all the previous values of uncertainties at DICz need to be given.

The calibration sheet was used to obtain the information about the uncertainty of the static pressure difference. For air volume flow, the calculation of uncertainty was used according to the standard ISO TS 16491 (2012) which can be seen in chapter 4.6.2.1 where evaluation of relative standard B uncertainties of air volume flow is calculated. Finally, for dry bulb and wet bulb temperature, no information about uncertainty was found, therefore the internal calculation of expanded uncertainty is performed. More details of this calculation can be seen in the next chapter.

4.1.1 Calculation of uncertainty for dry bulb and wet bulb thermometer PT-100

As mentioned in chapter 4.1 DICz does not have a value of uncertainty for PT-100 sensors. This leads to the need for self-evaluation as part of this thesis.

4.1.1.1 Determining standard B uncertainty

Firstly, for internal calibration of these thermometers there is a calibration furnace which is seen in Figure 13. This furnace can set specific conditions. It is also the subject of external calibration, and the calibration sheet states the value of standard B uncertainty as 0.05K. This value will be used for the calculation of combined uncertainty.



Figure 13 – Calibration furnace

4.1.1.2 Test procedure of standard A uncertainty and calculation

For the evaluation of standard A uncertainty, a specific measurement was performed. Wet bulb and dry bulb thermometers are put inside the calibration furnace with a condition of 0°C. After the temperature stabilises, the value is deducted from the display. After that, the thermometers are taken out for 5 minutes. Then the thermometers are put inside the furnace again with the same condition. This whole procedure is repeated until 20 values are measured. These measured values are shown in Table 6.

After that the evaluation of standard A uncertainty is performed according to chapters 2.23 and 2.25.1. The formula (7) is used for calculating the arithmetic mean. This is described by formulas (23) and (24)

$$\bar{T}_{db} = \frac{1}{n} \sum_{k=1}^n T_{db} = \frac{1.31}{20} = 0.0655 \text{ [K]} \quad (23),$$

where

\bar{T}_{db} – arithmetic mean of dry bulb temperature [K]

$$\bar{T}_{wb} = \frac{1}{n} \sum_{k=1}^n T_{wb} = \frac{3.09}{20} = 0.1545 \text{ [K]} \quad (24),$$

where

\bar{T}_{wb} – arithmetic mean of wet bulb temperature [K]

Once the arithmetic mean is calculated, experimental standard deviation $s_{T_{wb}}$ and $s_{T_{db}}$ is determined from formula (8). This is expressed by formulas (25), (26).

$$s_{T_{db}} = \sqrt{\frac{\sum_{j=1}^n (T_{db} - \bar{T}_{db})^2}{n-1}} = \sqrt{\frac{0.0058}{20-1}} = \mathbf{0.0176 [K]} \quad (25),$$

where

$s_{T_{db}}$ – experimental standard deviation for dry bulb temperature [K]

$$s_{T_{wb}} = \sqrt{\frac{\sum_{j=1}^n (T_{wb} - \bar{T}_{wb})^2}{n-1}} = \sqrt{\frac{0.0122}{20-1}} = \mathbf{0.1545 [K]} \quad (26),$$

where

$s_{T_{wb}}$ – experimental standard deviation for dry bulb temperature [K]

The calculation continues by using formula (9), which describes the outlying extreme values which have to be found. This comparison of the standard value H according to Table 3 is seen in Table 6. The value H=2.56 is chosen for the 20 measurements and a probability of 95%.

Table 6 – Measured values of dry bulb and wet bulb thermometer PT-100

Measurement No.	Value of standard [°C]	Measured value DB [°C]	Measured values WB [°C]	Standard value dry bulb H_n [°C]	Standard value wet bulb H_n [°C]
1	0	0.11	0.16	2.526	0.035
2	0	0.09	0.18	1.391	0.163
3	0	0.08	0.19	0.823	0.227
4	0	0.08	0.17	0.823	0.099
5	0	0.08	0.16	0.823	0.035
6	0	0.07	0.15	0.255	0.029
7	0	0.07	0.12	0.255	0.221
8	0	0.09	0.14	1.391	0.093
9	0	0.06	0.16	0.312	0.035
10	0	0.05	0.14	0.880	0.093
11	0	0.05	0.14	0.880	0.093
12	0	0.05	0.16	0.880	0.035
13	0	0.05	0.17	0.880	0.099
14	0	0.05	0.16	0.880	0.035
15	0	0.06	0.17	0.312	0.099
16	0	0.05	0.19	0.880	0.227
17	0	0.06	0.19	0.312	0.227
18	0	0.05	0.11	0.880	0.285
19	0	0.06	0.11	0.312	0.285
20	0	0.05	0.12	0.880	0.221

As can be seen, all the values of standard value H_n are within the tolerance limit value H .

After a rough error check, none of the measured values are suspected of being from rough errors. So the calculation of standard A uncertainty can be determined by using formula (10). This is described by formulas (27) and (28).

$$u_{A_{T_{db}}} = \sqrt{\frac{\sum_{j=1}^n (T_{db} - \bar{T}_{db})^2}{n(n-1)}} = \sqrt{\frac{0.005895}{20(20-1)}} = 0.003 \text{ [K]} \quad (27),$$

$$u_{A_{T_{wb}}} = \sqrt{\frac{\sum_{j=1}^n (T_{wb} - \bar{T}_{wb})^2}{n(n-1)}} = \sqrt{\frac{0.012295}{20(20-1)}} = 0.0057 \text{ [K]} \quad (28),$$

4.1.1.3 Combined uncertainty for dry bulb and wet bulb temperature

The calculation continues by using formula (17) to determine the value of combined uncertainty. This is reflected in formula (29) and (30).

$$u_{c_{Tdb}} = \sqrt{u_{A_{Tdb}}^2 + u_b^2} = \sqrt{0.003^2 + 0.05^2} = \pm 0.0501 \text{ [K]} \quad (29),$$

$$u_{c_{Twb}} = \sqrt{u_{A_{Twb}}^2 + u_b^2} = \sqrt{0.0057^2 + 0.05^2} = \pm 0.050 \text{ [K]} \quad (30),$$

4.1.1.4 Expanded uncertainty for dry bulb and wet bulb temperatures

Finally, it finishes by using formula (18) to determine expanded uncertainty with coverage factor of 95%. It is represented by formulas (31) and (32).

$$U_{Tdb} = u_{c_{Tdb}} k = 0.0501 * 2 = \pm 0.1 \text{ [K]} \quad (31),$$

$$U_{Twb} = u_{c_{Twb}} k = 0.050 * 2 = \pm 0.1 \text{ [K]} \quad (32),$$

After all the uncertainties of the factor described by standard EN 14 511-3 (2022) are stated, they are placed in Table 7 to evaluate if the values are satisfactory from the standard point of view and the calculation which the standard describes can be used for further evaluation for this thesis.

Table 7 – Values for minimum uncertainty EN 14511-3 (2022) and DICz results

Measured quantity for air parameters	Marking	Units	Maximum allowed uncertainty of measurement	Uncertainty in DICz measurement equipment	Result
Dry bulb temperature	T_{DB}	K	$\pm 0.2K$	$\pm 0.1K$	OK
Wet bulb temperature	T_{WB}	K	$\pm 0.4K$	$\pm 0.1K$	OK
Air volume flow	q_{vi}	m^3/s	$\pm 5\%$	$\pm 1.6\%$	OK
Static pressure difference	p	Pa	$\pm 5\%$	$\pm 0.053\%$	OK

4.2 Description of measuring chain, chamber layout and chamber structure

For a better idea of the measuring chain, this chapter analyses and describes the devices. Also, a diagram showing where the devices are situated in the chamber is included in Figure 14. Firstly, the measuring chain from the pressure sensor to the digital output is described and then the measuring chain from the temperature sensor to digital output.

Expanding on the structure of the chamber which was briefly outlined in chapter 3.3, the main parts of the testing chamber are described here. Basically, it is divided into two main parts; an outdoor testing chamber and an indoor testing chamber. Since this thesis deals with the indoor air enthalpy method for determining total cooling capacity and its uncertainties of measurement, only the indoor testing chamber is described below.

The specific humidity and temperature inside the testing chamber is set for the measurement. There is small box which is called the discharge chamber. The indoor unit is situated before this box and it is connected to it by a duct. Near this unit there is an air sampling tree which records the parameters of the air before it enters the indoor unit refrigerant system by the heat exchanger which is situated before the entrance itself to set the specific conditions in the chamber.

As indicated in chapter 3.3, the air sampling tree is shown in Figure 15. Number 1 is the air sampler, number 2 is the connection tube, number 3 shows the measuring vein including the instrumentation and a fan and arrows marked by number 4 represents the air flow direction. The measuring vein consists of a PT100 dry bulb and wet bulb thermometer. More parameters of this device will be described in the following chapters.

After the air enters the indoor unit refrigerant system, its temperature is changed based on the requirements and it continues through the duct to the discharge chamber, where another sampling tree is situated. It measures the parameters of the air leaving the indoor unit. After that, the air goes through the duct to the nozzle wall. Before it there is an absolute pressure

sensor which serves together with the differential pressure device in the duct to make zero pressure difference.

In the nozzle wall there are multiple combinations of nozzles which serve for measuring the pressure difference and the differential pressure device is situated here. There is also an absolute pressure sensor and dry bulb thermometer for making air parameters entering the nozzle wall more precise. There could be a multiple combination of nozzles and it depends on the recommended measuring range for a given combination of nozzles. The air continues to a fan. The fan serves here to create zero pressure difference in the air duct. After that the air goes through the heat exchanger and here the parameters of the air are set by software according to the demands. After that it continues to the chamber and the cycle is repeated again.

