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**AUTOMATION OF HANDLING OF THE VENTILATION CHAMBER**  
**DATA, THE STUDY CHALLENGES OF THE RECEIVED DATA**  
**INACCURACIES**

**VENTILIACIJOS KAMEROS DUOMENŲ APDOROJIMO**  
**AUTOMATIZAVIMAS, GAUTŲ DUOMENŲ TIKSLUMO PROBLEMOS**  
**TYRIMAS**

Master Thesis

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## SUMMARY

This work raises the problem of inaccuracy of data obtained as a result of performing testing of ventilation equipment, as well as the problem of automating the actions of a laboratory technician and a software for testing.

At the present time, the accuracy of the result is very important, especially in the evaluation of ventilation equipment. The customer needs to know all the parameters thoroughly, and as well to know how accurate these parameters are.

The aim of the work is to improve the methodology for obtaining accurate data, and to create an estimate of accuracy.

This work was developed in cooperation with Salda UAB, which manufactures ventilation equipment, and Siventa UAB laboratory, which performs testing of ventilation equipment.

The paper describes testing of equipment using a ventilation chamber into which air is pumped, setting the temperature, humidity and pressure. Ventilation chambers are additionally configured and represent installations for testing. This air passes through the equipment under test, as a result of which it is possible to determine the parameters at the output.

During the work of the laboratory, there was also a problem of increasing accreditation, for which the calculations should comply with new standards, in particular LST EN ISO 5801: 2009 and EA-4/02.

This work is a guideline for achieving these standards, focusing on the uncertainty of the result, as a measure of accuracy. The developed methods meet the standards, and likewise present additional ways to improve the accuracy of the result. Such approaches can be used at other enterprises to improve accuracy and introduce an additional criterion for estimating the accuracy of the result.

The paper reveals the problem of automation of the data acquisition process, the time spent by the technician on manual operations, which were subsequently automated to save time. The recognized principles of automation also affect the readout time of data, making it possible to do the reading fast and accurate, which also affects the accuracy of the result.

The result of the work is represented by a developed methodology for calculating parameters, methods for automating the process of measuring data, and a software product that implements techniques and established methods for optimizing working time, reading and processing data.

**Key words:** ventilation chamber; automation; air-measuring software; air parameter precision; uncertainty calculation algorithm.

## SANTRAUKA

Šis darbas iškelia problemas gautu duomenų netikslumą, kai atliekami bandymai vėdinimo įrangos, taip pat problemas automatizuojant laboratorijos techniko veiksmus ir bandymų programine įranga.

Šiuo metu, tikslumas yra labai svarbus, ypač vėdinimo įrangos vertinimo. Klientas turi žinoti visus parametrus, o taip pat žinoti, kaip tikslius šie parametrai yra.

Darbo tikslas yra pagerinti tikslu duomeniu gavimo metodiką, ir sukurti tikslumo įvertinimą.

Šis darbas buvo sukurtas bendradarbiaujant su Salda UAB, kuri gamina vėdinimo įranga, ir Siventa UAB laboratorija, kuri atlieka bandymus vėdinimo įrangai.

Dokumente aprašoma bandymus, naudojanti vėdinimo kamerą, į kuria oras siurbiamas, nustatoma temperatūrą, drėgnumą ir slėgį. Ventiliacijos kameros yra papildomai sukongfigūruotas ir atstovauja kaip įrenginiai būna įrengti. Šis oras praeina per įranga testavimo metu dėlto galima nustatyti, išėjimo parametrus.

Per laboratorinius darbus, taip pat buvo problema padidintos akreditacijos, dėl kurių skaičiavimai turėtų atitikti naujus standartus, ypač LST EN ISO 5801: 2009 ir EA-4/02.

Šis darbas yra taisyklės, norint pasiekti šiuos standartus, sutelkiant dėmesį į rezultato neapibrėžtumą, kaip tikslumo matas. Išsivystė metodai atitinka standartus, ir taip pat pateikti papildomą būdų, kaip pagerinti rezultato tikslumą. Tokie metodai gali būti naudojami ir kitų įmonių siekiant pagerinti tikslumą ir nustatyti papildomą kriterijų vertinant rezultato tikslumą.

Darbas atskleidžia automatizavimą duomenų įsigijimo procesą, laika sugaišintas technikams rankinėms operacijoms, kurios vėliau buvo automatizuotos taupyti laika. Pripažinti principai automatizavimui taip pat turi įtakos laiką duomenimis nuskaityti, kad būtų galima skaityti greičiau ir tiksliau, kurie taip pat turi įtakos rezultato tikslumui.

Darbo rezultatas yra atstovaujama sukūrė skaičiavimo metodiką parametrus, metodus automatizuojant matavimo duomenų procesą ir programinės įrangos produktą, kuris įgyvendina technika ir nustatyto metodus darbo laiko, skaitymo ir duomenų apdorojimui optimizavimui.

**Reikšminiai žodžiai:** vėdinimo kamera; automatizavimas; oro matavimo įranga; oro srauto tikslumas; neapibrėžties skaičiavimo algoritmas.

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## INTRODUCTION

Nowadays the absoluteness of measurements takes a crucial part in the manufacturing sphere. Only by getting the correct data from some required device we can be ensured that everything works as expected and device can function and play its role in community. The term of the results “correctness” has no boundaries and people can achieve as much precision as the technologies of our time can let us. For big scientific centers and companies, like NASA [1] or Microsoft [2], to achieve a required precision is not an issue because they got a lot of funding, huge material base and a strong sector of employees and scientists working on a specific precision issue to help the company to provide better results to audience and customers’ area. Accuracy is crucial, especially when it is told about solid hardware being used in public zones or designed for big communities.

The work is related to cooperation with Salda UAB [3] which is quite a big company the main purpose of which is to create ventilation equipment, test it and provide to the customer area. The company is working for long years and have a huge group of customers which are very interested in getting the most precise equipment and to know the exact physical parameters of it to expect the behavior, make planning and understand how long the device can be used, what will be the expenses of its service and just how confident they can be about their purchase in general.

Siventa UAB [4] laboratory is located next to Salda UAB and they are cooperating. The laboratory provides theoretical material for the company and makes all the necessary calculations, charts and whatsoever.

Thesis work is related to cooperation with Siventa UAB as well. The aim of cooperation was to provide to the customers what they need – very accurate measurements corresponding to the highest European standards. We had to think of the options of improvement, how to make current algorithms even more precise, what information about the equipment should be provided to the client to make him satisfied and our job clear. We had to request the clients about what measurements do they need. We also had to develop a software for testing devices and gathering all the technical data about measured device. The software already existed but it didn’t provide all the required data and its precision was far away of what was needed.

The aim of the work is to reduce the inaccuracies of received air chamber data and of the calculations based on this data by proposing and to make the mechanism of ventilation data handling more automated, independent from technician manual service.

To achieve the objective, following tasks have to be completed:

1. Get to know the research area: process of ventilation device testing in Siventa lab.
2. Understand the problem of inaccuracy and lack of the automation, create a problem description and analyze weaknesses of current setting.

3. Analyze similar issues and research field literature related to precision increasing and automation process, review the techniques of their solving to be familiar with the major themes relevant to the subject area to develop more insightful and focused questions about the topic.
4. Propose a solution to the problem – describe the methodology which is going to be used in order to reach the objectives of thesis work, justify the selection choice.
5. Test and validate the proposed solution – make tests in the laboratory regarding accuracy of measurements, speed of measurement and assess the automation level.
6. Analyze the research results, pros and cons of the developed solution, compare the solution with the previous one.



## 1. ANALYTICAL PART

### 1.1. Working area and installations

The main problem raised in this thesis work – automation of handling of the ventilation chamber data and the study challenges of the received data inaccuracies.

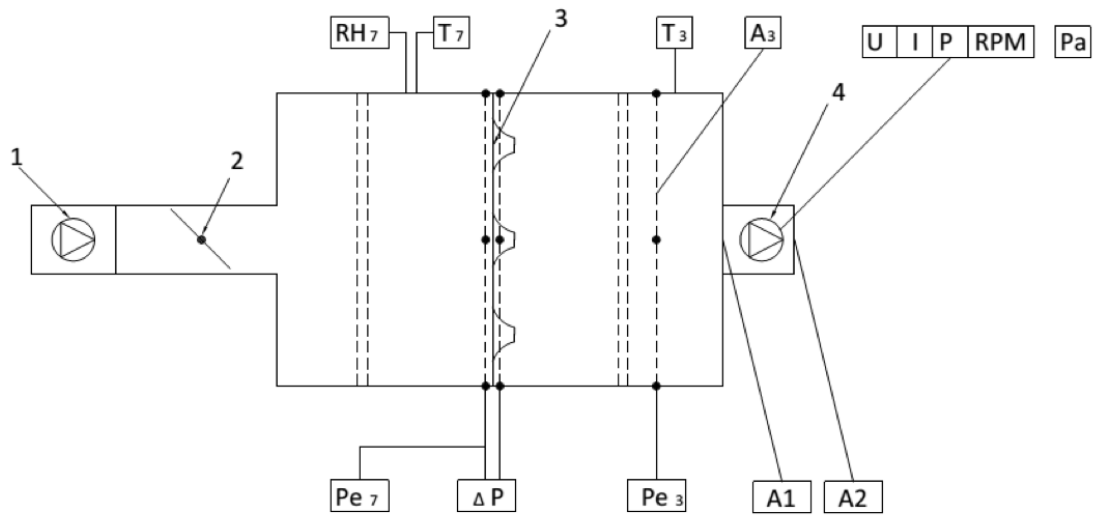
Automation is required for speed up the process of measurements, other words – for data handling. Salda UAB is specified on the ventilation supplies, as was mentioned in introduction part; customers should be aware of characteristics of certain device to know where and how it can be used. Supplied devices are represented by be air recuperators (counter-flow energy recovery heat exchanger), gas, electrical heaters, different inserts and technical parts etc. The majority of these supplies should be tested for correct work cycle execution (e.g. during the work of device air mass flow value should be in a specified range, fan should have certain rotation frequency, otherwise the measured device is not good or not enough good for performing an expected work).

Testing process is performed in laboratory with use of air (ventilation) chamber [5] (Figure 1.1.1).



*Figure 1.1.1. Laboratory – equipment testing.*

Scheme of air chamber is provided on 0.2 below.



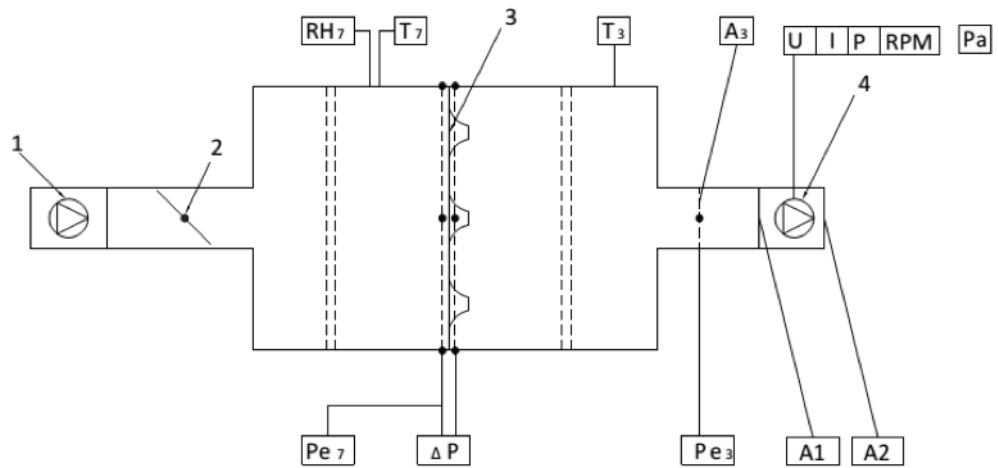
1. Chamber fan
2. Chamber valve
3. Nozzles' valves and nozzles
4. Test fan

- T - Temperature sensor
- Pe - Pressure inverter (static pressure)
- $\Delta p$  - Differential pressure inverter (nozzle pressure difference)
- RH - Relative humidity
- A1,A2,A3,A4 - Measurement plane

**Figure 1.1.2. Scheme of Installation A.**

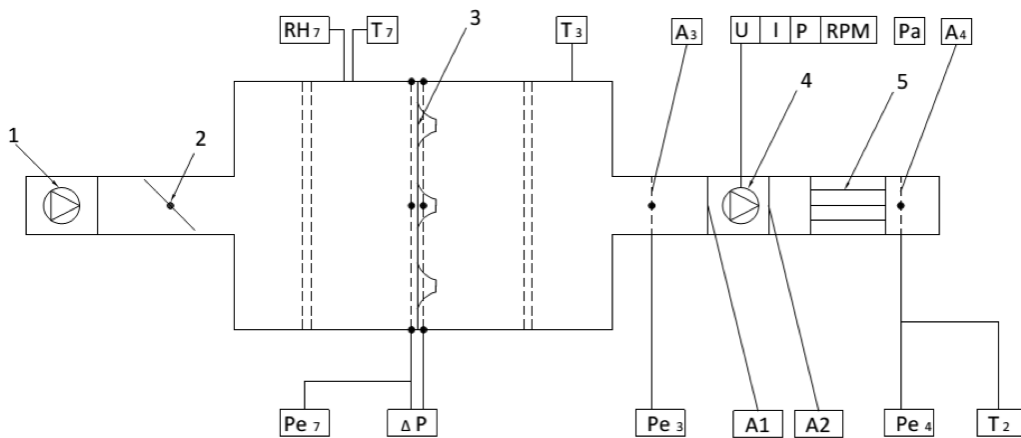
This scheme displays one of 4 installations of air chamber. Installation represents a special air chamber configuration and designed for different testing facilities. Installation provided on 0.2 is called base installation. Other installations are configurations of the base one. Air chamber *Inlet Fan* (1), displayed at the very beginning on Figure, creates an air pressure inside the ventilation chamber, which brings the change of the temperature, humidity and pressure. *Chamber valve* (2) is used to control the air amount coming to the air chamber. *Nozzles* (3) are mounted inside for the purpose of creating differential pressure ( $\Delta p$ ) that causes a change of temperature and humidity in the second part (at the right side from nozzles plane) of air chamber. The objective of a such configuration is to provide a flexible control of physical air parameters – the very crucial part for completing the measurement of the tested device. The *Test Fan* (4) or *Outlet Fan* represents a fan connected consequently to the device being tested and is located after it, at the very end of installation. Sensors connected to the *Outlet Fan* provide the information regarding amperage, voltage and power of the fan and, in addition, a laser beam sensor is pointed to the *Outlet Fan* and provides the information regarding fan rotation frequency.