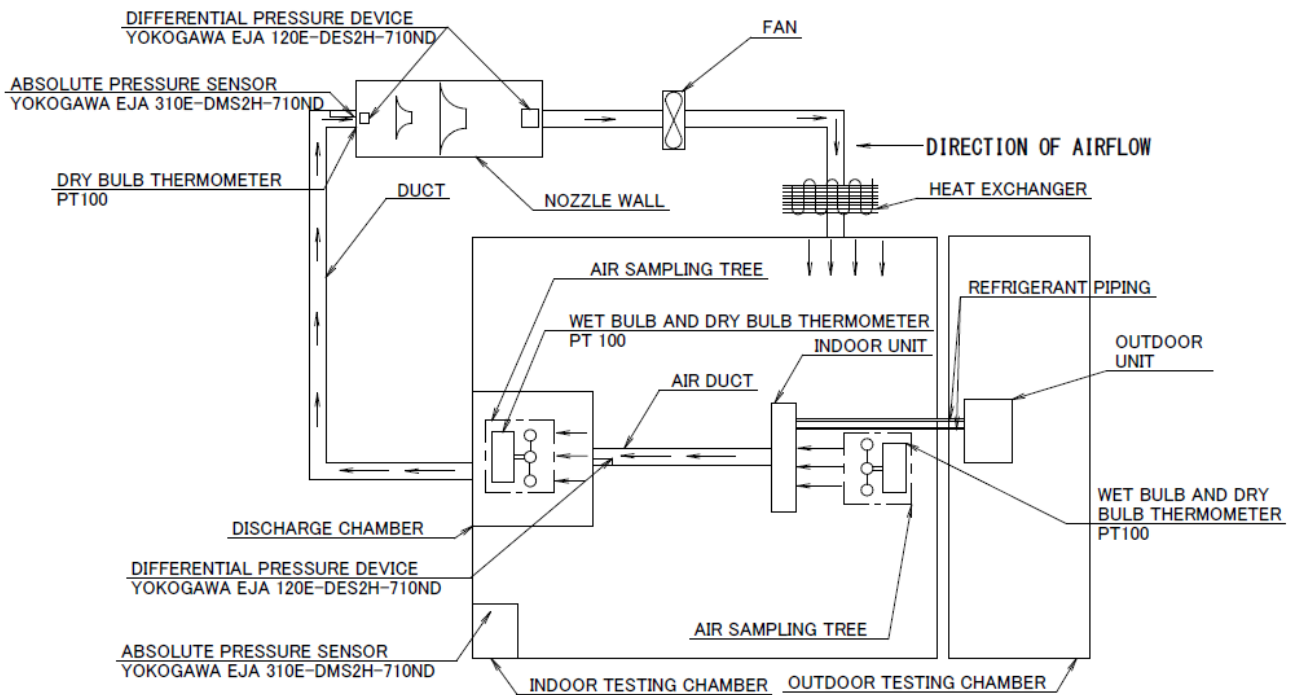


Figure 14 – Chamber layout with measuring devices

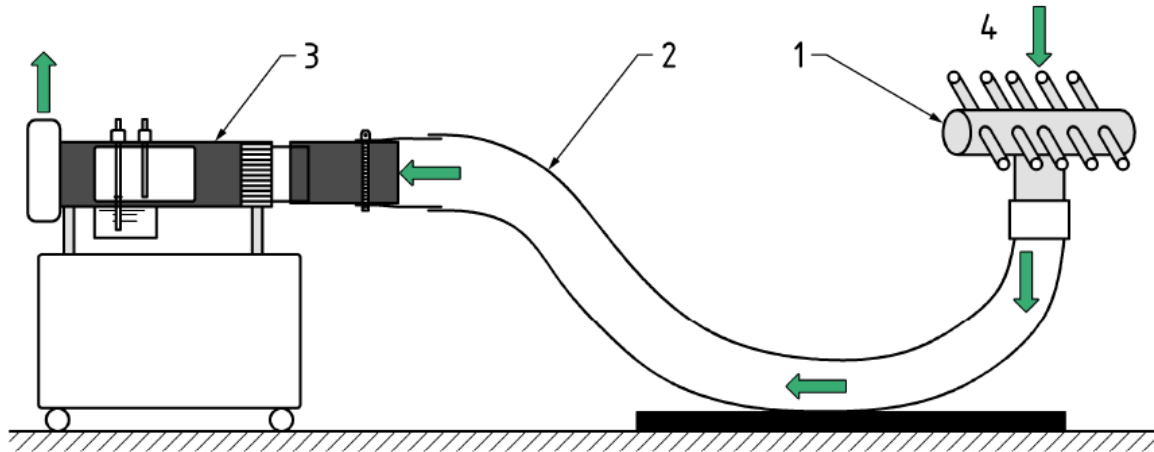


Figure 15 – Air sampling tree [15]

4.2.1 Pressure measurement

As stated above, the first chain investigates the pressure and can be seen in Figure 16.

PRESSURE MEASUREMENT CHAIN

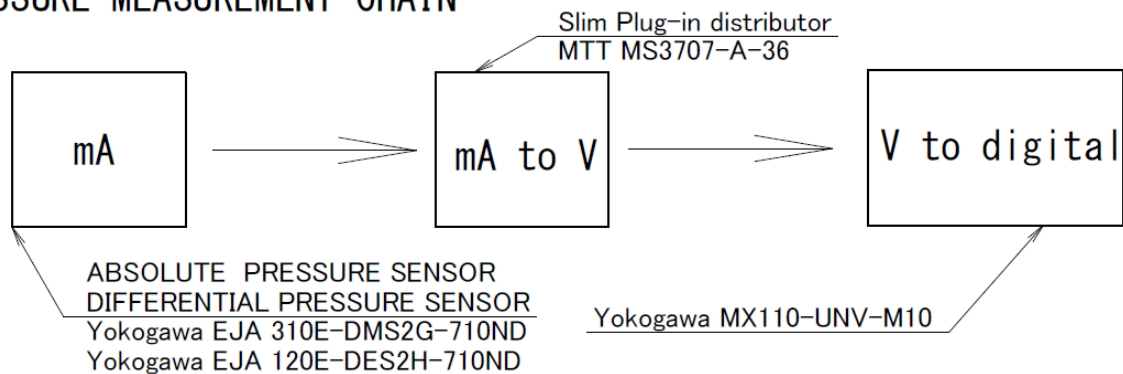


Figure 16 – Pressure measuring chain

It starts with a Yokogawa EJA 310E-DMS2G-710ND pressure sensor. This sensor is used for absolute pressure measurement inside the chamber. Figure 17 shows the pressure sensor and Table 8 gives some of its important characteristics and values. It is an absolute pressure transmitter and its location in the layout is shown in Figure 14. Generally, these types of pressure devices work on the principles of a single crystal silicon resonant sensor and it is perfectly suitable for liquid and gas measurement. The output signal is in the form of milliamperes, so another signal transformer has to be used to create a digital value for the output signal. The Slim Plug-in distributor MTT MS3707-A-36 (Figure 18) is used to transform the units from milliamperes to volts. Table 9 lists some of its important characteristics. Finally, when the signal is in the form of volts, the Yokogawa MX110-UNV-M10 is used to create a digital output. After that the signal leads via an ethernet connection to a computer and a .csv file.



Table 8 – Characteristics of absolute pressure transmitter [16]

Span	950 – 1050 Pa
Accuracy	±0,2% span
Output signal	amps
Output signal range	4-20mA
Operating range of temperature	-40 °C to +85°C

Figure 17 – Absolute pressure transmitter [16]



Table 9 – Characteristics of MTT signal converter [17]

Span	0V – 1V
Accuracy	±0.1% of span
Input signal	4-20mA
Output signal	volts
Operating range of temperature	-5°C to +55°C

Figure 18 – MTT signal converter [17]

A differential pressure device is used as the second measurement device for the pressure. It is the Yokogawa EJA 120E-DES2H-710ND and it is situated in the area of the nozzle wall. This device measures the pressure differences before and after the measuring device. It can also be found in the duct. Here it serves to create zero pressure difference in the duct with the comparison of the pressure in the indoor testing chamber. It works on the same principle as the absolute pressure transmitter. There is a single crystal silicon resonant sensor which is suitable for measuring liquid and gas pressure. The specifications are the same as for the other pressure device.

4.2.2 Temperature measurement

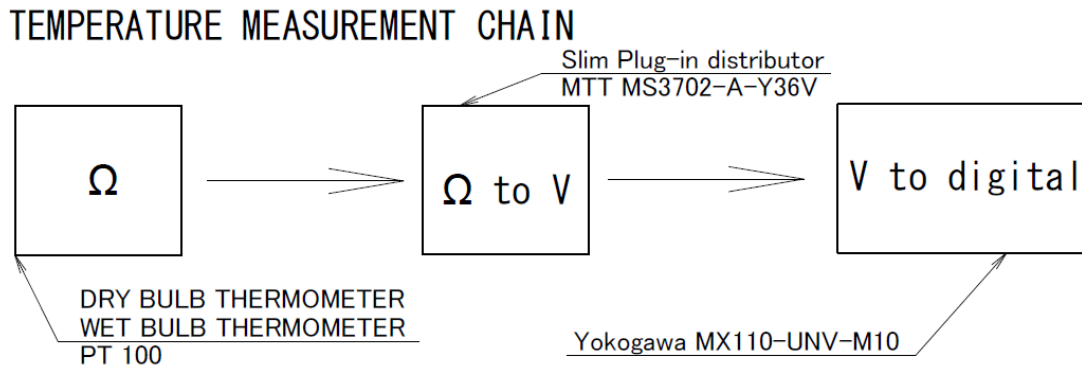


Figure 19 – Temperature measurement chain

In Figure 19 the temperature measurement chain is described. The PT-100 thermometer is shown in Figure 20. But as stated in chapter 2.3 two kinds of temperature exist. For the dry bulb temperature only a single PT-100 thermometer without any accessory is used. But for the wet bulb temperature, the PT-100 thermometer is wrapped in wet gauze. Number 1 represents the PT-100 wet bulb thermometer and as can be seen, there is gauze all around it. It is soaked in water and it has to be ensured, that this condition is maintained for the whole duration of the measurement.

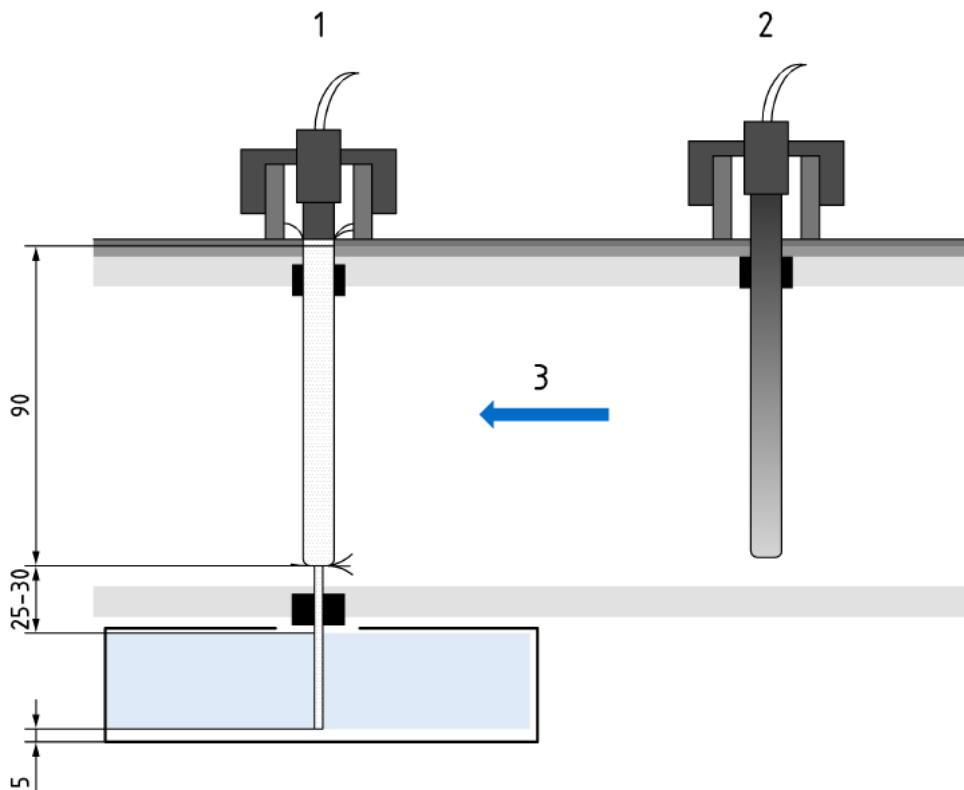


Figure 20 – Dry bulb and wet bulb PT-100 thermometers [15]

The output value of this thermometer is in the form of electrical resistance, so it needs to be converted firstly to volts using an MTT MS3702-A-Y36V signal converter and then an MX 110-UNV-M10 is used to convert the volts to the digital signal. After that via ethernet connection the signal leads to the computer and a .csv file.

As mentioned above, signal convertors are used to convert the signal to the required one. Figure 21 shows the MTT MS3702-A-Y36 convertor and as mentioned previously, it serves to convert the signal from amps to volts. Also, in Table 10 are shown some important values.



Table 10 – Characteristics of MTT temperature transmitter [17]

Span	-30°C to 70 °C
Accuracy	± 0.15% of span
Input signal	Ohms
Output signal	0-1V
Operating range of temperature	-200°C to +850°C

Figure 21 – MTT temperature transmitter [17]

Secondly, the Yokogawa MX 11-UNV-M10 (Figure 22) is used to convert volts to a digital signal. No other specifications for this device are important for evaluating the measurement, so no specifications table is given.



Figure 22 Yokogawa MX110-UNV-M10 [18]

4.3 Uncertainty description according to the standard EN 14511-3 (2022)

Standard EN 14511-3 (2022) which describes air conditioners, liquid chilling packages and heat pumps for space heating and cooling and process chillers with electrically driven compressors expresses how the air enthalpy method is designed and performed. Connected with this standard is also a standard which involves the evaluation of uncertainty itself. This is ISO TS 16491 (2012). There is a chart which describes which specific factors could influence the final uncertainty and which should be involved in calculating the uncertainty of capacity measurement by using the indoor air enthalpy method.

There is no mention of the accuracy of measuring devices but only a few factors which have the biggest impact on the results. Table 11 lists these factors. These influences have been chosen based on the experience and the calculations of the standard's creators. Although there is no mention about the accuracy of the measuring devices, specifically thermometers and pressure sensors, both of these items were used for calculating all the factors which are shown in Table 11. Also, the creators of the standard ISO TS 16491 (2012) give the standard value of uncertainty which should be used for the final calculation. This value is also shown in the table. Since there is no evidence of how the standard creators reached these factors, there is no certainty that all the mentioned influences are relevant and valid for DICz, because there are multiple methods for acquiring the input values for the final calculation of the total cooling capacity.

Finally, standard ISO 5151 (2017) is related to the standard ISO TS 16491 (2012) and it contains some additional information about the evaluation. For the purposes of this thesis the most important data is information about the maximum allowed uncertainty of the capacity measurement.

Standard EN 14511-3 (2022) gives the maximum value of combined uncertainty as less than 5%. According to ISO 5151 (2017) the expanded uncertainty is required to be less than 10%.

Table 11 – Uncertainties and values for cooling according to the ISO TS 16491 (2012) [19]

Input quantity and/or source of uncertainty	Symbol	Uncertainty	Physical units	Marking in the calculations
Indoor air volume flow rate	q_{vi}	4.8% of q_{vi}	m^3/s	z_1
Specific enthalpy of air entering the indoor side	h_{a1}	$0.66 \cdot 10^3$ (for 0.2°C wet bulb)	J/kg of dry air	z_2
Specific enthalpy of air leaving the indoor side	h_{a2}	$0.50 \cdot 10^3$ (for 0.2°C wet bulb)	J/kg of dry air	z_3
Air dry bulb temperature	T	0.2	K	z_4
Atmospheric pressure	p	1.0%	Pa	z_5
Water vapour partial pressure at wet-bulb temperature T_w	p_w	2.3% of p_w	Pa	z_6
Indirect contribution	C_1	1.5% of ϕ_{tci}	W	z_7

4.4 Ishikawa diagram and its design at DICz

Based on the previous chapter which dealt with the factors affecting final uncertainty, a meeting with DICz was arranged with the aim of creating an Ishikawa diagram to describe what could affect the final uncertainty of capacity measurement and also confirm that measurements in DICz are performed according to the standard ISO TS 16491 (2012). Test engineers, engineers from the system control section and structural engineers were involved to use their extensive experience with capacity measurement to choose items which have the biggest impact on the final uncertainty of measurement. The meeting was structured into two sub-meetings, each lasting about two hours.

Finally, the Ishikawa diagram was created with a lot of items which are divided into two main groups by using a scale of 1-5 where values greater than or equal to 3 are considered as the ones with the greatest influence. In the first group were placed items which although they have some impact on the result, the impact is not so great that it has to be considered in the final evaluation of the results. Therefore, these factors were ignored. As already mentioned, the second group were factors which have a bigger impact on the results, so they need to be considered for the final evaluation. When the output of the Ishikawa diagram is compared to the factors in the standard mentioned above, particularly EN 14511-3 (2022), it is found that the factors thought to have an influence on uncertainty match totally. By using this procedure, it is confirmed that the chosen factors fully match with the standard and that is why they can be considered as valid and relevant for further work and evaluation.

Even at first sight there are more items in the Ishikawa diagram than in the standard EN14511-3 (2022) itself. All the factors which are mentioned in EN14511-3 (2022) are reflected in the fish bone diagram. The Ishikawa diagram described in this chapter can be seen in Figure 23

below. As is evident from that figure, the five main factors which have the biggest impact on the uncertainty of capacity measurement are human sources, installation, outdoor and indoor unit, system of measurement and equipment. In the following chapters all five factors are described.

4.4.1 Human sources

The human sources include incorrect zero setting of pressure sensors, insufficient training of participants, incorrect installation of the unit (bad orientation of the unit, insufficient insulation, etc.), inappropriate setting of the airflow of the flap where the sampler receives only a low volume of airflow causing incorrect measurement of parameters in the suction or in the discharge box. The test leakage of refrigerant to ensure that there is not even a small refrigerant leakage could also be incorrectly performed. In general, there is a big effort to reduce human sources as much as possible.

4.4.2 Installation

The second factor is the installation of the unit. In this part it is possible to have a clogged refrigerant path which may appear in the form of dirt inside the refrigerant path, water shortage in the sampler which could cause incorrect output values of the wet bulb thermometer or mis-determination of the heat losses by using sealing material of box. Heat loss is partially covered by software but there could still be a big impact.

4.4.3 Outdoor and indoor units

The outdoor and indoor units are the third factor. There could be refrigerant leakage during transportation of the unit from the production to the testing chambers, an incorrect amount of refrigerant in the outdoor unit. This could cause insufficient cooling performance which could affect the capacity measurement.

4.4.4 System of measurement

The fourth factor is the system of measurement. Incorrect calculation of the specific enthalpy of air leaving the indoor unit and incorrect calculation of the specific enthalpy of air entering the indoor unit could cause an incorrect evaluation of the uncertainty. This is followed by the incorrect measurement of power consumption due to incorrect connection of the measuring devices and incorrect calculation of the indoor unit's air volume flow rate due to factors which are mentioned earlier in this chapter.

4.4.5 Equipment

This is the most comprehensive sequence of the whole diagram due to the reflection of all the potential problems which are described above. These factors also include a dried wick being used for measuring the wet bulb temperature, incorrect values of wet bulb temperature due to dirt on the wick itself, incorrect values of the dry bulb temperature which is influenced by the inaccuracy of the dry bulb thermometer. Inaccuracy of the sampler sensor due to factors which are mentioned previously. There could also be incorrect calibration of the wattmeter and some inaccuracy of the pressure sensors could appear. Finally, there is inaccuracy of Vaisala, which is a humidity sensor.