Other installations can also have insets in the tube leading to the *Outlet Fan* (for air behavior control). The schemes of installations are provided below.



- |                                |  |
|--------------------------------|--|
| 1. Chamber fan                 | T - Temperature sensor   |
| 2. Chamber valve               | Pe - Pressure inverter (static pressure)                                 |
| 3. Nozzles' valves and nozzles | $\Delta p$ - Differential pressure inverter (nozzle pressure difference) |
| 4. Test fan                    | RH - Relative humidity   |

**Figure 1.1.3. Scheme of Installation C.**



- |                                |  |
|--------------------------------|--|
| 1. Chamber fan                 | T - Temperature sensor   |
| 2. Chamber valve               | Pe - Pressure inverter (static pressure)                                 |
| 3. Nozzles' valves and nozzles | $\Delta p$ - Differential pressure inverter (nozzle pressure difference) |
| 4. Test fan                    | RH - Relative humidity   |
| 5. Air flow straightener       |  |

Installation D

**Figure 1.1.3. Scheme of Installation B and D.**

Installations B and D can have additional configurations because they have inserts which can be replaced.

## 1.2. Measurement procedure

Measurements are performed by the technician in laboratory. He configures nozzles by opening or closing the nozzle cap that influences on *differential pressure* ( $\Delta p$ ), his control panel consists of various devices displaying sensors' values on screen (KIMO CP300 [6], Figure 1.2.1), controller for changing the speed of rotating *Inlet Fan* (Toshiba VF-S11 [7], Figure 1.2.2), devices for measuring electrical parameters – power analyzers Yokogawa WT1800 [8] (Figure 1.2.3) and Janitza UMG 96RM [9] (Figure 1.2.4). Power analyzers are displaying phases of current because current can be configured for measuring of different phases that brings more reliable information, makes the device to work with specified type of current or simply cuts the data which is not required.



*Figure 1.2.1. KIMO CP300 sensors.*



*Figure 1.2.2. Toshiba VF-S11 – Inlet Fan Controller.*



*Figure 1.2.3. Yokogawa WT1800 – Power Analyzer.*



*Figure 1.2.4. Janitza UMG 96RM – Power Analyser.*

All the sensors have Ethernet connection and are using *TCP/IP protocol* [10] or either *ModBus protocol* [11] for connection and data handling. This provides all the required data to control panel of the worker and all the data can be handled by a programme, processed and displayed in data grids.

A special software was developed for need of making measurements of ventilation device. Technician could start measurement by pressing the corresponding button in application. After the button was pressed, there were performed **30 measurements within 60 seconds**, their average result was computed and used for further calculations of physical parameters which give information about device. List of measurements could be saved to the file and be loaded again for additional measurement. Each measurement represents by a row which contains measured data and calculated physical parameters. *Air flow* and *pressure* values represent a dot on a chart. Each row is used to create a chart and build curves. Every curve has its number. The number specifies that this measurement cycle was made when one of the inlet parameters was forced to be constant. Such method of measuring is implemented to provide a stress test of equipment when one or few inlet parameters are not changing. To know what kind of measurement was performed, technician sets the name of the project according to the data contained in it.

Software which is used by technician is provided on the Figure 1.2.5 below.

Application shows the live data of inlet values got from sensors.

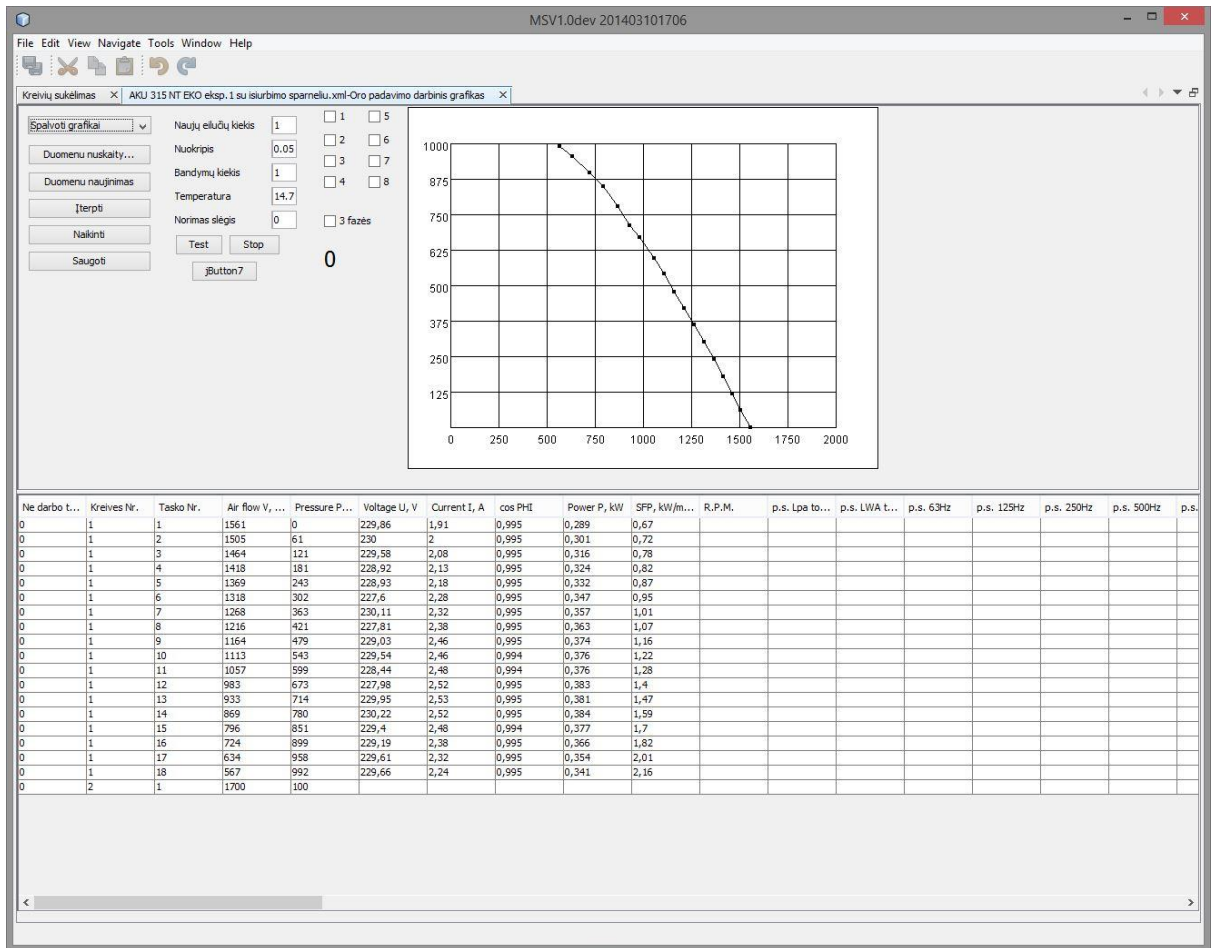


Figure 1.2.5. Old application interface.

Technician can choose the type of chart what is required, can modify table values. Full range of measured and calculated parameters is provided in Table below.

Table 1.2.1.

### Measured parameters

Parameter name	Description
Air Flow V, m3/h	Volume of air flow, cubic meters per hour
Pressure Pst, Pa	Stagnation pressure
Voltage U, V	Device voltage
Current I, A	Device current
cos PHI	Device power characteristic, <b>cos φ</b>
Power P, kW	Device power
SFP, kW/m3/s	Specific fan power
R.P.M.	Rotation per minute
Voltage L1_N	Voltage, line 1
Voltage L2_N	Voltage, line 2



Voltage L3_N	Voltage, line 3
Voltage L2_L3	Combined voltage, lines 2 and 3
Voltage L3_L1	Combined voltage, lines 3 and 1
Current L1	Current, line 1
Current L2	Current, line 2
Current L3	Current, line 3
cos PHI L1	Device power characteristic, <b>cos <math>\varphi</math></b> , line 1
cos PHI L2	Device power characteristic, <b>cos <math>\varphi</math></b> , line 2
cos PHI L3	Device power characteristic, <b>cos <math>\varphi</math></b> , line 3
Power P, W L1	Power, line 1
Power P, W L2	Power, line 2
Power P, W L3	Power, line 3
Temperature	Inlet temperature
Humidity %	Inlet humidity
Pressure	Inlet pressure (atmospheric)
RHO	Inlet density
Voltage L_N Sum	Sum of voltages in all lines
Voltage L1_L3 Sum	Sum of voltages in lines 1 and 3
Current N	Current in all lines
cos PHI Sum.	Sum of device power characteristic, <b>cos <math>\varphi</math></b>
Power P, W Sum	Sum of power on all lines

### 1.3. Problem occurrence

The application, described previously, was performing good but it couldn't be used anymore because of next reasons:

- Calculations are based on the old standards and cannot provide sufficient level of data accuracy to customers.
- For Siventa laboratory the accreditation level was insufficient because their measurement techniques and calculations were based on old EU standards and couldn't be enough to get the maximal level of accreditation; this fact influences tested devices' certification and customer demand.
- Programme used for performing measurements was heavy in usage, non-customizable or flexible, it wasn't providing a sufficient automation and many actions had to be performed by technician manually.



- Measurements took too long time to be accomplished.
- The application could work only with certain devices (sensors, power analyzers), whereas new hardware configuration has appeared which assumed the way of direct connection to sensors through Modbus protocol, nevertheless the software used a TCP/IP connection to end devices (screens) which were displaying measured data.

In addition, it should be mentioned that the laboratory got a new air chamber, much bigger than previous one, with dampers airflow control (instead of nozzles configuration), which can be controlled completely from the application (nozzles should be closed or opened manually by technician). Therefore, these issues pushed forward to the idea of creating new calculations that meet EU standards required for device certification and a new application that will cope with all the minuses of previous one and will bring the measured data precision to significantly higher level without much costs.

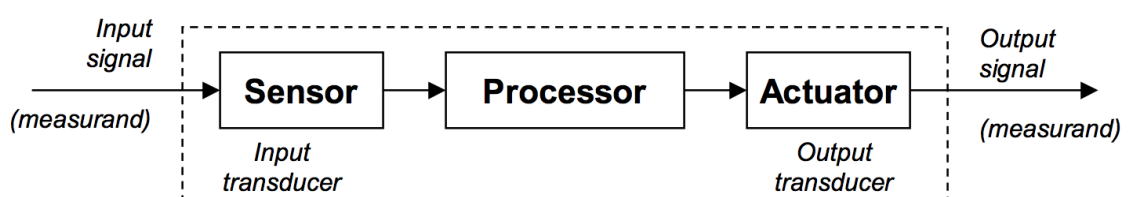
#### 1.4. Sensors and actuators mechanism

Previously the application that was deployed in the laboratory PC for handling the data measurements was reading the input data from *actuators* [12] connected to sensors and making calculations based on the input data. Sensors are working in pair with actuators and together they create a transducer [13] interaction mechanism.

A *transducer* is a device that converts one form of energy to another. Usually a transducer converts a signal in one form of energy to a signal in another. Transducers are often employed at the boundaries of automation, measurement, and control systems, where electrical signals are converted to and from other physical quantities (temperature, pressure, humidity, etc.).

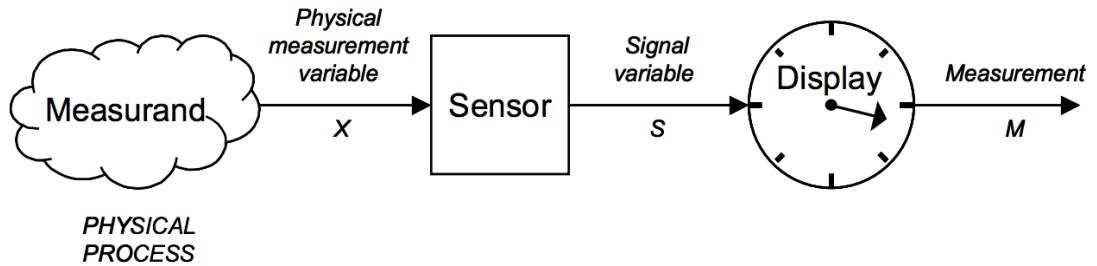
An *actuator* is a component of a machine that is responsible for moving or controlling a mechanism or system, or for displaying system values. In case of current workspace, actuators are represented by Toshiba controller (Inlet Fan speed), Yokogawa and Janitze devices, and screens displaying the current measured value, handled from sensor.

In a nutshell, sensor is an input transducer, and actuator is an output transducer. A diagram of transducer mechanism is provided on Figure 1.4.1 below.



*Figure 1.4.1. Transducers' interaction mechanism.*

Sensor and actuator form an instrument. For the purposes of simplifying the content of the thesis work instruments are called sensors because their main feature is just to obtain the physical parameters of the measured air (measurand). The scheme representing the instrument workflow is shown on the Figure 1.4.2 provided below.



*Figure 1.4.2. Instrument scheme.*

Sensors are the core of the measurement system. The data they provide is a key factor for making evaluations of additional physical quantities describing tested device. Data accuracy is very important. Each sensor device was provided with documentation describing input value range, sensitivity and errors and other physical parameters.

Several characteristics' descriptions and examples are provided below [14]:

**a) Sensitivity.**

The sensitivity of the sensor is defined as the slope of the output characteristic curve ( $DY/DX$  in Figure 1.4.3) or, more generally, the minimum input of physical parameter that will create a detectable output change. In some sensors, the sensitivity is defined as the input parameter change required to produce a standardized output change. In others, it is defined as an output voltage change for a given change in input parameter. For example, a typical blood pressure transducer may have a sensitivity rating of 10 mV/V/mm Hg. That is, there will be a 10-mV output voltage for each volt of excitation potential and each mm Hg of applied pressure.

**b) Sensitivity Error.**

The sensitivity error (shown as a dotted curve in Figure 1.4.3) is a departure from the ideal slope of the characteristic curve. For example, the pressure transducer discussed above may have an actual sensitivity of 7.8 mV/V/mm Hg instead of 10 mV/V/mm Hg.

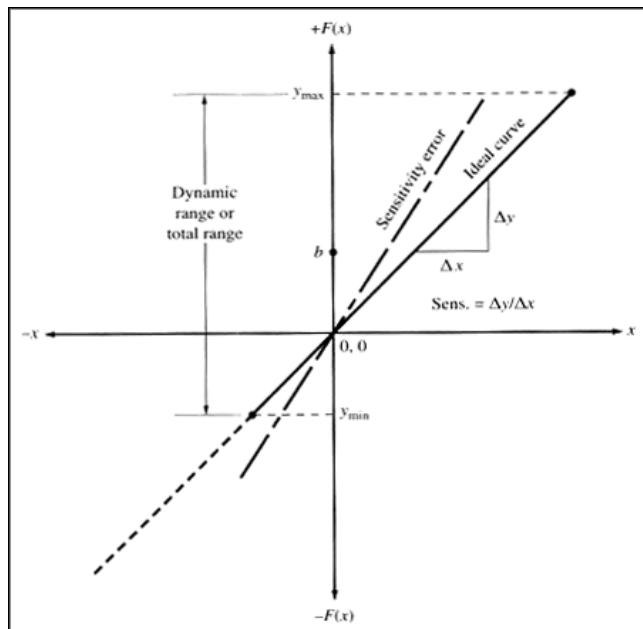
**c) Range**

The range of the sensor is the maximum and minimum values of applied parameter that can be measured. For example, a given pressure sensor may have a range of -400 to +400 mm Hg. Alternatively, the positive and negative ranges often are unequal. For example, a certain medical blood pressure transducer is specified to have a minimum (vacuum) limit of -50 mm Hg ( $Y_{\min}$  in Figure 1.4.3) and a maximum (pressure) limit of +450 mm Hg ( $Y_{\max}$  in Figure 1). This specification

is common, incidentally, and is one reason doctors and nurses sometimes destroy blood pressure sensors when attempting to draw blood through an arterial line without being mindful of the position of the fluid stopcocks in the system. A small syringe can exert a tremendous vacuum on a closed system.

**d) Precision**

The concept of precision refers to the degree of reproducibility of a measurement. In other words, if exactly the same value were measured a number of times, an ideal sensor would output exactly the same value every time. But real sensors output a range of values distributed in some manner relative to the actual correct value. For example, suppose a pressure of exactly 150 mm Hg is applied to a sensor. Even if the applied pressure never changes, the output values from the sensor will vary considerably. Some subtle problems arise in the matter of precision when the true value and the sensor's mean value are not within a certain distance of each other (e.g., the 1-s range of the normal distribution curve).

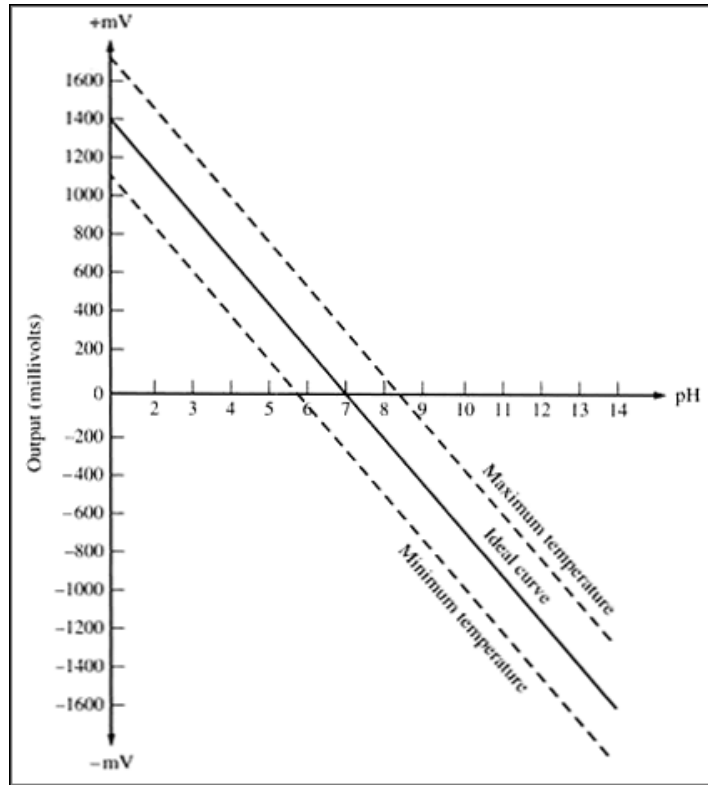


**Figure 1.4.3.** Ideal curve and sensitivity error. Source: J.J. Carr, *Sensors and Circuits* Prentice Hall.

**e) Offset**

The offset error of a transducer is defined as the output that will exist when it should be zero or, alternatively, the difference between the actual output value and the specified output value under some particular set of conditions. An example of the first situation in terms of Figure 1 would exist if the characteristic curve had the same sensitivity slope as the ideal but crossed the Y-axis (output) at b instead of zero. An example of the other form of offset is seen in the characteristic curve of a pH electrode shown in Figure 1.4.4. The ideal curve will exist only at one temperature (usually 25°C),

while the actual curve will be between the minimum temperature and maximum temperature limits depending on the temperature of the sample and electrode.



**Figure 1.4.4.** Typical pH electrode characteristic curve showing temperature sensitivity. Source: J.J. Carr, *Sensors and Circuits* Prentice Hall.

There are also such parameters as *linearity*, *response time*, *hysteresis curves*, *dynamic linearity calculations* etc., which are not mentioned here but which may be applied for calculations as well. The *offset* parameter is crucial, it's role in data processing is major for accuracy determination. Knowing the offset, we can write input value as follows [15]:

$$a_r = a_m \pm \Delta a, \quad (1.1)$$

where  $a_r$  – resulting value,  $a_m$  – measured value,  $\Delta a$  – offset or range of value deviation.

For better practice, it is required to calculate a percentage of measurement accuracy, which will provide additional stochastic evaluation of the value. For such purpose MAPE [16] approach is used.

Mean absolute percentage error (MAPE), also known as *mean absolute percentage deviation (MAPD)*, is a measure of prediction accuracy. It usually expresses accuracy as a percentage, and is defined by the formula:

$$M = \frac{100}{n} \sum_{t=1}^n \left| \frac{A_t - F_t}{A_t} \right|, \quad (1.2)$$

where  $A_t$  is the actual value and  $F_t$  is the forecast value.

However, statistically MAPE value is not enough to provide the full specter of input values behavior. Standard deviation [17] method is used often in statistics and is required for data measurement as well.

Standard deviation – is a measure that is used to quantify the amount of variation or dispersion of a set of data values []. A low standard deviation indicates that the data points tend to be close to the mean (also called the expected value) of the set, while a high standard deviation indicates that the data points are spread out over a wider range of values.

$$\sigma = \sqrt{\frac{1}{n} \sum_{i=1}^n (x_i - \bar{x})^2}, \quad (1.3)$$

where  $\sigma^2$  – dispersion,  $x_i$  –  $i$ -th element of sampling,  $n$  – sample size,  $\bar{x}$  - arithmetic mean of sampling.

In pair with mentioned statistical approaches, a *calibration method* is used as well. Calibration is performed once in a year and is required to check if sensor is working as expected. A sensor or instrument is calibrated by applying a number of known physical inputs and recording the response of the system.

### 1.5. Problem analysis. Standards.

Despite the fact that mentioned methods are sufficient for providing error of input and calculated data, the level of accuracy is still not enough high, calculations based on the input data are getting even higher error, which leads to insufficient accuracy of end results, and some customers cannot use such equipment because of some unpredicted (or badly predicted) behavior.

Laboratory doesn't have a sufficient accreditation to be accredited at highest level due to the usage of old ISO standards for making calculations. This leads as well to the problem of accuracy mentioned before.

List of the standards and their descriptions is given below in Table 1.5.1:

Table 1.5.1.

**List of standards**

<b>Standard name</b>	<b>Description</b>
LST EN 13141-7:2011; LST EN 308:2001; LST EN 1886:2008	Ventilation equipment for external and internal leak tests
LST EN 1751:2014	Ventilation valves and vents leak tests
LST EN 15727:2010	Air tightness testing of components
LST EN ISO 5801:2009	HRV fans and flow/pressure characteristics

LST EN 13053:2006 + A1:2011	Ventilation devices air flow/pressure characteristics
LST EN 13141-7 2011; LST EN 13053:2006 + A1:2011	Ventilation equipment noise during the testing body
EN 13141-4:2011	Ventilation fan noise measurements
LST 1886:2008	Air preparation units' acoustic suppression tests
LST EN ISO 3744:2010	Any kind of noise measurement
LST EN 13141-7:2011	Ventilation equipment noise channel tests
LST EN 13141-4:2011	Ventilation fan noise channel tests
LST 5136:2010	Fan, ventilation equipment, air conditioning units the noise emission tests
LST EN 13141-7 2011; LST EN 308:2001	Recuperator thermal efficiency

Measurements and calculations problem description:

- **Standard LST EN ISO 5801:2009** [18] is not implemented in the calculations. Older version of the standard was used. Standard specifies how the testing in air chambers should be handled; what are installations, how should they be built and configured; how to set up sensors in air chamber, how to calibrate them and take measurements, etc. The difference between the old standards is that laboratory should test Heat Recovery Ventilators (HRV) [19] and calculate flow/pressure characteristics differently, using *uncertainty approach, making calibration tables of more detailed type* (with information regarding calibration point possible error value) and other improvements regarding pressure and airflow measurement.
- To reach the accreditation level, laboratory should implement European standard **EA-4/02 – Evaluation of the Uncertainty of Measurement in Calibration** [20]. The standard stands for uncertainty approach for calibration data and combines with the standard mentioned before.

Both standards mention uncertainty and its usage in the assessment of the data precision. Uncertainty provides information regarding how accurate is the result, in what range the result it is considered to be correct.

The uncertainty of measurement is a non-negative parameter, associated with the result of a measurement that characterizes the dispersion of the values that could reasonably be attributed to the measurand [20].

## 1.6. Problem summary.

The problem raised in this research work consists of two parts:

1. Automation of handling of ventilation chamber data.
2. Received data inaccuracy.

During the process of software issues analyzing next problems were allocated:

- Application doesn't provide a function to save measured data to Excel file or report, technician has to copy data from data grid, paste it to the Excel/report and create it manually.
- Application connects to actuators which display data been read from sensors; such connection leads to slowing down the measurement speed. Due to the change of network structure and implementation of Modbus interface for each sensor, the speed of measurements can be raised, which will reduce delay between read operations and will increase accuracy of measured data – *average value of several consecutive measurements is used for calculations.*
- There is no fan control in the app, technician is able to change the fan frequency value only manually using a fan actuator (controller). Nevertheless, fan controller implements Modbus interface as well and may be accessed over the local network.
- Calibration points are hardcoded into software. Technician cannot change them by himself.
- Due to the desire to raise the accreditation level, laboratory should provide more parameters characterizing the device. These parameters are not calculated in the mentioned software.