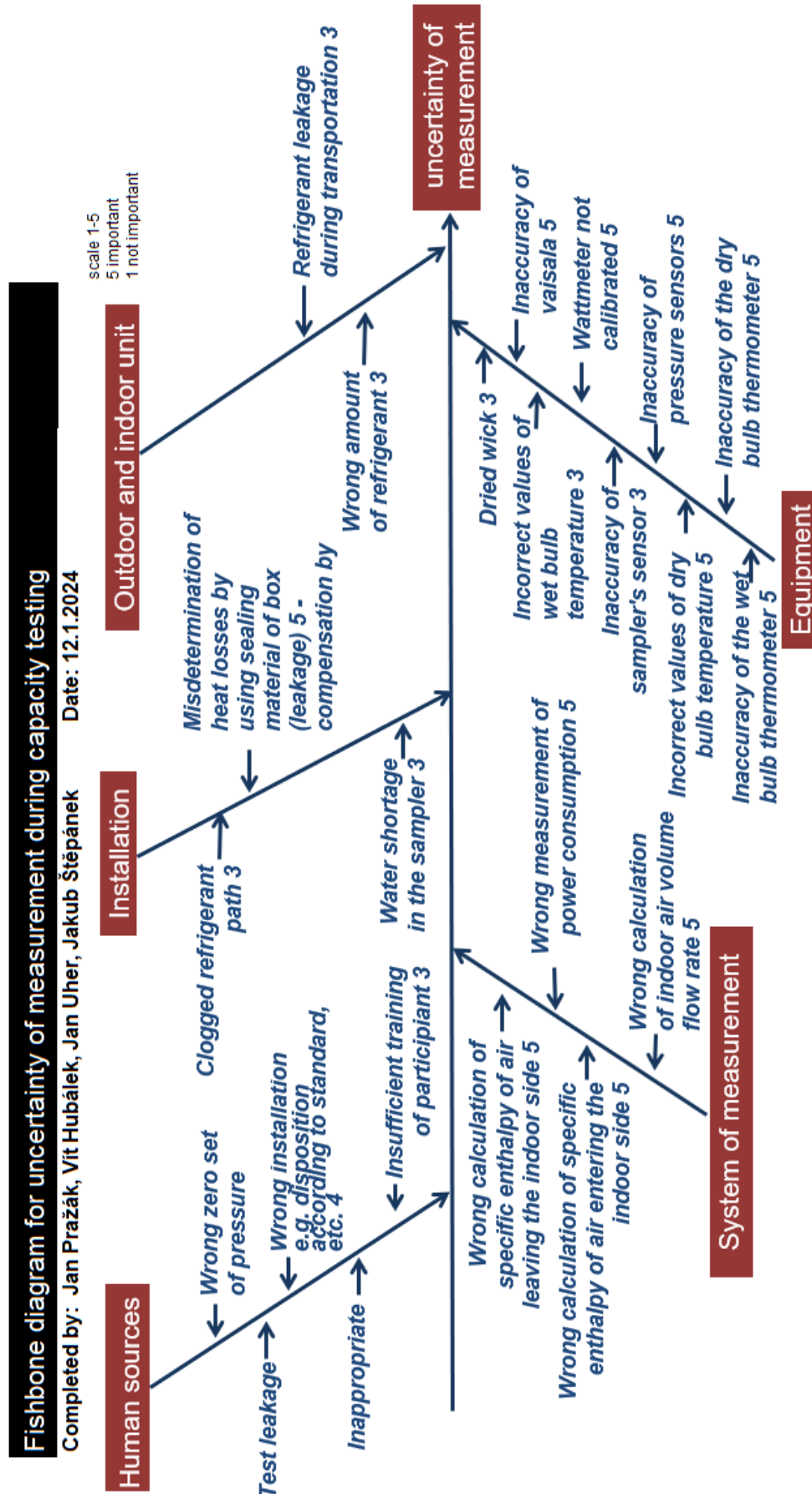


Figure 23 – Ishikawa diagram

4.5 Calculation of physical quantities

Now the measuring chain has been explained in chapters 4.2.1 and 4.2.2, and the factors which affect the measurement itself are stated in chapter 4.3 and 4.4, a detailed description of the calculation of uncertainties can be given. However, before that, it is also important to learn something about the procedure of how the data are filtered according to the demands of the standard itself. When the measuring of the necessary values and their transformation to the required type of signal is complete, all the values are exported into a .csv file. The measuring data is recorded every 4 seconds.

The chamber system records even data which is needed for diagnostics of operation. In practice this means that there are more than 70 measured values. That is why the output .csv file needs to be filtered according to the demands which reflect standard EN 14511-3 (2022) and the output factors of the Ishikawa diagram. In practice it means that from the original file which contains more than 60 columns, only six values are needed for the following evaluation.

These values are the indoor dry bulb temperature (T_{DB}), indoor wet bulb temperature (T_{WB}), cyclometric dry bulb temperature (T_{DBC}) and the cyclometric wet bulb temperature (T_{WBC}). The values in units of °C have to be converted to the correct units which are Kelvin. The indoor side atmospheric pressure, which is in hPa needs to be converted to Pa, the nozzle specific volume (WET) is a dimensionless quantity and airflow (q_{vi}) needs to be converted to cubic metres per second instead of cubic metres per minute.

Once all the values have been measured and transferred to the .csv file and all the required quantities are converted into the correct units, the whole calculation of the total cooling capacity can be stated. As mentioned above in the theoretical part of this thesis, in chapter 3.5, CoolProp software is used for calculating values such as enthalpy, water vapour partial pressure at wet bulb temperature and total cooling capacity. But it is necessary to insert the required value in the correct units. In this case the measurement has more than 500 rows, so the excel sheet is adjusted to the volume of data it enters to the evaluation. Basically, it does not matter how many measured values are inserted in the excel sheet. In formula (33) there is an example of how the water vapour partial pressure can be calculated by using CoolProp software in excel. The HAPropsSI represents using CoolProp software. In CoolProp, the calculated values are determined by using shortcuts. Below the values and shortcuts which are used for calculating the total cooling capacity are shown.

- Enthalpy IN/OUT – H_a
- Water vapour partial pressure – P_w

As mentioned above, the value “ P_w ” is stated for the quantity that is required to be calculated. Specifically, it is the value that expresses partial water pressure. “ T_{wb} ” represents the values for the wet bulb temperature and the number 273.15 represents the conversion to the correct units in Kelvins. The same is for “ T_{db} ” which represents the dry bulb temperature. Finally, “ P ” represents atmospheric pressure. It is multiplied by 100 to give the units in pascals.

$$P_w = \text{coolprop function}(T_{wb}, T_{db}, P) \quad (33),$$

where

P_w – partial pressure of water vapour [Pa]

T_{wb} – wet bulb temperature [K]

T_{db} – dry bulb temperature [K]

P – pressure [Pa]

The same procedure of calculation is used for the remaining values which were described earlier in this chapter. The only difference is that input is different according to the value which is to be calculated. The following quantities are calculated.

- Specific enthalpy of entering the indoor side marked by ha_1
- Specific enthalpy of leaving the indoor side marked by ha_2

According to the standard which describes the procedure for evaluating and calculating the uncertainty ISO TS 16491 (2012), two additional values are required.

- Specific enthalpy of entering the indoor side $+0.2^\circ\text{C}$ marked as $ha_{1+0.2^\circ\text{C}}$
- Specific enthalpy of leaving the indoor side $+0.2^\circ\text{C}$ marked as $ha_{2+0.2^\circ\text{C}}$

When all the values are measured or calculated, all the necessary quantities are gained for the evaluation of the uncertainty. Finally, the total cooling capacity can be stated by using formula (34) which is related to formula (22) in chapter 3.4. Formula (34) reflects the data which is measured and calculated for the chamber, so only one value is used in the denominator, but it represents the same state as in formula (22).

$$\Phi_{tci} = \frac{(ha_2 - ha_1) q_{vi}}{WET} \text{ [W]} \quad (34),$$

where

ϕ_{tci} – total cooling capacity [W]

ha_2 – Specific enthalpy of leaving the indoor side [–]

ha_1 – Specific enthalpy of entering the indoor side [–]

q_{vi} – airflow [m^3/s]

WET – specific volume of humid air which is measured and calculated for the chamber [m^3/kg]. The specific volume is shown in Table 1

In this chapter, the whole procedure of calculating the necessary values for evaluating the uncertainty of capacity measurement is described and the cooling capacity is determined.

The following chapter will describe type A and type B uncertainties and their implementation in the case of capacity measurement.

4.6 Standard uncertainty A type and standard uncertainty B type

The next step is to calculate and evaluate standard uncertainty A type and standard uncertainty B type which is used for calculation of combined uncertainty.

4.6.1 Calculation of uncertainty A type

When all the values of the physical quantities are calculated as shown in the chapter 4.5, the final determination of uncertainty can be performed. Firstly, uncertainty A type is calculated.

4.6.1.1 Rough error check

The procedure for evaluating this uncertainty is related to chapter 2.25.1. All the data must be checked using a rough error to see if all the measured data are in the scope of the evaluation. This starts by using formula (7) which is mentioned in chapter 2.23 and determines arithmetic mean.

$$\bar{\phi}_{tci} = \frac{1}{n} \sum_{k=1}^n \phi_{tci} = \frac{1}{526} * 1692818.57 = 3218.29 \text{ [W]} \quad (35),$$

where

$\bar{\phi}_{tci}$ – arithmetic mean of total cooling capacity [W]

Once the arithmetic mean is calculated the experimental standard deviation can be also calculated by using formula (8) which is shown below in formula (36).

$$s(\phi_{tci}) = \sqrt{\frac{\sum_{j=1}^n (\phi_{tci} - \bar{\phi}_{tci})^2}{n-1}} = \sqrt{\frac{18753}{525}} = 5.98 \text{ [W]} \quad (36),$$

where

$s(\phi_{tci})$ – experimental standard deviation [W]

When all the values mentioned above are gathered it leads to the calculation of the standard value H_n . The calculation itself is based on formula (9) which has to be performed for each measurement as x_n represents the measured value of each measurement. For illustration a calculation for measurement number 1 is shown and this process was repeated for each measured value. Next it is compared to the value in Table 3. According to the number of measurements, which is 526, and required probability 95% the value for H is 3.723. The calculation is seen in formula (37).

$$H_n = \frac{x_n - \bar{\phi}_{tci}}{s(\bar{\phi}_{tci})} = \frac{3204.87 - 3218.29}{5.98} = |-2.25| \quad (37),$$

It is determined that the maximum value H_n is 2.89 and the minimum value is |-3.60|. Therefore, it is assumed that none of the measured values are not considered as rough errors so no values are deleted for further evaluation for standard A uncertainty.

4.6.1.2 Calculation of standard A uncertainty itself

After checking the values for the rough error the standard A uncertainty evaluation begins.

Once the evaluation is about the total cooling capacity, data of this quantity is evaluated as follows. The input data which are processed consists of 526 measurements. Every measurement was repeated each 4 seconds. When the formula (10) is applied in this case there can be seen specific formula (38) for the measured data.

$$u_A = \sqrt{\frac{\sum_{j=1}^n (q_j - \bar{q})^2}{n(n-1)}} = \sqrt{\frac{18753}{526 \cdot (526-1)}} = 0.26 \text{ [W]} \quad (38),$$

Because the standard requires values of uncertainties in percentage form, the final calculation needs to be converted a percentage. It must not be stated in watts. This change is shown below in formula (39).

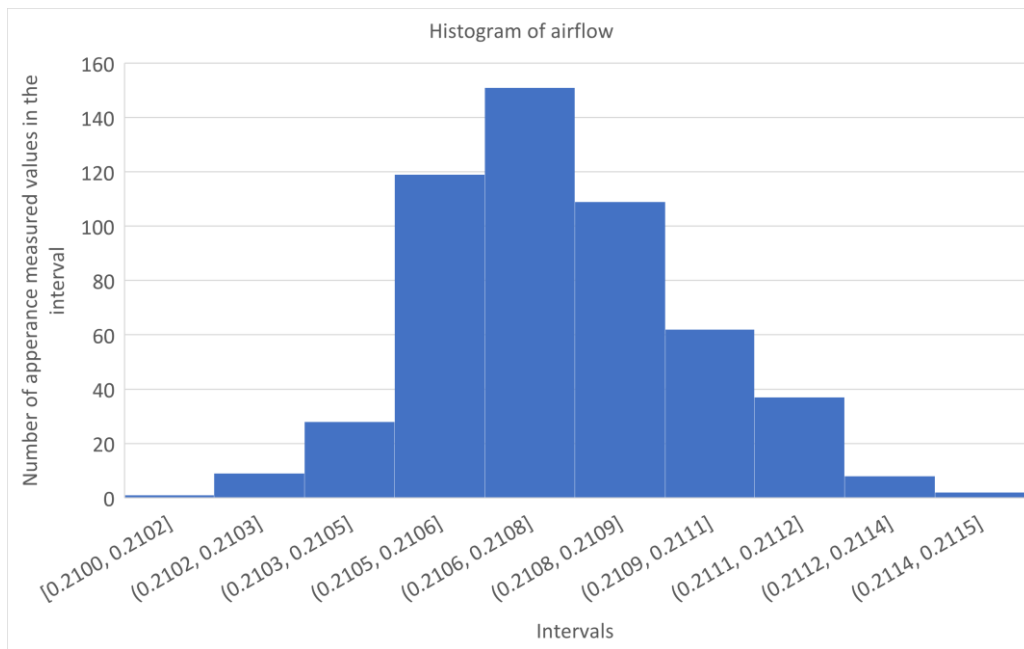
$$u_A(r) = 100 \cdot \frac{u_A}{\bar{\phi}_{tci}} = \frac{100 \cdot 5.98}{3218.29} = 0.18 \text{ [%]} \quad (39),$$

4.6.2 Calculation of partial standard B uncertainty

After the standard A uncertainty is calculated, we can proceed to standard B uncertainty evaluation. This is reflected Table 11 which represents factors, which are described in the standard ISO TS 16491 (2012). The following part of the thesis shows how the partial standard B uncertainties are calculated.

4.6.2.1 Relative standard B uncertainty of airflow

The first factor to be described is airflow. As mentioned before, all values were calculated by using CoolProp software.



Graph 1 – Histogram of airflow

Next, a histogram is constructed to decide which distribution according to Figure 7 the values reflect. From Graph 1 it can be said that the airflow has Gaussian distribution.

According to the distribution the divisor k is chosen as 3. Also for further calculation the arithmetic mean needs to be calculated as follows in formula (40).

$$\bar{q}_{vi} = \frac{1}{n} \sum_{k=1}^n q_{vi} = \frac{1}{526} \cdot 110.84 = 0.21 \quad [\text{m}^3/\text{s}] \quad (40),$$

where

$$\bar{q}_{vi} - \text{arithmetic mean of air volume flow } [\text{m}^3/\text{s}]$$

where the arithmetic mean is calculated and it is known that standard ISO TS 16491 (2012) states the value of airflow uncertainty z_1 as 4.8% of the arithmetic mean. Thanks to this the standard B uncertainty can be calculated by using formula (41).

$$ub_{qvi} = \frac{z_1}{k} = 0.048 * \frac{0.21}{3} = 0.00336 \quad [\text{m}^3/\text{s}] \quad (41),$$

The value of relative standard B uncertainty of airflow can be expressed as follows by using formula (42)

$$ub(r)_{qvi} = \frac{ub_{qvi}}{\bar{q}_{vi}} = \frac{0.00336}{0.21} = 0.016 [-] = 1.6 [\%] \quad (42),$$

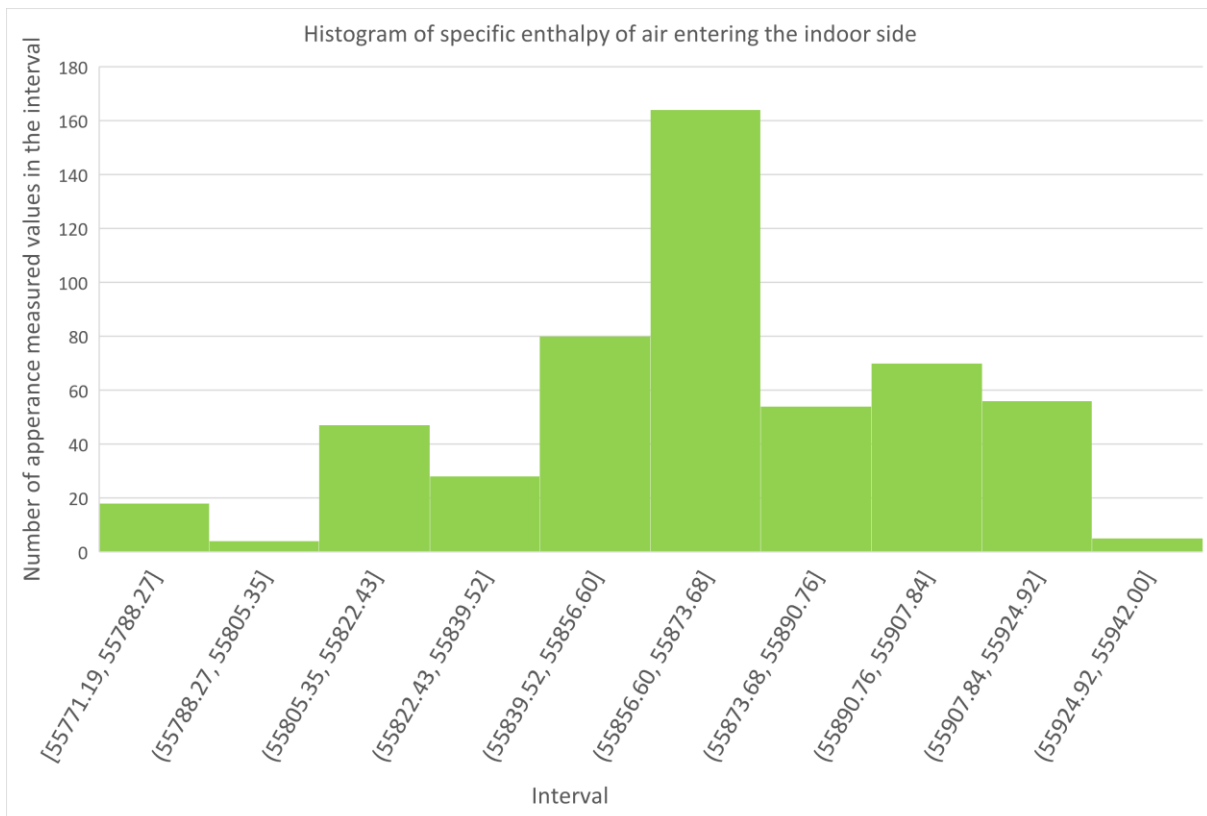
where

$ub(r)_{qvi}$ – value of relative standard B uncertainty of air volume flow [%]

A similar procedure is used for all the remaining factors. They are calculated below.

4.6.2.2 Relative standard B uncertainty of specific enthalpy of air entering the indoor side and specific enthalpy of air leaving the indoor side

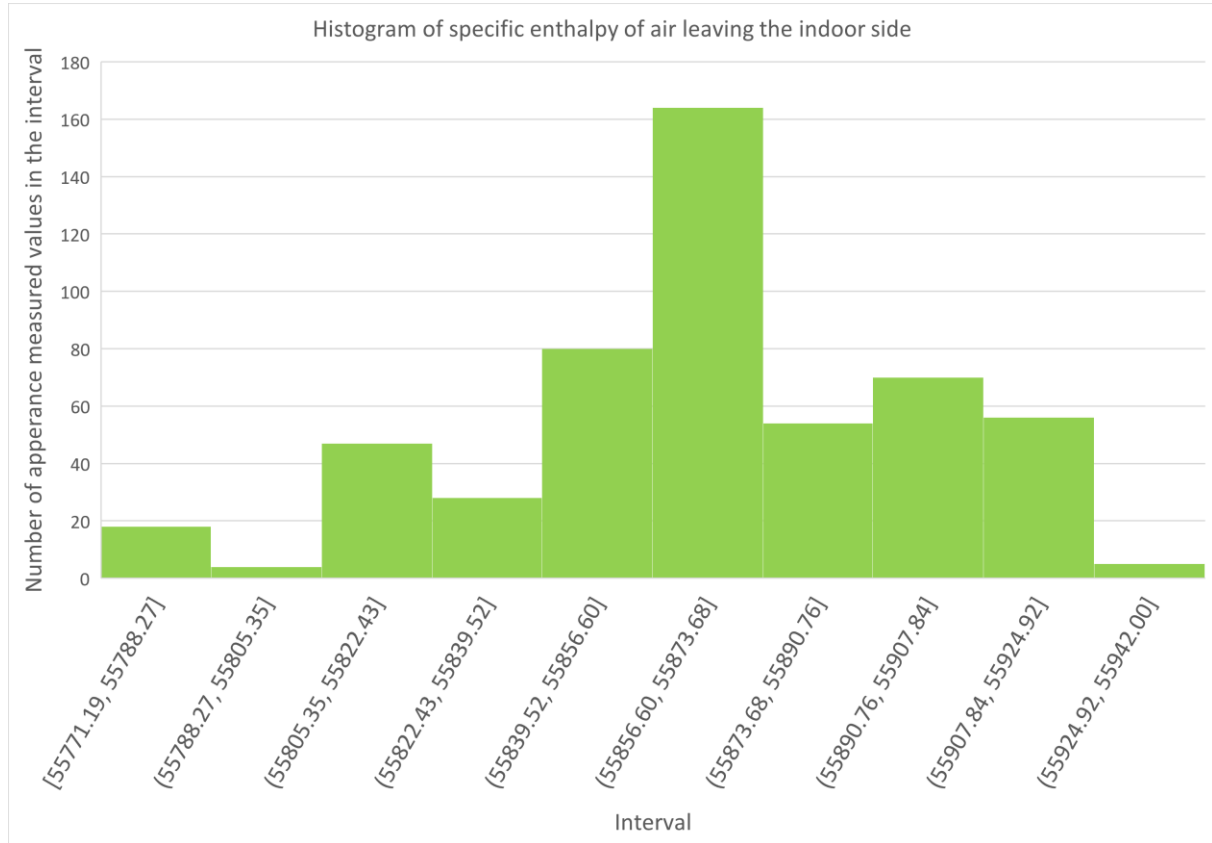
Next, the impact of specific enthalpy of air entering the indoor side h_{a1} and specific enthalpy of air leaving the indoor side h_{a2} is calculated. Both quantities depend on each other. It can also be seen in Table 10.



Graph 2 – Histogram of specific enthalpy of air entering the indoor side

Graph 2 shows a histogram for the specific enthalpy of air entering the indoor side and Graph 3 shows the specific enthalpy of air leaving the indoor side.

As can be seen, the distribution is Gaussian. Therefore the value of divisor k is 3 it is the same as the previous quantity.