During the process of measurements accuracy analyzing next problems were allocated:

- Measurements' calculations are outdated, they should meet the standard LST EN ISO 5801:2009 **and** EA-4/02.
- Due to new standards, big attention should be paid to uncertainty calculation for parameters.
- Calculated uncertainty and other data provided for sensors calibration and testing can be used for increasing the accuracy of the measurements and calculations.

## 1.7. Analysis of standards and existing accuracy increasing approaches.

To build a solution of inaccuracy problem we have to review given standards and existing approaches for increasing the accuracy of the data received from sensors, analyze them and develop a method which will provide calculations based on new techniques and conforming standards.

Below is standards literature analysis. These standards should be implemented by the demand of Salda UAB to provide information to customers, by Siventa UAB to get the desired level of accreditation, and to cope with data inaccuracy problem.

**LST EN ISO 5801:2009** [18] standard informs how to perform a test of ventilation equipment, how to construct installations, where to locate sensors and which calculations can be done for certain installation. Standard describes how to measure physical parameters as well and specifies that all measured values should have their *uncertainty* parameter calculated. This information is required to configure the laboratory for making tests.

**EA-4/02** [20] is a European standard for all laboratories which test ventilation equipment and want to be accredited with the level corresponding to one mentioned in the standard. The document gives the information about the term of *uncertainty*, how to calculate *standard* and *extended uncertainty*. Documentation informs that *uncertainty* is a parameter characterizing the dispersion of the values attributed to a measured quantity. Other words, *uncertainty* is a range of a parameter in which parameter can have deviation and such deviation represents a precision of measured value. Measurement uncertainty has important economic consequences for calibration and measurement activities. In calibration reports, the magnitude of the uncertainty is often taken as an indication of the quality of the laboratory, and smaller uncertainty values generally are of higher value and of higher cost. The dispersion of the measured values would relate to how well the measurement is performed. Their average would provide an estimate of the true value of the quantity that generally would be more reliable than an individual measured value. The dispersion and the number of measured values would provide information relating to the average value as an estimate of the true value []. The technique described in this standard for *uncertainty* calculation is obligate to implement. Further uncertainty calculations will be based on this technique.

However, the way of implementation of the technique is unique and varies in different laboratories. We should provide certain range of calculated parameters with uncertainty specified for each of them. These parameters are computed in accordance with installation configuration that is described in a standard *LST EN ISO 5801:2009*. Although the approach can be created not only been based on standards, but also implementing other techniques which will be discussed further.

The following question may arise – why should uncertainty be provided? In most of cases, the requirement to present an estimated uncertainty is mandatory for the laboratory. Such cases may include:

- customer requirements;
- the possibility of incorrect interpretation of the result due to lack of information about uncertainty;



- an increase in uncertainty compared to calculated from the data given in the methodology.

Below there is a literature analysis of scientific publications and articles. Selected articles contain approaches which were considered useful and reliable for creating a final solution to solve data inaccuracy problem.

Rucki M. describes a calibration method of gauge air pressure sensor measured value – with uncertainty approach [21]. Such measurements are simple, precise and cheap, which is an unbeatable plus for their usage in the work area. At present time, most of new pneumatic devices, which have sensors, are very sensitive to the changes of pressure in testing (ventilation) chamber. Flowing phenomena cause fluctuations of measured pressure and have an influence on the end result. If not taking into account this process as an important one, fluctuations can influence on measuring results, and especially on the adjustment of the gauge sensor. This work represents method of gauge pressure uncertainty calculation taking into account pressure fluctuations and shows practical meaning of such method. Technique, outlined in this work, can be used not only for calculations of uncertainty of the gauge pressure but also for temperature, humidity and other physical characteristics. This method is reflected in this thesis paper and found its usage for creating a calculation methodic for installations.

In addition to Rucki M. [21], Ospina J.A. [22] describes the analysis of uncertainty obtained as a result of measurement of temperature by sensor. This analysis can have a successful usage in thesis work because it simplifies methods of temperature sensor calibration. The objective is to reconcile the difference between measurements, making a wider tolerance to their absolute value. This work provides the analysis of uncertainty of two measurements difference happened due to the error in sensor calibration. It is shown how calibration by method of comparison, which can be performed without expert request, can lead to essential uncertainty reduction. As a result of calibration technique and uncertainty reduction, the end result value becomes more precise. Customers are interested in lowering of uncertainty parameters, thus this paper gives a necessary material for measurement technique construction and found its usage in calculations.

## **1.8. Chapter Conclusions**

In this chapter, the working environment and its variations, work in the given environment, configurations of installations and responsibility of the laboratory assistant were considered. Besides, we examined the problem that arose due to the insufficient accuracy of the data obtained during the measurement process, the mismatch of computations with the required standards, and the lack of proper automation of the process of taking measurements and controlling the physical devices involved into measurements. The mechanism of sensors operation and data reading from these

sensors was described. We show the problems of the accuracy of the measurements received from the sensors and their existing solutions at that time.

During the analysis we considered key standards, their significance and application in testing of ventilation equipment, their role for the company, laboratory and customer. The main feature of these standards is the computation of uncertainty, which shows with what accuracy the measurements were made. Reducing the uncertainty of the result demonstrates higher accuracy and decreases the spread. Such an indicator is necessary for the customer, but at the same time it can help the laboratory calibrate and adjust its instruments in such a way that the accuracy of the measurements will be higher. LST EN ISO 5801:2009 **and** EA-4/02 standards served as a starting point for subsequent computations and the creation of a computational methodology. In addition to the above standards, scientific articles were considered that provided techniques for increasing the accuracy of calculations, calculating uncertainty, taking into account air fluctuations in the chamber, and improving the method of sensors calibration of instruments.

## 2. PRACTICAL PART

### 2.1. Workflow

To perform this work, a methodology for calculating parameters has been created, and software has been developed that takes into account the shortcomings of the old one and performs automation of the testing of ventilation equipment.

The calculation methodology was developed in cooperation with Siventa UAB and especially with dr. Sergėjus Rimovskis, PhD in Mechanical Engineering, lecturer at Siauliai University and co-worker of Siventa laboratory. Methodology describes a different, not used before approach of providing data accuracy – using uncertainty and making adjustments to calculations based on the EA-4/02 standard technique as well as on techniques mentioned articles.

The accuracy can be increased by adding the calibration points and the uncertainty of the corresponding sensor, and perform a special calculation, the result of which will be the value adjusted by the calibration data. Developed method for obtaining such calculations will be provided in the next chapter.

In a nutshell, technique is to measure the number of values obtained from the sensor, find their average value and calculate the standard deviation. After that, on the basis of calibration points and the resulting standard deviation the standard and extended uncertainty can be calculated. The expanded uncertainty shows interval – the deviation from the calculated point where the real value can be located. Thus, the customer will certainly have information not only about the equipment but also about the accuracy of the measurements. Major parts of methodology will be examined in this chapter.

The list of calculations gets a large number of parameters, which can vary depending on the used installation (equipment configuration). For example, the density of air is calculated, stagnation and static pressure, the Reynolds number, mass flow and etc. Also, it should be noted that for derived parameters it is required to calculate the standard and extended uncertainty, and corresponding correction is done to the resulting calculations.

Totally there are 43 measurements to be completed and 176 possible calculations of physical parameters describing tested equipment depending on the installation type.

### 2.2. Precision methodology

Calculations are provided with help of Siventa UAB.

Below will be described precision methodology created during the research activity.

Type A standard uncertainty (the experiment).

$Q$  – measured parameter.  $N$  – number of measurements – may vary (the sound is to obtain preferably  $n \geq 10$ ).

Table 1 gives the measured parameter value. For example, the number of measurements  $n = 10$ .

**Table 2.2.1.**

**Measurement result**

Measurement No.	Parameter
	Dimension (Pa)
1	$q_1 = 250,00$
2	$q_2 = 252,00$
3	251,00
4	250,00
5	248,00
6	249,00
7	250,00
8	251,00
9	253,00
$n = 10$	$q_n = 250,00$

Main measurement parameters:

Measurement average  $\bar{q} = \frac{1}{n} \sum_{i=1}^n q_i$  (2.1)  $\rightarrow \bar{q} = 250,40$  Pa.

Experimental standard deviation  $s^2(q) = \frac{\sum_{i=1}^n (q_i - \bar{q})^2}{(n-1)}$  (2.2)  $\rightarrow s^2(\bar{q}) = 1,4298$  Pa

Experimental mean standard deviation  $s(\bar{q}) = \sqrt{\frac{\sum_{i=1}^n (q_i - \bar{q})^2}{n(n-1)}}$  (2.3)  $\rightarrow s(\bar{q}) = 0,4522$  Pa.

Standard uncertainty  $u(\bar{q}) = s(\bar{q}) = 0,4522$

The results shall be made out to the uncertainty components of row "measurement result (average)". Sensitivity factor  $c_1 = 1$ .

Type B standard uncertainty (device scale discretion).

In the line "Device scale interval" recorded standard deviation, which is equal to half of the scale device discretion (eg., the measuring device scale interval – 1 Pa, so the standard deviation equals to 0,5). In type B, the standard uncertainty factor applied to obtain  $\frac{1}{\sqrt{3}}$  ( $\frac{0,5}{\sqrt{3}} = 0,2887$ ).

Sensitivity factor  $c_2 = 1$ .

Type A standard uncertainty (instrument calibration result).

Using the calibration protocol data, the measured point of the device error and the standard deviation.

Device error  $\Delta\bar{q}$  is measured in the range (between the two adjacent instrument calibration points  $q_{m-1}$  and  $q_m$ ) is calculated using a linear approximation. The linear approximation formula:

$$\Delta\bar{q} = \Delta q_{m-1} - (q_{m-1} - \bar{q}) \frac{\Delta q_m - \Delta q_{m-1}}{q_m - q_{m-1}}$$

here:  $q_m$  and  $\Delta q_m$  -  $m$ -th calibration point value and its error;

$q_{m-1}$  and  $\Delta q_{m-1}$  -  $m-1$  calibration point value and its error;

Standard deviation threshold measured in the range (between two adjacent instrument calibration points) to be larger by two adjacent calibration points expanded uncertainty. Estimation uncertainty is determined by applying a multiplier  $\frac{1}{2}$  ( $\frac{1,1}{2} = 0,55$ ). Sensitivity factor  $c_3 = 1$ .

Total uncertainty  $u(q)$  calculation equation:

$$u(y) = \sqrt{(c_1 u(x_1))^2 + (c_2 u(x_2))^2 + (c_3 u(x_3))^2}$$

Advanced uncertainty (95% confidence level):  $U(y) = 2 \cdot u(y)$ .

**Table 2.2.2.**

**Uncertainty components**

Sources of uncertainty	Value type, $X_j$	Estimate, $x_j$	Standard deviation threshold	Estimation type (A, B)	Probability distribution type	Input estimate uncertainty, $u(x_j)$	Sensitivity coefficient, $c_j$	Standard uncertainty, $u_j(y)$
A measurement result (average)	$p_s$	$\bar{q} = 250,40$	$s^2(\bar{q}) = 1,4298$	A	Normal	$u(q_1) = 0,4522$	$c_1 = 1$	0,4522
Device scale interval	$p_s$		0,5	B	Rectangular	$u(q_2) = 0,2887$	$c_2 = 1$	0,2887

The calibration result	$p_s$	$\Delta\bar{q} = 1,9008$	1,1	A	Normal	$u(q_3) = 0,55$	$c_3 = 1$	0,55
		<b>252,41</b>			Uncertainty (total/combined), $u$			0,7683
					Extended uncertainty, $U$			<b>1,5366</b>

Table 2.2.3.

Measuring device calibration results

Measurement No.	Pressure value, Pa	Error value, Pa	Extended uncertainty, $\pm$ Pa
1	-1000	-3	1,1
2	-400	-0,5	0,8
3	-100	0	0,6
4	0	1,1	0,9
<b>5</b>	<b>100</b>	<b>1,6</b>	0,85
<b>6</b>	<b>500</b>	<b>2,4</b>	<b>1,1</b>
7	1000	1	1,3
8	2000	2	1,8
9	3000	2,4	2
10	4000	3,5	2,1

*Lithuanian version of methodology can be found in Additions section.*

**Differences and novelty.**

The previous software used other types of calculations, where the standard deviation was not taken into account in order to clarify the final result. In addition, there was no calculation of uncertainty, which could allow us to determine with what accuracy the measurements were made. **Such calculations, based on standards and the reviewed articles techniques,** allow to increase the accuracy of the final result.

### 2.3. Installation methodology.

Using the developed methodology mentioned in section 2.2, appropriate calculations were performed to calculate the parameters for all installations. In doing so, methods were used to obtain the uncertainty of the result, which was also applied to the calculated parameters.

General methodology of installation calculations is provided below. Full material belongs to Siventa UAB and can be accessed by contacting with company.