Graph 3 – Histogram of specific enthalpy of air leaving the indoor side

Also, the arithmetic mean for each specific enthalpy needs to be calculated. This is described by formulas (43) and (44).

$$\bar{h}_{a1} = \frac{1}{n} \sum_{k=1}^n h_{a1} = \frac{1}{526} * 29385169.3 = 55\,865.34 \text{ [J/kg of dry air]} \quad (43),$$

where

\bar{h}_{a1} – arithmetic mean of specific enthalpy of air entering the indoor side [J/kg]

$$\bar{h}_{a2} = \frac{1}{n} \sum_{k=1}^n h_{a2} = \frac{1}{526} * 22311293.6 = 42\,461.91 \text{ [J/kg of dry air]} \quad (44),$$

where

\bar{h}_{a2} – arithmetic mean of specific enthalpy of air leaving the indoor side [J/kg]

Standard ISO 16941 (2012) also describes the arithmetic mean for both enthalpies but with increased wet bulb temperature per 0.2°C. These values are calculated below in formulas (45) and (46).

$$\bar{h}_{a1+0.2^\circ\text{C}} = \frac{1}{n} \sum_{k=1}^n h_{a1+0.2^\circ\text{C}} = \frac{1}{526} * 29746101.76 = 56\,551.52 \text{ [J/kg of dry air]} \quad (45),$$

where

$\bar{h}_{a1+0.2^\circ\text{C}}$ – arithmetic mean of specific enthalpy of air entering the indoor side +0.2°C [J/kg dry air]

$$\bar{h}_{a2+0.2^{\circ}\text{C}} = \frac{1}{n} \sum_{k=1}^n h_{a1+0.2^{\circ}\text{C}} = \frac{1}{526} \cdot 22614836.85 = 49\,993.99 \text{ [J/kg of dry air]} \quad (46),$$

where

$\bar{h}_{a2+0.2^{\circ}\text{C}}$ – arithmetic mean of specific enthalpy of air leaving the indoor side +0.2°C [J/kg dry air]

Formula (47) below is used to calculate the uncertainty of the specific enthalpy of air entering the indoor side.

$$z_2 = \bar{h}_{a1+0.2^{\circ}\text{C}} - \bar{h}_{a1} = 55\,865.34 - 56\,551.52 = 686.18 \text{ [J/kg of dry air]} \quad (47),$$

where

z_2 – uncertainty for specific enthalpy of air entering the indoor side which is described by standard ISO 16491 (2012) [J/kg of dry air]

For the calculation of the uncertainty of the specific enthalpy of air leaving the indoor side the similar formula (48) is used.

$$z_3 = \bar{h}_{a2+0.2^{\circ}\text{C}} - \bar{h}_{a2} = 42\,461.91 - 49\,993.99 = 577.08 \text{ [J/kg of dry air]} \quad (48),$$

where

z_3 – uncertainty for specific enthalpy of air leaving the indoor side which is described by standard ISO 16491 (2012) [J/kg of dry air]

When it is all calculated as shown above the standard uncertainty for both enthalpies can be determined as follows in formulas (49) and (50).

$$ub_{ha1} = \frac{z_2}{k} = \frac{686.18}{3} = 228.73 \text{ [J/kg dry air]} \quad (49),$$

where

ub_{ha1} – standard B uncertainty specific enthalpy of air entering the indoor side [J/kg dry air]

and

$$ub_{ha2} = \frac{z_3}{k} = \frac{577.08}{3} = 192.36 \text{ [J/kg dry air]} \quad (50),$$

where

ub_{ha2} – standard B uncertainty of specific enthalpy of air leaving the indoor side [J/kg dry air].

After this determination comes the final calculation for relative standard uncertainty which is expressed in formulas (51) and (52) below.

$$ub(r)_{ha1} = \frac{ub_{ha1}}{\bar{h}_{a1} - \bar{h}_{a2}} = \frac{228.73}{55865.34 - 42416.91} = 0.017 [-] = 1.7 [\%] \quad (51),$$

where

$ub(r)_{ha1}$ – relative standard uncertainty of specific enthalpy of air entering the indoor side [%]

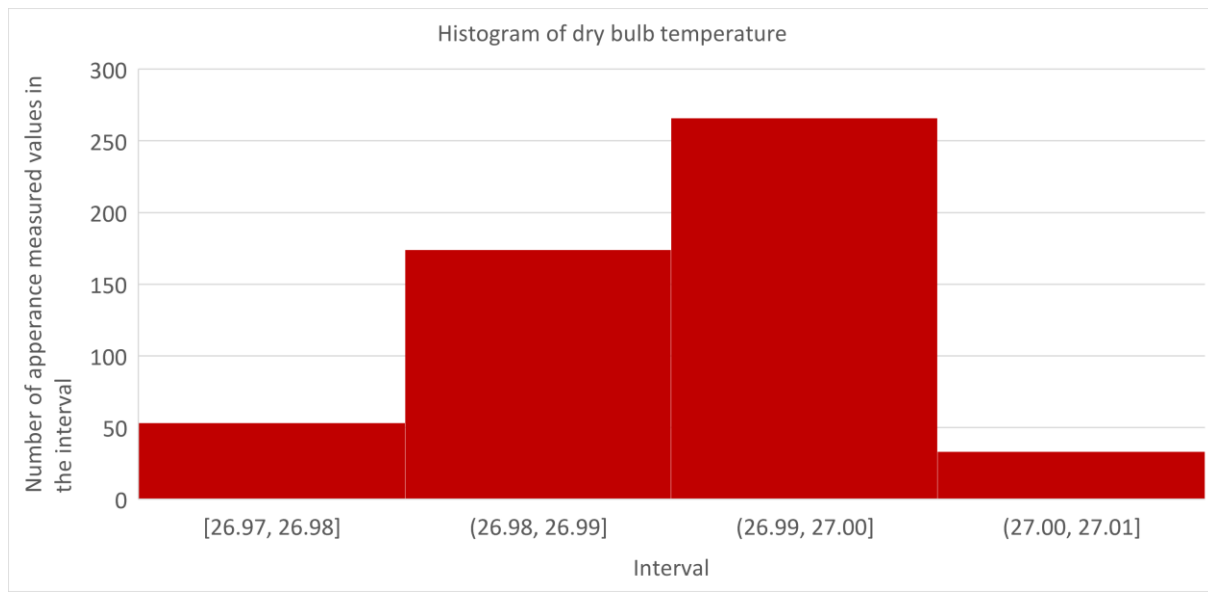
$$ub(r)_{ha2} = \frac{ub_{ha2}}{\bar{h}_{a1} - \bar{h}_{a2}} = \frac{192.36}{55865.34 - 42416.91} = 0.014 [-] = 1.4 [\%] \quad (52),$$

where

$ub(r)_{ha2}$ – relative standard uncertainty of specific enthalpy of air leaving the indoor side [%]

4.6.2.3 Relative standard B uncertainty of dry bulb temperature

The fourth evaluated value is the dry bulb temperature near the suction of the indoor unit. As in the cases above, firstly the histogram is constructed, as shown in Graph 4. From the theory point of view, seven columns should be used for constructing the histogram. But for the case of dry bulb temperature measurement, there is no possibility to divide the measured values into more than four columns since the difference between the highest and the lowest value is only 0,04K.



Graph 4 – Histogram of dry bulb temperature

Because the distribution is Gaussian the divisor k is chosen as 3. Also, for further calculation the arithmetic mean needs to be calculated using formula (53) as follows.

$$\bar{T}_{DB} = \frac{1}{n} \sum_{k=1}^n T_{DB} = \frac{1}{526} \cdot 14199.52 = 300.15 \text{ [K]} \quad (53),$$

where

\bar{T}_{DB} – arithmetic mean of dry bulb temperature

After calculation of the arithmetic mean and it is known that standard ISO TS 16491(2012) states the value of dry bulb temperature uncertainty as $z_4 = 0.2\text{K}$, the value of standard B uncertainty can be expressed in formula (54) as follows.

$$ub_{TDB} = \frac{z_4}{k} = \frac{0.2}{3} = 0.07 \text{ [K]} \quad (54),$$

where

ub_{TDB} – standard B uncertainty for dry bulb temperatures [K]

Finally, after determining the value above, relative standard uncertainty can be calculated in formula (55).

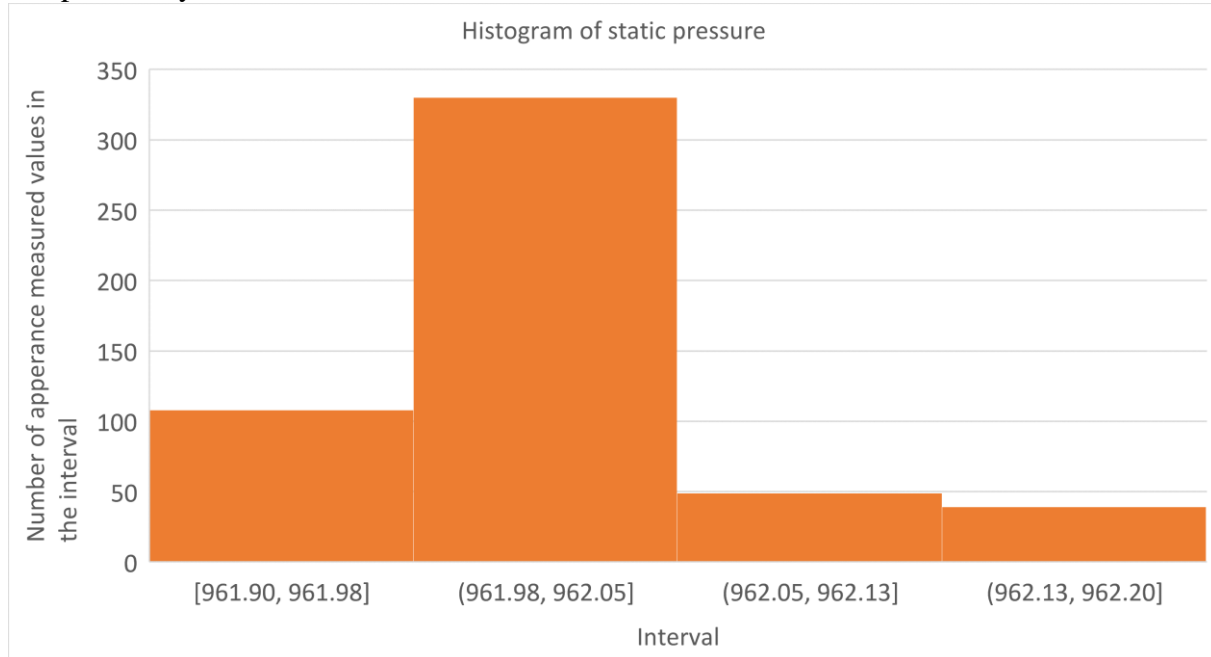
$$ub(r)_{TDB} = \frac{ub_{TDB}}{\bar{T}_{DB}} = \frac{0.07}{300.15} = 0.0002 \text{ [-]} = 0.02 \text{ [%]} \quad (55),$$

where

$ub(r)_{TDB}$ – relative standard B uncertainty for dry bulb temperature [%]

4.6.2.4 Relative standard B uncertainty of static pressure

The fifth factor is the uncertainty of static pressure. The procedure is the same as for the calculations above. The histogram is created to find the distribution. The case is the same as in chapter 4.6.2.3. Here the intervals have bigger gaps than in the previous chapter, and there is no possibility to divide it into more than four intervals.



Graph 5 – Histogram of static pressure

Divisor k is chosen as 3 because the distribution is Gaussian. The calculation continues by determining the arithmetic mean of the static pressure. The calculation is shown in formula (56).

$$\bar{p} = \frac{1}{n} \sum_{k=1}^n p = \frac{1}{526} \cdot 50601390 = 96200.36 \text{ [Pa]} \quad (56),$$

\bar{p} – arithmetic mean of static pressure [Pa]

After calculation of arithmetic mean, and it is known that standard ISO TS 16491 (2012) states the value of uncertainty of static pressure is 1% of this pressure, so the value of uncertainty can be expressed as z_5 as follows in formula (57).

$$z_5 = 0.01\bar{p} = 926.36 \text{ [Pa]} \quad (57),$$

where

z_5 – uncertainty for static pressure which is described by standard ISO 16491 (2012) [J/kg of dry air]

From the stated z_5 value, standard B uncertainty can be expressed as shown by formula (58).

$$ub_p = \frac{z_5}{k} = \frac{926.36}{3} = 320.67 \text{ [Pa]} \quad (58),$$

where

ub_p – standard B uncertainty for static pressure [Pa]

Finally, after determining the value above, relative standard uncertainty can be calculated with formula (59).

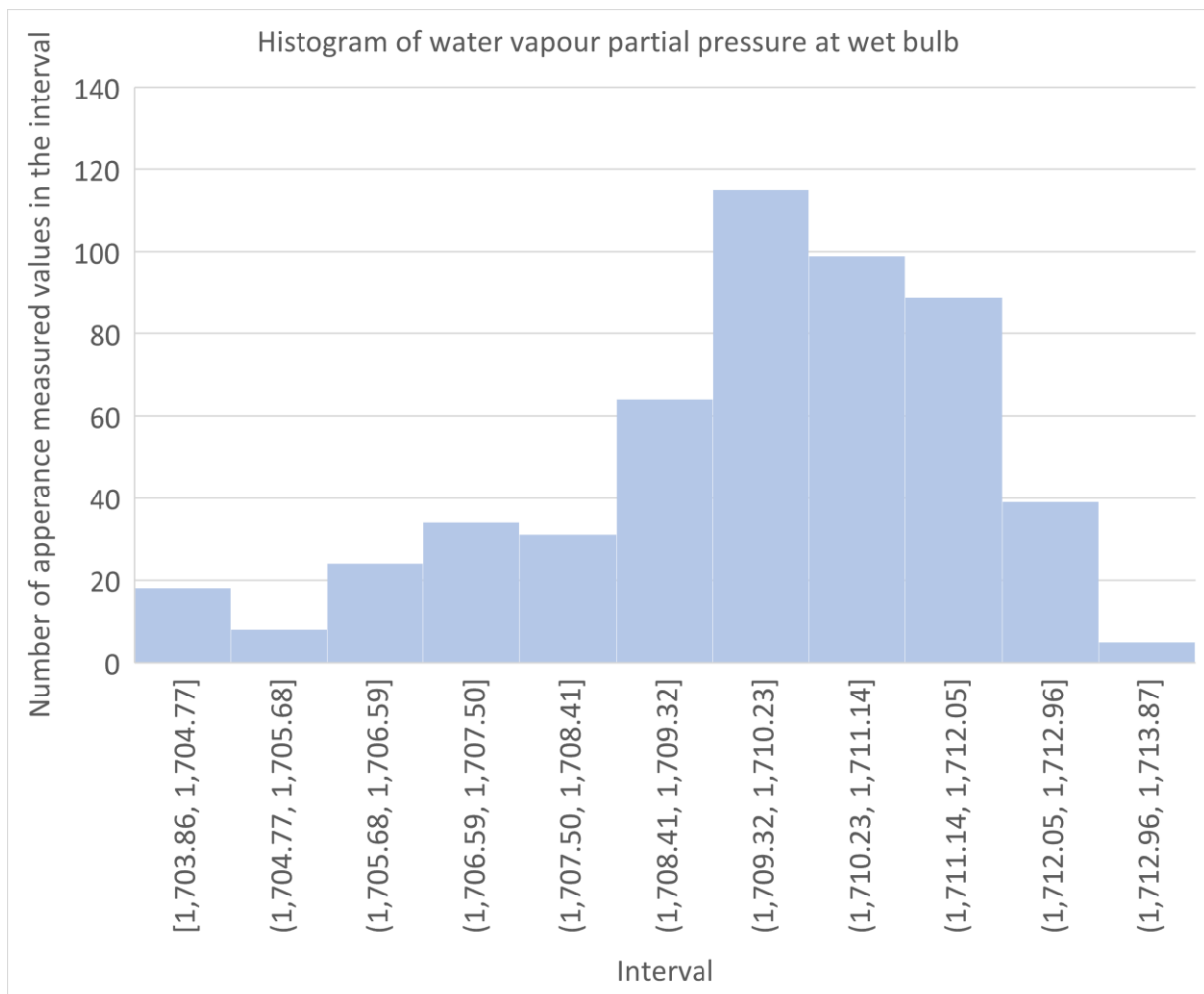
$$ub(r)_p = \frac{ub_p}{\bar{p}} = \frac{320.67}{96200.36} = 0.0034 [-] = 0.34 [\%] \quad (59),$$

where

$ub(r)_p$ – relative standard B uncertainty for static pressure [%]

4.6.2.5 Relative standard B uncertainty of water vapour partial pressure at wet bulb temperature

The sixth step is to calculate the water vapour partial pressure at wet bulb temperature marked as p_w . It follows the procedure for the previous factors which are evaluated above. Firstly, the histogram is constructed from the measured values. It can be seen in Graph 6 that the distribution is Gaussian. Therefore the divisor k is equal to 3.



Graph 6 – Histogram of water vapour partial pressure at wet bulb

The next step is to determine the arithmetic mean of the measured values. This is shown below in the formula (60).

$$\bar{p}_w = \frac{1}{n} \sum_{k=1}^n p_w = \frac{1}{526} \cdot 899282.64 = 1709.66 [\text{Pa}] \quad (60),$$

where

\bar{p}_w – arithmetic mean of water vapour partial pressure at wet bulb temperature [Pa]

Standard ISO TS 16491 (2012) says that value of uncertainty z_6 is equal to 2,3% of \bar{p}_w . The calculation is described in formula (61) as follows

$$z_6 = 0.023 \cdot \bar{p}_w = 0.023 \cdot 1709.66 = 39.32 \text{ [Pa]} \quad (61),$$

where

z_6 – uncertainty for water vapour partial pressure at wet bulb which is described by standard ISO 16491 (2012)

Now, the standard B uncertainty is calculated by using values from the above in the formula (62).

$$ub_{pw} = \frac{z_6}{k} = \frac{39.32}{3} = 13.11 \text{ [Pa]} \quad (62),$$

where

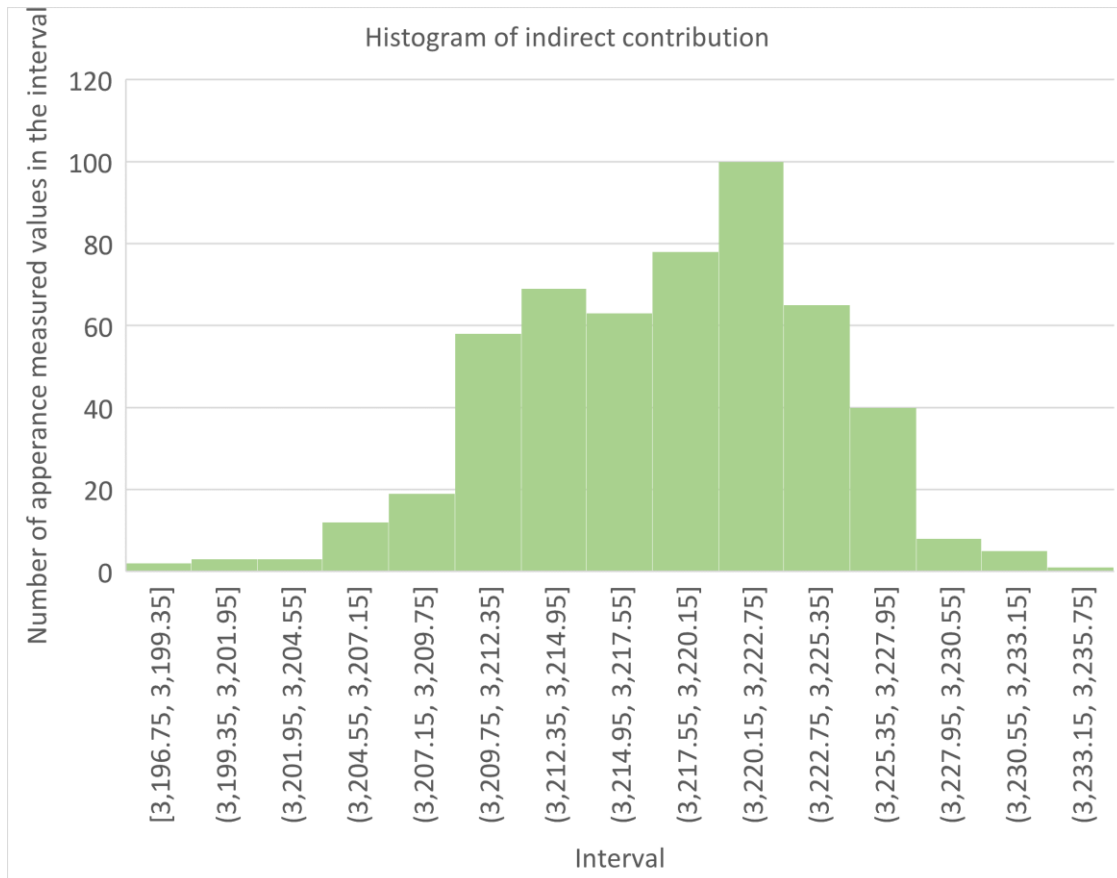
ub_{pw} – standard B uncertainty for water vapour partial pressure at wet bulb [Pa]

Next, relative standard uncertainty is determined. Standard ISO TS 16941 (2012) describes this calculation as follows, and it is shown in formula (63)

$$ub(r)_{pw} = \frac{ub_{pw}}{\bar{p}_w} = \frac{13.11}{96200.36 - 1709.66} = 0.00014 \text{ [-]} = 0.014\% \quad (63),$$

where

$ub(r)_{pw}$ – relative standard B uncertainty for water vapour partial pressure [%]



Graph 7 – Histogram of indirect contribution

4.6.2.6 Relative standard B uncertainty of indirect contribution

The factor of indirect contribution is the final value which affects the final size of the relative standard B uncertainty. This comes from the calculation of value $\bar{\phi}_{tci}$ which is calculated in the formula (35). Standard ISO TS 16491 (2012) defines that the uncertainty of indirect contribution z_7 is calculated as shown in formula (64).

$$z_7 = 0.015 \cdot \bar{\phi}_{tci} = 0.015 \cdot 3218.29 = 48.27 [W] \quad (64),$$

where

z_7 – uncertainty for indirect contribution which is described by standard ISO 16491 (2012)

Also, for further evaluation the histogram needs to be constructed, as shown in Graph 7.