#### 2.3.1. Adjusted gauging devices calculation.

Parameters values are not measured accurately during reading from measuring-instrument. Calibration of the measured parameter is determined by error (systematic error) in certain points. Real points of the measured value (determined in accordance with standard) equal to:

$$\textit{Real Value} = \textit{Instrument Reading Value} - \textit{Bias}$$

$(RV = X - \Delta)$	(2.1)
---------------------	-------

When measuring a parameter that is in the range of calibration points, the margin of error is determined using linear interpolation from adjacent points of calibration results:

$Paklaida = \Delta_n - (X_n - \bar{X}) \frac{\Delta_n - \Delta_{n-1}}{X_n - X_{n-1}}$	(2.2)
---	-------

where:  $X_n$  and  $\Delta_n$  - n-th calibration point **Value** and **Error**;

$X_{n-1}$  and  $\Delta_{n-1}$  - (n-1)- th calibration point **Value** and **Error**;

$\bar{X}$  - measured values (data points) of the average value (average value measurement) as determined from measurements made.

#### 2.3.2. Algorithm.

The calculations use only adjusted (precised) values computed on the base of the average value of number of measurands. Values  $p_a$ ,  $\Delta p$ ,  $p_{e7}$ ,  $T_7$ ,  $h_{u7}$  are considered to be adjusted. Nozzle diameters are taken from the calibration table.

**Air density (kg/m<sup>3</sup>) calculation (before nozzle pane):**

$\rho_7 = \frac{p_a + p_{e7} - 0,378 \cdot h_{u7} (610,8 + 44,442 \cdot T_7 + 1,4133 \cdot T_7^2 + 0,02768 \cdot T_7^3 + 2,5567 \cdot 10^{-4} \cdot T_7^4 + 2,8917 \cdot 10^{-6} \cdot T_7^5)}{78394,05 + 287 \cdot T_7}$	<b>(7.1.1)</b>
---	----------------

where:  $p_a$  - atmospheric pressure in the laboratory (Pa);  
 $p_{e7}$  - gauge pressure (Pa), before the nozzles;  
 $p_7 = p_a + p_{e7}$  (Pa) - absolute air pressure before nozzles ( $p_a$  [mmHg] = 133,3224 ·  $p_a$  [Pa]);  
 $T_7$  (°C) - air temperature before nozzles;  
 $h_{u7}$  - the relative humidity before nozzle.

**Air compressibility  $\varepsilon$  factor calculation:**

$\varepsilon = \sqrt{\left( \frac{\kappa r_d^{2/\kappa} 1 - r_d^{\frac{\kappa-1}{\kappa}}}{\kappa - 1} \right)}$	<b>(7.1.2)</b>
--	----------------

where:  $r_d = 1 - \frac{\Delta p}{p_7}$ , ( $r_d = 1 - \frac{\Delta p}{p_a + p_{e7}}$ );  
 $\kappa$  - isentropic exponent ( $\kappa = 1,4$ ).

**Mass flow  $q_m$  (kg/s), calculation is requiring one or more nozzle being opened**

$q_m = \varepsilon \frac{\pi}{4} \sqrt{2\rho_7 \Delta p} \sum_{i=1}^n (\alpha_i d_i^2)$	<b>(7.1.9)</b>
---	----------------

where:  $i$  - open nozzle number ( $i = 1, 2 \dots n$ )  
 $\alpha_i$  -  $i$ -th open nozzle flow rate (calculated according to (7.1.6) the equality);  
 $d_i$  -  $i$ -th open nozzle diameter.



### 2.3.3. Uncertainty calculation.

#### Air density $\rho_7$ standard uncertainty calculation.

#### Air density formula:

$\rho_7 = \frac{p_a + p_{e7} - 0,378 \cdot h_{u7} (610,8 + 44,442 \cdot T_7 + 1,4133 \cdot T_7^2 + 0,02768 \cdot T_7^3 + 2,5567 \cdot 10^{-4} \cdot T_7^4 + 2,8917 \cdot 10^{-6} \cdot T_7^5)}{78394,05 + 287 \cdot T_7} \quad (7.1.1)$
<p>where: <math>p_a</math> - atmospheric pressure in the laboratory (Pa);</p> <p><math>p_{e7}</math> - gauge pressure (Pa), before the nozzles;</p> <p><math>T_7</math> (°C) - air temperature before nozzles;</p> <p><math>h_{u7}</math> - the relative humidity before nozzle.</p>

$p_a$ ,  $p_{e7}$  and  $T_7$  - the measured values; the standard uncertainty is determined by the precision calculation method, described in the section 2.2.

The sensitivity coefficients for calculating air density  $\rho_7$  uncertainty:

Derivative	Sensitivity coefficient formula
$c_{\rho_7-pa} = \frac{df(\rho_7)}{dp_a}$	$c_{\rho_7-pa} = c_{\rho_7-pe7} = \frac{1}{78394,05 + 287 \cdot T_7}$
$c_{\rho_7-pe7} = \frac{df(\rho_7)}{dp_{e7}}$	
$c_{\rho_7-T7} = \frac{df(\rho_7)}{dT_7}$	$c_{\rho_7-T7} = \frac{(-0,378) \cdot h_{u7} (44,442 + 2,8266 \cdot T_7 + 0,08304 \cdot T_7^2)}{78394,05 + 287 \cdot T_7} - \frac{287(p_a + p_{e7} - 0,378 \cdot h_{u7} (610,8 + 44,442 \cdot T_7 + 1,4133 \cdot T_7^2 + 0,02768 \cdot T_7^3))}{(78394,05 + 287 \cdot T_7)^2}$
$c_{\rho_7-hu} = \frac{df(\rho_7)}{dh_{u7}}$	$c_{\rho_7-hu} = \frac{-230,8824 - 16,799076 \cdot T_7 - 0,5342274 \cdot T_7^2}{78394,05 + 287 \cdot T_7} + \frac{-0,010463 \cdot T_7^3 - 0,966433 \cdot 10^{-4} \cdot T_7^4}{78394,05 + 287 \cdot T_7}$

Air density  $\rho_7$  standard uncertainty:

$u(\rho_7) = \sqrt{(c_{\rho_7_{pa}} \cdot u(p_a))^2 + (c_{\rho_7_{pe7}} \cdot u(p_{e7}))^2 + (c_{\rho_7_{T7}} \cdot u(T_7))^2 + (c_{\rho_7_{hu7}} \cdot u(h_{u7}))^2}$	<b>(7.2.1)</b>
--	----------------

**Mass air flow  $q_m$  (kg/s) standard uncertainty calculation**

Formula:

$$q_m = \varepsilon \frac{\pi}{4} \sqrt{2\rho_7 \Delta p} \sum_{i=1}^n (\alpha_i d_i^2)$$

Compressibility factor  $\varepsilon$  uncertainty not be measured because in case of small pressure differences, its influence is not significant. Standard uncertainty of nozzle diameters  $d_i$  are known;

The pressure drop  $\Delta p$  calculated according to the standard uncertainty of the precision calculation method (section 2.2).

i-th nozzle flow coefficient  $\alpha_i$  extended uncertainty - 1.2 percent of the  $\alpha_i$ , then  $u(\alpha_i) = 0,006 \cdot \alpha_i$  [BS EN ISO 5801].

uncertainty:

The sensitivity coefficient calculation of the air mass flow rate  $q_m$  uncertainty:

Derivative	Sensitivity coefficient formula	Remark
$c_{q_m_{\rho_7}} = \frac{df(q_m)}{d\rho_7}$	$c_{q_m_{\rho_7}} = \frac{\varepsilon\pi}{8\sqrt{\rho_7}} \sqrt{2\Delta p} \sum_{i=1}^n (\alpha_i d_i^2)$	
$c_{q_m_{\Delta p}} = \frac{df(q_m)}{d\Delta p}$	$c_{q_m_{\Delta p}} = \frac{\varepsilon\pi}{8\sqrt{\Delta p}} \sqrt{2\rho_7} \sum_{i=1}^n (\alpha_i d_i^2)$	
$c_{q_m_{\alpha_i}} = \frac{df(q_m)}{d\alpha_i}$	$c_{q_m_{\alpha_i}} = \frac{\varepsilon\pi d_i^2}{4} \sqrt{2\rho_7 \Delta p}$	For each opened i-th nozzle
$c_{q_m_{d_i}} = \frac{df(q_m)}{dd_i}$	$c_{q_m_{d_i}} = \frac{\varepsilon\pi\alpha_i d_i}{2} \sqrt{2\rho_7 \Delta p}$	For each opened i-th nozzle

Air mass flow  $q_m$  (kg/s) standard uncertainty:

$u(q_m) = \sqrt{(c_{qm_{\rho_7}} \cdot u(\rho_7))^2 + (c_{qm_{\Delta p}} \cdot u(\Delta p))^2 + \sum_{i=1}^N [(c_{qm_{\alpha_i}} \cdot 0,006 \cdot \alpha_i)^2 + (c_{qm_{d_i}} \cdot u(d_i))^2]}$	<b>(7.2.3)</b>
<i>N</i> - the number of opened nozzles	

**Air mass flow  $q_m$  (kg/s) expanded uncertainty calculation**

The level of confidence - 95%, coefficient  $k = 2$ :

$U(q_m) = 2 \cdot u(q_m)$	<b>(7.2.4)</b>

**Result:**  $q_m \pm U(q_m)$  kg/s.

2.3.4. Summary

This methodology is based on the standards and approaches mentioned in section 2.2. Thanks to this technique, standard and extended uncertainty can be calculated, as well as a refinement of the final result. Obtained calculations extend the previous ones, and also correspond to the tasks and requirements set.

Algorithms are implemented in the program and actively used by laboratory. In the process of testing the operation of the algorithms, their error-free execution was established.

During testing, these algorithms have proven themselves well. It should be noted once again that only a part of the algorithms is described here. More detailed description is available in the Additions section.

**2.4. Application developing technique**

During the planning of the application, we reviewed several variations of ready software products for conducting testing of ventilation equipment in laboratories. Considered software products are property of laboratories to which they belong, and information that can be freely provided in this thesis is too small to indicate it in the work paper and to build analysis on their basis. However, based on observations of testing in accredited laboratories, the requirements for the application to correspond are formed. Such demands will provide more automation for time and money saving purposes. These requirements are listed below.

**Application requirements:**

1. Interface should be customizable. User can:
  - choose which columns (parameters) on data grid should be displayed;
  - configure rows order in a grid;
  - choose values displayed in real-time;
  - adjust size of different application panes with graphs, data or installation view;
  - choose which columns (parameters) will be exported to excel.
2. Application should have a mechanism to create  $n$  measurements per  $m$  seconds; number of measurements and seconds is chosen by user; required for calculating parameters' averages, uncertainty and increasing precision.
3. Application should have a mechanism to create/save/load project; project configuration will be stored in xml format with certain tag structure.
4. Application has to provide a dialog window where user can enter calibration points for each sensor, see error graph for each point and can enter value for processing it with adjustment to the error value. It is required for manual comparison.
5. There should be a dialog window where user can enter square size of each pane (A1, A2, A3, A4) used in installations. Each size can be named and user will choose the appropriate size in interface by selecting area (paned) size from the list. Selected pane size will be used in calculations.
6. Application has to have 3 tabs:
  - Project management – to locate xml files and write comments in <comments> tag section, send xml via email, write information about project.
  - Control panel and calculations – to make measurements, control fan speed, choose power analyzer, display data grid with measured data and calculations, show data charts, show real-time values on installation scheme, separately on the value pane and as dots on charts.
  - Export – to choose what data will be exported to Excel, have controls to perform exporting procedure.

**Chosen tools:**

Development platform is Microsoft .NET 4.5 [23], using a C# programming language [24] and Windows Forms programming API [25]. The choice of the platform and language can be specified with next points:

- Reliability of the language and platform.
- Huge time in the market area.
- Big community providing solutions for various tricky occurrences.
- Excellent documentation with reach number of examples.

- The language and platform are constantly evolving, new tools and features are provided with every new release.
- Great IDE – Microsoft Visual Studio [26] – provides a lot of possibilities for development.
- Perfect for Windows OS.
- Cross-platform (MonoDevelop [27]) – benefit for future purposes.

The application solution should provide an interface for sensors data observation, mechanism of accuracy improvement, buttons and controls to perform timed measurements, for configuring fan speed, power analyzers, getting information about connection, displaying graphs and real-time values of different parameters, showing grids of calculated and read data, Excel report exports, creating, saving and loading projects, nozzles and dampers control.

After picking the strategy and instrument, it is necessary to consider the topic of the optimization done in detail. This will be described in the next section.

## 2.5. Automation of processes

One of the key tasks set in this paper is the automation of the data acquisition process. To solve this problem, it was decided to develop new software that will take into account the shortcomings of the previous one, and will also perform new functions. Software was successfully created and tested, list of automations that were applied is provided below.

### **List of automations:**

- **Software configuration automation** – *creation, saving and loading of project files with application configuration.*

Such demand is required to store measured data in the project files and use them to continue measurements or change measured data in the future.

- **Project description automation** – *displaying a file explorer in the app showing project xml-files and providing mechanism to write comments into <comments> tag section.*

Due to the need to comment the project, an idea to store comments in project files has appeared. Project file is represented as xml-file and special section <comments> should be created for storing project comments.