From Figure 7 it can be said that the distribution is again Gaussian. So the divisor is equal to 3.

So it is possible to calculate the standard B uncertainty for indirect contribution by using formula (65) and the values from above.

$$ub_{c_1} = \frac{z_7}{k} = \frac{48.27}{3} = 16.09 [W] \quad (65),$$

where

ub_{c_1} – standard B uncertainty for indirect contribution

After determining the standard B uncertainty in the formula (66), relative standard uncertainty of indirect contribution can be expressed as follows.

$$ub(r)_{c_1} = \frac{ub_{c_1}}{\bar{\phi}_{tci}} = \frac{16.09}{3218.29} = 0.005 [-] = 0.5[\%] \quad (66),$$

where

$ub(r)_{c_1}$ – relative standard B uncertainty for indirect contribution

For better clarity Table 12 shows all the partial uncertainties in one place.

Table 12 – Summarised values for all partial uncertainties

Factors	Values of uncertainties [%]
Indoor air volume flow rate	1.6
Specific enthalpy of air entering the indoor side	1.7
Specific enthalpy of air leaving the indoor side	1.4
Air dry bulb temperature	0.02
Atmospheric pressure	0.34
Water vapour partial pressure at wet-bulb temperature T_w	0.014
Indirect contribution	0.5

As can be seen the biggest influence is the air flow rate which is hard to measure more accurately. The uncertainties of the enthalpies are also very high, but they are given by the requirement of the standard by which they are evaluated. This is an estimate of the uncertainty of the moist air model, so we cannot improve this uncertainty by using a more accurate thermometer.

4.6.3 Combined uncertainty calculation

After all the partial relative standard B uncertainties have been calculated, and standard A uncertainty has also been calculated, the final calculation of combined uncertainty can be performed. But firstly, the standard B uncertainty has to be stated by using the following formula (67).

$$ub(r) = \sqrt{ub(r)_{vi}^2 + ub(r)_{ha_1}^2 + ub(r)_{ha_2}^2 + ub(r)_T^2 + ub(r)_P^2 + ub(r)_{p_w}^2 + ub(r)_{c_1}^2} \quad (67),$$

where

$ub(r)$ – relative standard B uncertainty [%]

$$ub(r) =$$

$$= (\sqrt{0.016^2 + 0.017^2 + 0.014^2 + 0.0002^2 + 0.0034^2 + 0.00014^2 + 0.005^2}) \cdot 100 =$$

$$= 2.8 \text{ [%]}$$

Finally the combined uncertainty u_c is calculated based on the previous values as follow by using formula (68). It reflects formula (17) from chapter 2.25.3.

$$u_c = \sqrt{u_A(r)^2 + u_B(r)^2} = \sqrt{0.18^2 + 2.80^2} = \pm 2.81 \text{ [%]} \quad (68),$$

where

u_c – combined relative standard uncertainty

4.6.4 Expanded uncertainty calculation

As mentioned in the theoretical part, the final step is to determine the expanded uncertainty. This is done by using a coefficient which ensures a probability of 95% and is equal to 2. It is described in chapter 2.25.4. in formula (18). Below the formula (69) is calculated.

$$U = u_c k_u = 2.81 * 2 = \pm 5.62 \text{ [%]} \quad (69),$$

where

U – expanded uncertainty with a coverage factor of 95% [%]

4.7 Evaluation of results

As calculated above, the value of combined uncertainty is 2.81 %. As stated in chapter 4.3, according to the standard EN 14511-3 (2022) the maximum allowed combined uncertainty should be less than 5%. From this point of view it can be said that the measuring process for capacity measurement by using the air enthalpy method is compliant with the mentioned standard, as the combined uncertainty is below 5%.

As mentioned in chapter 4.3, the standard EN 14511-3 (2022) is related to standard ISO 16491 (2012), and this standard is related to ISO 5151 (2017). The last one determines the maximum allowed expanded uncertainty as lower than 10%. As can be seen in chapter 4.6.4 the value of expanded uncertainty is equal to 5.62%. Also in this case it can be stated that the measuring process at DICz meets the requirements of the standard ISO 5151 (2017).

When the comparison is done according to the values and sentences above, it can be said that DICz complies with all the standards that are used for the evaluation of the uncertainty of capacity measurement when using the air enthalpy method.

5 Conclusion

As stated in chapter 1.2, the motivation for this research comes from the current trends for ACs. In Daikin Czech Republic, these trends fall within the scope of the compliance group. If a producer of air conditioners wants to declare that its products are at a certain level or wants to show that it is compliant with the laws of a specific country, it needs to be compliant with the relevant standard. In this case, the standards are mainly EN 14 511-3 (2022), ISO TS 16491 (2012) and ISO 5151 (2017). These specific standards contain information about the evaluation of uncertainties of measurement for cooling or heating operations by using the air enthalpy method. For the purposes of this thesis, only the cooling mode is evaluated. How the refrigerant cycle works and how it is divided is described in chapters 3.1 and 3.2.

This is the first time in DICz, that the calculation of the uncertainty of measurement has been performed and the measuring chain has been described. We start with the chamber logic and how the data from the measurement is processed by using the chamber software and ending with the accuracy of measuring devices.

The evaluation of uncertainty using mainly standards EN14511-3 (2022), ISO TS 5151 (2017) and ISO TS 16491 (2012) is performed in this thesis. The air enthalpy method was used for measurement of cooling capacity.

In the theoretical part, there is a description of the basics of the refrigerant cycle, the main principle of heat pumps and air conditioners followed by an explanation of the theory of uncertainties and their calculation. In chapter 3, there is an explanation of the workings of the software logic of the chamber, the principle of, how output data are calculated and there is an explanation of how the measuring chain for temperature measurement and pressure measurement works.

Before starting the calculation of uncertainties, it was necessary to confirm that the measurement process matches the requirements of the standards which are mentioned above.

Standard A uncertainty was calculated for dry bulb and wet bulb thermometers because data was not available from DICz. After that it was combined with standard B uncertainty which comes from calibration sheet. Finally expanded uncertainty was stated. There was also a calculation of expanded uncertainty for air flow measurement and pressure devices. This needed to be performed for the measurement chain to satisfy the minimum requirements in the standard EN 14 511-3 (2022). Also, further description is given in chapter 4.1. The evidence that the measuring devices fulfil the demands of the standard is shown in Table 13. After the minimum demands of the standard were met, Ishikawa diagram was created to check which factors affect the final uncertainty of measurement. The diagram was created also to confirm that measurements in DICz are performed according to the standard ISO TS 16491 (2012). More details can be seen in chapter 4.4.

Table 13 – Confirmation of minimum requirements

Measured quantity for air parameters	Maximum allowed uncertainty of measurement	Uncertainty in DICz measurement equipment	Result
Dry bulb temperature	$\pm 0.2\text{K}$	$\pm 0.1\text{K}$	OK
Wet bulb temperature	$\pm 0.4\text{K}$	$\pm 0.1\text{K}$	OK
Air volume flow	$\pm 5\%$	$\pm 1.6\%$	OK
Static pressure difference	$\pm 5\%$	$\pm 0.053\%$	OK

After the Ishikawa diagram was created the final part of the uncertainties evaluation began. This was described in chapter 4.6.

Firstly, the measured data for total cooling capacity were checked for rough error. After that the standard A uncertainty was calculated.

In the second step, the relative standard B uncertainties were calculated. As can be seen in the previous chapters all the evaluated values have Gaussian distribution. The values of the divisors can be seen in chapter 2.25.2. Some of the factors were measured directly by measuring devices, some of them depended on more values such as the specific enthalpy of air entering the indoor side h_{a1} and specific enthalpy of air leaving the indoor side h_{a2} . Specific enthalpy of air entering the indoor side depends on the parameters of the air which enters the heat pump. On the other hand, the specific enthalpy of air leaving the indoor side depends on the parameters of the air which leaves the heat pump. As it can be seen in Table 14, the values for both the enthalpies and also the air volume flow rate have the biggest impact on the final results.

Table 14 gives the results for the relative standard A uncertainty, partial relative standard B uncertainty, combined uncertainty and expanded uncertainty.

Table 14 – Results of uncertainty evaluation

Calculated factors	Values of uncertainties [%]
Relative standard A uncertainty (u_A)	0.18
Indoor air volume flow rate	1.6
Specific enthalpy of air entering the indoor side	1.7
Specific enthalpy of air leaving the indoor side	1.4
Air dry bulb temperature	0.02
Atmospheric pressure	0.34
Water vapour partial pressure at wet-bulb temperature T_w	0.014
Indirect contribution	0.5
Relative standard B uncertainty (u_B)	2.8
Relative combined uncertainty (u_C)	2.81
Expanded uncertainty (U)	5.62

The final expanded uncertainty with a probability of 95% appearance was calculated by using formulas from chapters 4.6.2, 4.6.3 and 4.6.4. These formulas are described in the standard ISO TS 16491 (2012). As mentioned in chapter 4.3, the standard EN 14551-3 (2022) defines the maximum value of combined uncertainty as 5%. According to Table 12, the value of the combined uncertainty is equal to 2.81%. Finally, as stated in chapter 4.7, the maximum value of expanded uncertainty should be lower than 10% according to the standard ISO 5151 (2017). From this point of view it can be said that the measurement process of the total cooling capacity by using the air enthalpy method at DICz fulfils the demands of this standard.

The targets which were stated in chapter 1.3 which were to determine the value of the combined uncertainty according to the standard EN 14 511-3 (2022) and the value of expanded uncertainty according to the standard ISO 5151 (2017) are accomplished. Finally, a semi-automatic excel file for uncertainty calculations was created and developed. It will serve for the purpose of evaluation of uncertainties inside of DICz during air conditioners capacity measurements in cooling mode.

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