- **Sharing automation** – *sending project configuration via post directly from application.*

This opportunity is required, if technician wants to report a broken project file and send it for maintenance. Likewise, if any measured data is required to prepare changes to a project structure, such function is mandatory.

- **Working area automation** – *providing an interface for choosing current installation and air chamber settings.*

As a result of possibility of the software to work with different ventilation chambers and installations, this addition is needed.

- **Data grid automation** – *providing interface for picking parameters and calculations which should be displayed on grid.*

Data grid serves for displaying measured and calculated data. As a result of a big number of columns available in the grid, part of the data can be redundant, if the ventilation device documentation does not require to include unnecessary data for customers. Redundant columns can be hidden or rearranged by technician, which will restrict data overflow.

- **Calculation automation** – *providing full range of calculations based on calculation methods developed for equipment testing (section 2.2).*

Due to accuracy methodology changing and developing of the new precision approach (section 2.2), calculations range had to be expanded. They got additional uncertainty parameter represented in separated column, required for precision documentation.

- **Fan control automation** – *providing Inlet Fan frequency control and displaying of its current frequency value.*

Inlet Fan controller serves for the purpose to change the frequency (and, as a consequence, the speed) of the Inlet Fan directly from the application.

- **Real-time data automation** – *expansion of the interface for displaying real-time measurement data.*

Due to the need of the input data control, the number of real-time values is not sufficient anymore. More parameters should be displayed for faster problem recognition by a technician.

- **Measurements timing automation** – *providing an interface for making measurements: certain number per certain time.*

Timing of measurements is crucial. In the older solution technician couldn't specify the number of measurements and time within which they might be taken. Some of measurements are enough to be complete in a short period of time, others require more. Thus, such modification is required for flexibility and time saving.

- **Export automation** – *providing a mechanism of exporting data to Excel reports.*

For creating ventilation equipment reports, data should be exported from the programme. Data sheets should be stored into Excel file. Such demand is required to save the time of technician of doing the paper work.

- **Installation scheme automation** – *displaying current installation scheme.*

This solution will help technician to keep an eye on air parameters inside ventilation chamber.

- **Input data automation** – *providing an interface for input of calibration data points and chamber planes' (areas') size values.*

Despite the fact that calibration process takes part only once in a year, it was decided to let the technician a possibility to input calibration data by himself through the programme. Furthermore, calibration points are provided with the error (bias) and uncertainty values (according to precision methodology, section 2.2). Entire calibration data can be changed by technician or a person in charge which leads to economy of time and resources.

## 2.6. Application components and interaction

Software is based on several components, which interact with each other and with outlet system, Figure 2.5.1 below characterizes application interaction with the system and also represents the structure of application by itself.

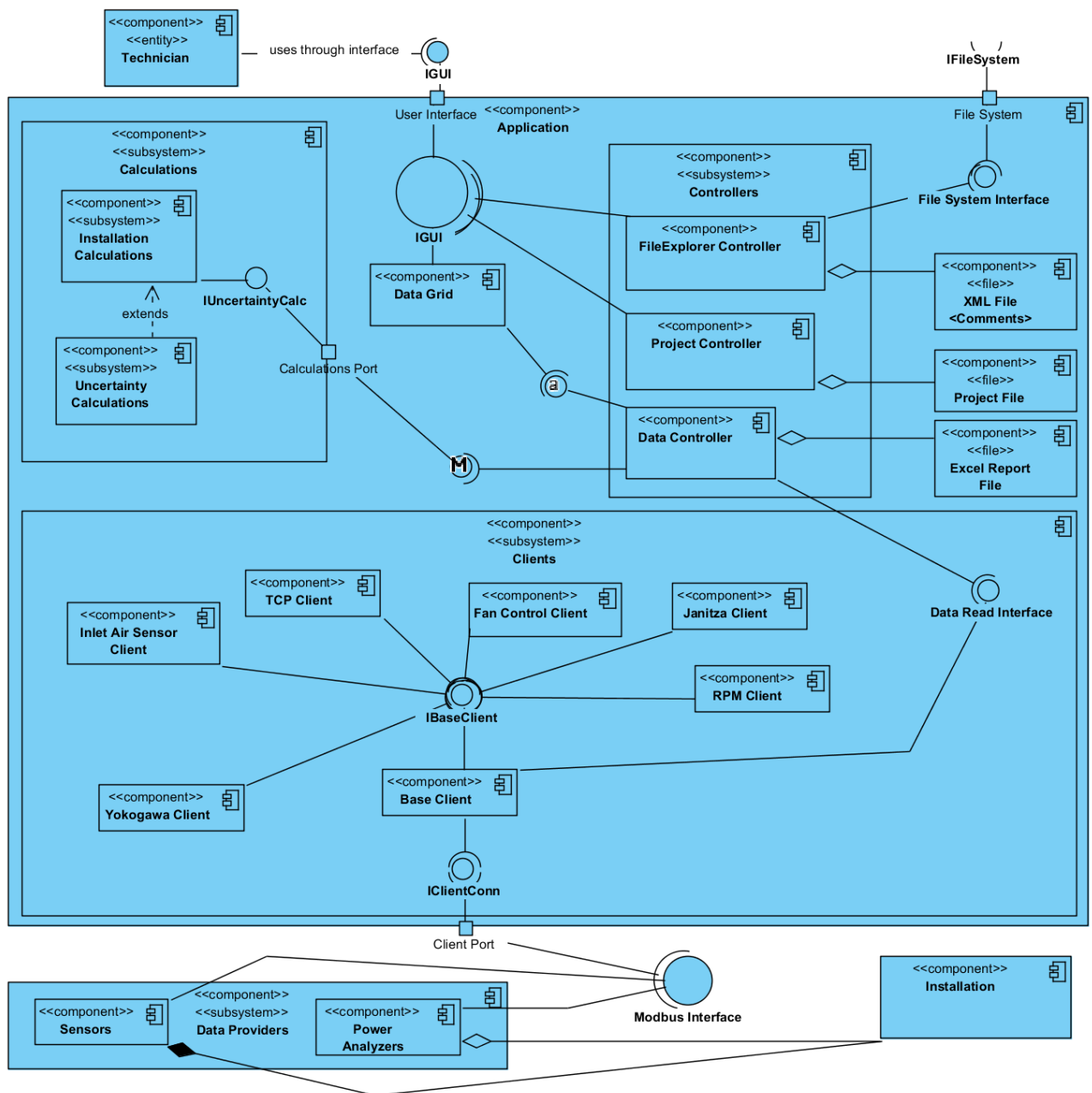


Figure 2.5.1. System UML Component Diagram.

Below we will review components of the system.

- 1. Calculations subsystem.** Consists of several classes that are represented by two components – *Uncertainty Calculations* and *Installation Calculations*. The first one is designed to make calculations of standard and extended uncertainty, and includes calculation of standard deviation as well. Second component uses first one and consists of classes for creating installation computations. It includes 4 classes for each installation (A, B, C, D) and a base class for performing calculations which are same for all installations. Component provides *IUncertaintyCalc* interface, which can be accessed through abstract *Calculations* port.
- 2. Controllers subsystem.** Consists of several components called *controllers* and represent corresponding classes in the application: FileExplorer Controller, Project Controller and Data Controller. FileExplorer controller serves for the purpose to display in application FileExplorer interface, where technician is able to browse through project xml files and edit <comments> tag section. Project Controller serves for the purpose to create, save, load and clean the existing project; in addition, it implements autosaving function. Data Controller is designed for data manipulations: reading, making calculations, displaying on the Data Grid and exporting to Excel Report File.
- 3. Clients subsystem.** Consists of clients – sensors and power analyzers data readers (program classes), which are shown as components on the diagram. In application, these components are represented by classes, which are derived as well from the Base Client class (component). This class (component) provides interfaces for all clients, and provides interface for data reader (which is Data Controller in this case).
- 4. Data Providers subsystem.** Consists of actual hardware devices – sensors and power analyzers, which are measuring physical parameters. They implement *Modbus interface* and provide connection via this interface. This connection is used by *Clients subsystem*.
- 5. Technician entity.** Technician component represents actual laboratory technician or any user, who interacts with application. Obviously, he interacts with application through *IGUI* interface (graphic user interface), which represents the application window.

## 2.7. Program interface

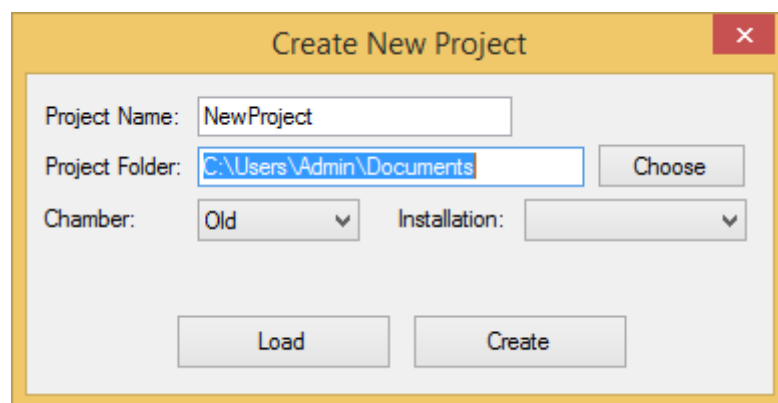
### 1. Startup – Create New Project



The first thing user encounters on a startup is a window which is responsible for the major project settings that he can configure there (Figure 2.6.1). All the settings can be configured later, although the loss of data is possible, therefore it's strongly recommended to do it before the launch.

### The Settings:

- *Project Name:* important, clear setting; “NewProject” by default.
- *Project Folder:* the folder where you most probably keep all you project files, can vary; you can press “Choose” button to select a decent directory via Open File Dialog or you can set the path explicitly; displays path to user documents directory or to last chosen directory by default.
- *Chamber:* one of the major settings – specifies the Chamber program is working with as well as calculation algorithms, later this can be changed if obligatory; “Old” by default.
- *Installation:* very important setting because calculations are related to chosen installation; can be A, B, C, D; B and D have 3 additional types you will need to choose from.
- *Load button:* shows File Open Dialog where you can select a project to be opened, dialog can be canceled.
- *Create button:* creates a new project file with currently set parameters and opens the main window of application.
- *Close button:* shows you a dialog window with the caption “Do you want to Exit?”. If you press Yes, you're proceeding to exit the application, otherwise the dialog is closed and you are returning to “Create New Project” window.



**Figure 2.6.1.** Create New Project window.

After picking the installation from the combo box, the columns' settings appear at the bottom of the window (window actually is expanded after pick). Here it is possible to choose what columns

you want to display in the application, or another words what data is it required to display. User is able to press “All” to select/deselect all the columns at once. Later columns can be configured as well.

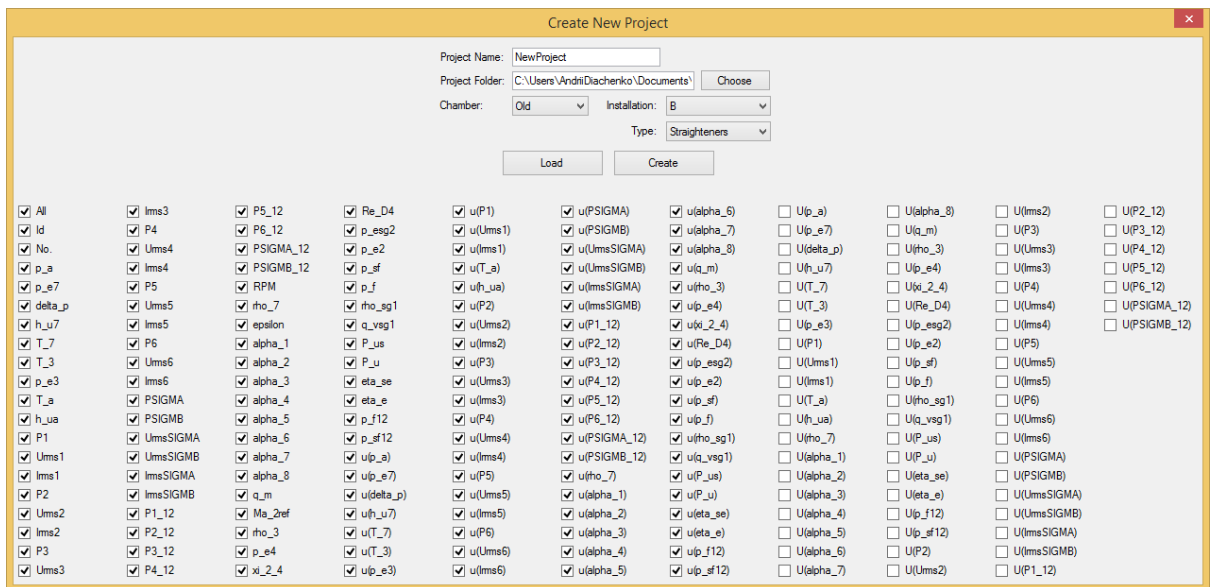


Figure 2.6.2. Create New Project – expanded window with visible columns selection.

## 2. The Workflow – Air Flow Measurement [\*Project Name\*]

The main window of application includes several tabs where user can manage resources, control values etc.

### 2.1. Project Tab:

This tab is responsible for editing the project details. Either there is a file explorer presented where user is able to browse for project xml files and add or edit comments in a text box.

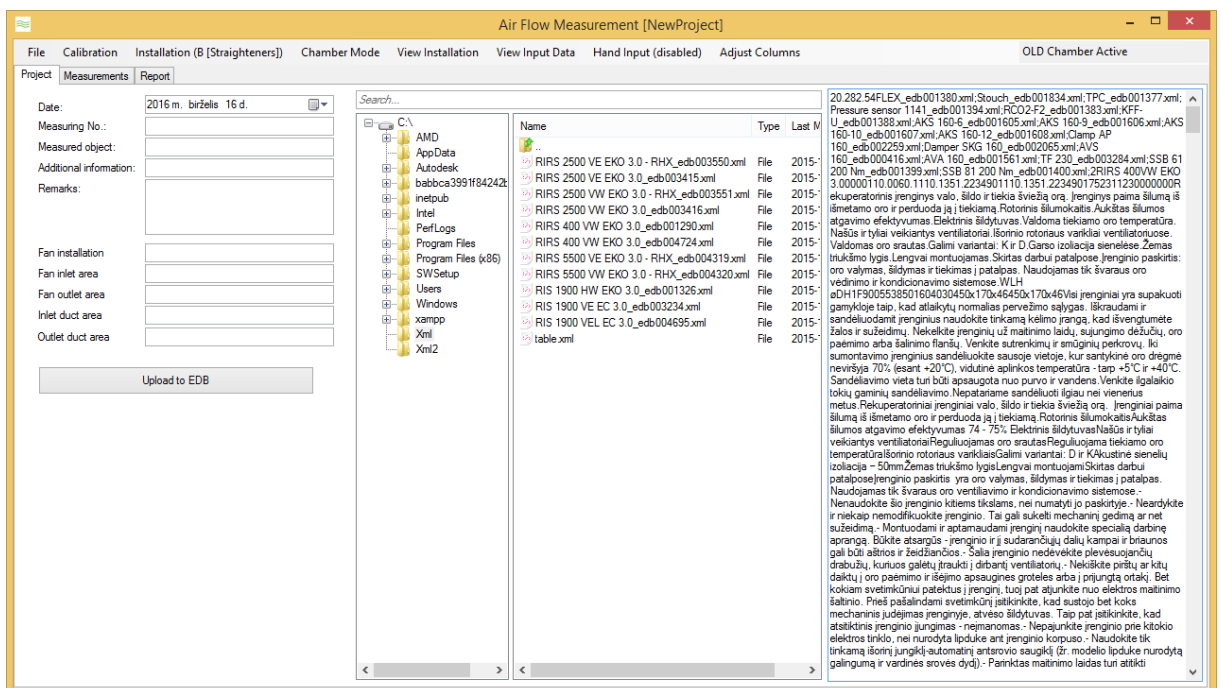


Figure 2.6.3. The Project Tab.



The connection information is displayed in top left corner of the tab. If the connection is properly established, “<Connected>” will be shown next to appropriate device. In cases of impossibility to connect or either a connection try, it will be displayed “<Connection lost>” or “<Attempting to connect>” correspondently. If user hovers the mouse over the connection status, the notification will pop up displaying additional data about connection. This can be useful for fixing connection issues. Underneath the *Connection Status section* the fan connection status is located.

- **Areas Settings:**

In this section user can choose what size of each area is used in chamber. Because it's very critical for time of the calculations, the appropriate area size must be chosen. A user can edit areas' sizes in Calibration window that will be described further.

- **Real-time data:**

To display the most valuable parameters this section is used. It is displaying voltage, rotation and air state values in real-time mode. Such representation helps to easy configure the equipment being used. The check boxes next to several parameters can toggle the data being showing in real-time mode on charts.

- **Nozzle Control:**

Nozzle Control is used for the ventilation chamber to configure the current setup of opened and closed nozzles. It is important because it influences a lot on the results, nozzles must be configured exactly the same as in the chamber. There are 8 nozzles totally. User can adjust nozzles' parameters in **Calibration Nozzles** window that will be described further.

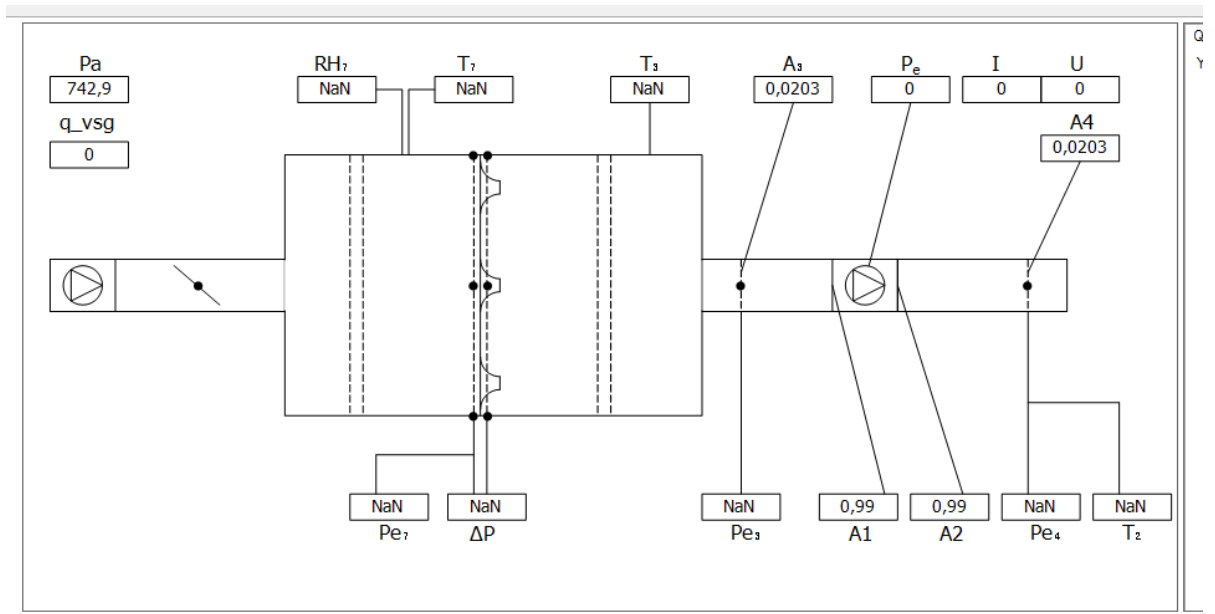
- **Measure Configuration:**

This section is for configuring the time periods in measurement. *Measurements Total Interval (sec.)* is a total time of one measurement. Because one measurement is an average value of several ones, the *Measurements Count* parameter is presented. It sets how many measurements will be completed during the total interval. All the measurements are done through equal amount of time. The measure progress is shown on the toolbar over the table of completed measurements. The measure can be stopped by pressing the **Stop Measuring** button which is appearing after the measurement has started.

- **Installation Scheme:**

The scheme (Figure 2.6.5) represents currently chosen installation and some values which are displaying on the scheme in real-time mode. It can be opened in a separate

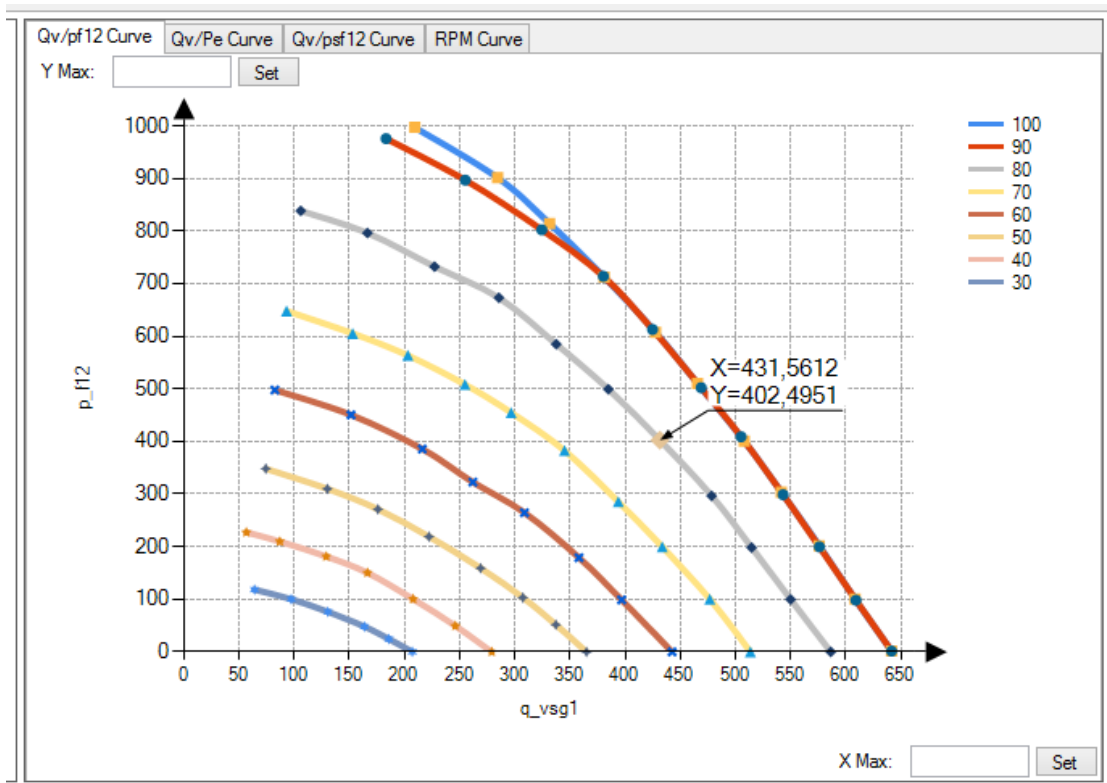
window with the help of **View Installation** item in the main menu. The size of the scheme can be changed dragging the splitter in the right part of it.



*Figure 2.6.5. Installation Scheme window.*

- **Data Charts:**

The charts (Figure 2.6.6) are representing completed measurements in graphical mode. User can click on the row in the table of measurements and the corresponding data point on the chart will be highlighted. There are 4 charts presented, they are accessible by clicking on the appropriate tab. **Y Max** and **X Max** fields are used to set the correct scale level of a chart. By default, all charts are scaled automatically. The size of the section can be changed dragging the splitter in the left part of it.



**Figure 2.6.6.** Data Charts pane.

- **Measurement Table:**

The measurement table (Figure 2.6.7) containing all the measurements been completed. User can adjust the columns of the table and watch only the necessary information. All the values with same **Id** located next to each other are highlighted with yellow color when a row is clicked. Cells' values are editable and can be changed. This is very handy for **Id** column due to the fact that its values represent different series on charts. **Id** can be a number or a text. The second column **No.** is a point number which is set automatically, however can be adjusted in case of need. Table contains voltage, amperage, power parameters, fan rotation frequency, values that characterize an air state and standard and expanded uncertainties of the most parameters.

There is a toolbar on the top displaying a measurement progress, a text field “**Go To Column**” where user can put the name of any column to instantly scroll to it. The **Clean** button at the very left of the toolbar is used to clean all the data in the table.

User can drag rows and columns to reposition them for his convenience. Column can be hidden by right clicking on the header and pressing “**Hide column**”.

If the cell in **Id** column will be clicked, all the values from the current cell up until the different **Id** at the bottom will be changed to the same value been set in the edited cell.

If it is double clicked, all the same values in top and bottom directions with same **Id**

will be selected to change their **Id**'s to different value. All the changed values are updated on charts.

User can double click on the empty cell in the very first column (left to **Id**) to insert a row above the clicked one.

If user selects a row and presses **Start Measuring** button, the data in the row will be overwritten with the new values. To deselect the row, user should click on the empty space in the table or any other blank space. If the row is selected, the corresponding point on the chart is highlighted.

To *delete* the row, user should press the very first cell to select the full row and then press **Delete** button. The changes are committed to the charts.

	Id	No.	pe3	P1	Urms1	lrms1	pe4	pzf	pf
	90	15	-938,228...	160,830...	230,8375	0,747175	4,9608	940,018...	943,73
	80	2	45,47988...	176,597...	230,1375862...	0,81469655...	41,33147...	-38,309...	0,2141
	80	6	-55,5436...	176,893...	230,3341379...	0,81528275...	38,01897...	63,5939...	97,451
	80	8	-155,516...	176,5375	229,165	0,81712142...	34,5312	163,885...	193,49
▶	80	10	-255,804...	175,611...	230,9327586...	0,80843103...	30,12182...	263,385...	288,95
	80	11	-363,483...	171,177...	231,1979310...	0,78944137...	25,65533...	370,882...	391,65
	80	14	-462,541...	164,929...	230,2320689...	0,76584137...	20,80998...	468,901...	485,40
	80	15	-551,051...	157,904...	229,3632142...	0,73853928...	15,408	555,399...	568,08
	80	16	-642,08675	150,368...	229,7953571...	0,70599642...	9,9648	644,192...	653,26
	80	3	-704,793...	137,698...	231,334	0,65028666...	6,86112	705,014...	712,46
	80	4	-769,325...	124,982	230,9706666...	0,5962	4,2336	770,032...	774,02
	80	5	-812,214...	110,310...	230,0636666...	0,53627333...	2,16048	812,972...	814,58
	70	2	34,79885...	126,96	230,3944827...	0,60489310...	31,71028...	-29,188...	0,3572
	70	4	-66,015	129,016...	229,8678571...	0,61484285...	28,9872	72,5878...	98,017

*Figure 2.6.7. Measurements table.*

### 2.3. The Report Tab

Tab contains duplicates of the **Measurement Table** and **Data Charts** but the table contains check boxes in column headers. The toolbar above the table contains few elements: **“Filter Id”** used to filter table by **Id**, export to excel button and button to save the project with polynomic data included (chart points) and build a new xml-file with polynomic calculations. Check boxes in column headers are presented to mark the columns that will be exported to excel. The very left check box marks/unmarks all columns.

Exported excel document contains all the marked columns and all 4 charts.

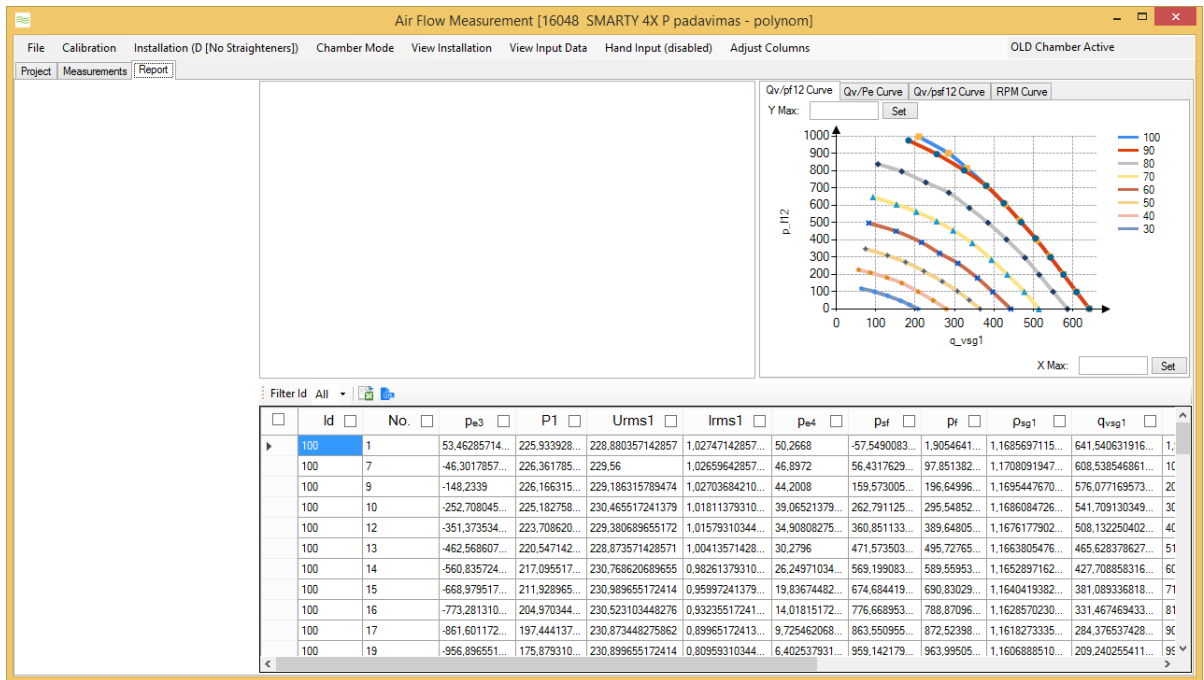


Figure 2.6.8. The Report Tab.

### 3. Menu Bar

- **File:**

File menu item is related to project management like create, save, open or clear a project. The application uses database to keep the crucial data and if case of need of moving the database the new path can be chosen with **Change Database Location** item.

- **Calibration:**

This menu item is responsible for sensors, nozzles and areas calibration. By pressing on the one of inner menu items the corresponding window for calibration is opened. Those windows will be described further.

- **Installation:**

Here user can choose the current installation. When it's done, the changes are reflected throughout the application: the table columns, installation scheme and calculations are changed.

- **Chamber Mode:**

This is a switch between two chambers. Upon the switch the nozzle (Old chamber) or damper (New chamber) control is appearing. The data will be erased and calculations will be change to correspond the chamber type.

- **View Installation:**



This menu item opens the window with installation schema with real-time values. It is presented for convenience.

- **View input Data:**

This menu item opens a window where user can see all the intermediate results of physical measurements of the current session. This data can be exported to excel file by pressing the corresponding button in the top left.

- **Hand Input:**

This menu item opens up a window that can configure hand input data. It is used for testing to check the correctness of the calculated values.

The window has a switch for hand input. To save the input status, the **Save** button must be pressed. When the input is switched to hand one, calculations will be done with the given values in the text fields. The field must contain at least 2 values to calculate the result.

After switching to *Hand Input*, user has to close the window and press **Start Measuring** to calculate and fill the table. There will be no time periods, calculations would be done immediately using the input data.

- **Adjust Columns:**

This menu item opens a window where user can set up which columns should be visible and which shouldn't. Visible columns are checked. If you want to select or deselect all the columns, click on the "All" check box. Press **OK** to confirm the changes.

- **Active Chamber:**

This is a status text field at the very right in the menu bar displaying information about currently used chamber.

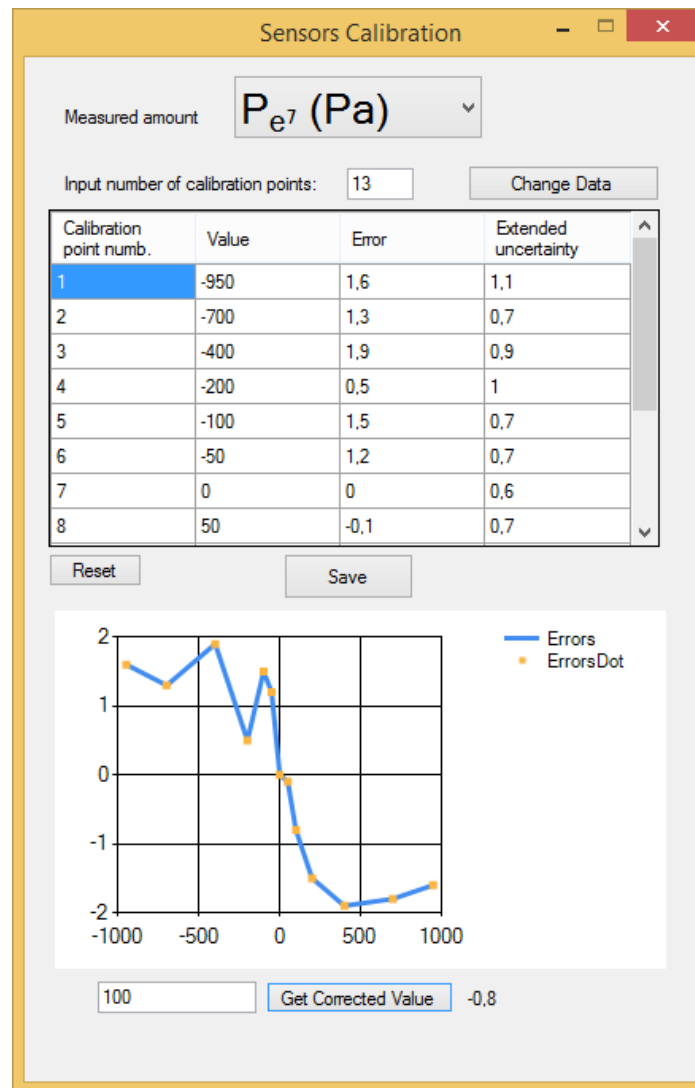
#### 4. Calibration

There are 3 calibration windows presented in the program. Calibration is performed each certain amount of time per year (depending on the type of data).

- **Sensors:**

**Calibration Sensors** window (Figure 2.6.9) is used to adjust sensors parameters such as error, uncertainty, calibration points. These parameters are used in further calculations so should be set extremely precisely.

On the top of the window there is a combobox designed to choose the sensor user wants to adjust. The text field under the combobox shows current number of rows with calibration data. The number can be changed and to accept changed user should press button **Change Data**.



*Figure 2.6.9. Sensors Calibration.*

- **Nozzles:**

Window is similar to the *Sensors Calibration* window and serves for purpose of editing nozzles calibration data, such as diameter and uncertainty.

- **Chamber areas:**

Again, window is similar to the *Sensors Calibration* window. Provides a way to add new area (pane) name, its size and uncertainty value. Panes are used for calculations, and user can choose them later while using in a programme.

### 3. VAIDATION OF PROPOSED SOLUTION

#### 3.1. Data accuracy validation

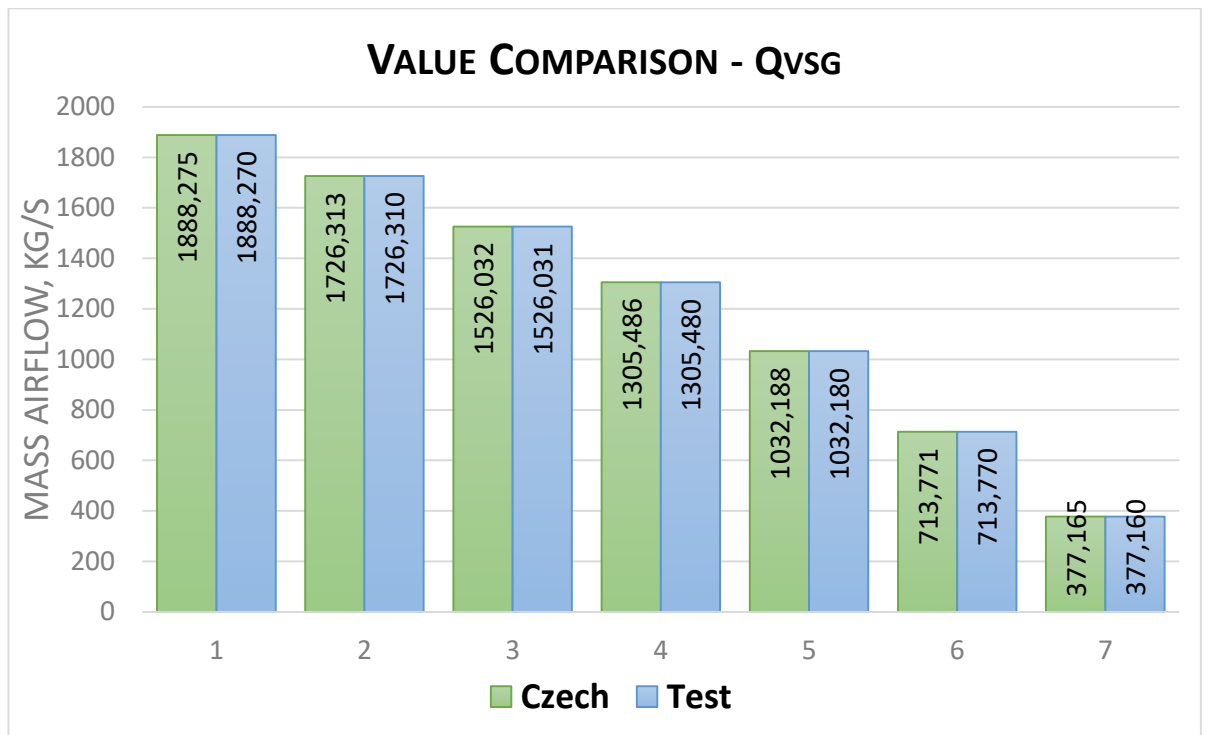
In order to demonstrate the correctness of the developed methodology, an experiment will be executed. The data obtained from measurements using the designed application and methodologies will be compared with the data obtained in the **Air-lab s.r.o.** [] laboratory for testing ventilation equipment located in Prague, Czech Republic. This laboratory can serve as a reference for comparison, since it has the necessary level of accreditation. Such experiment was executed in cooperation with Siventa laboratory. More information regarding **Air-lab s.r.o.** tests can be provided by Siventa.

To execute the experiment, it is necessary to use an identical ventilating equipment, lock the values of certain parameters, and then compare the results by the following criteria:

1. Measured value
2. Standard uncertainty of the value
3. Referenced and test value difference
4. Influence on result

We chose for testing **16174 Compact 5CXH + F1 Fresh Air** ventilation device, tested on **installation D** configuration (with no air straighteners). Test results are provided below on the graphs.

1. **Comparing Mass Airflow values.** During the test there were no obvious data differences, tested data is slightly lower. Obtained values are represented on graph below (Figure 3.1.1).



*Figure 3.1.1. Mass Airflow Values Comparison.*

2. **Comparing Mass Airflow Uncertainty parameters.** Again, during the test and detailed comparison no big differences were found, tested data has slightly lower values; the data is provided on the graph below (Figure 3.1.2).

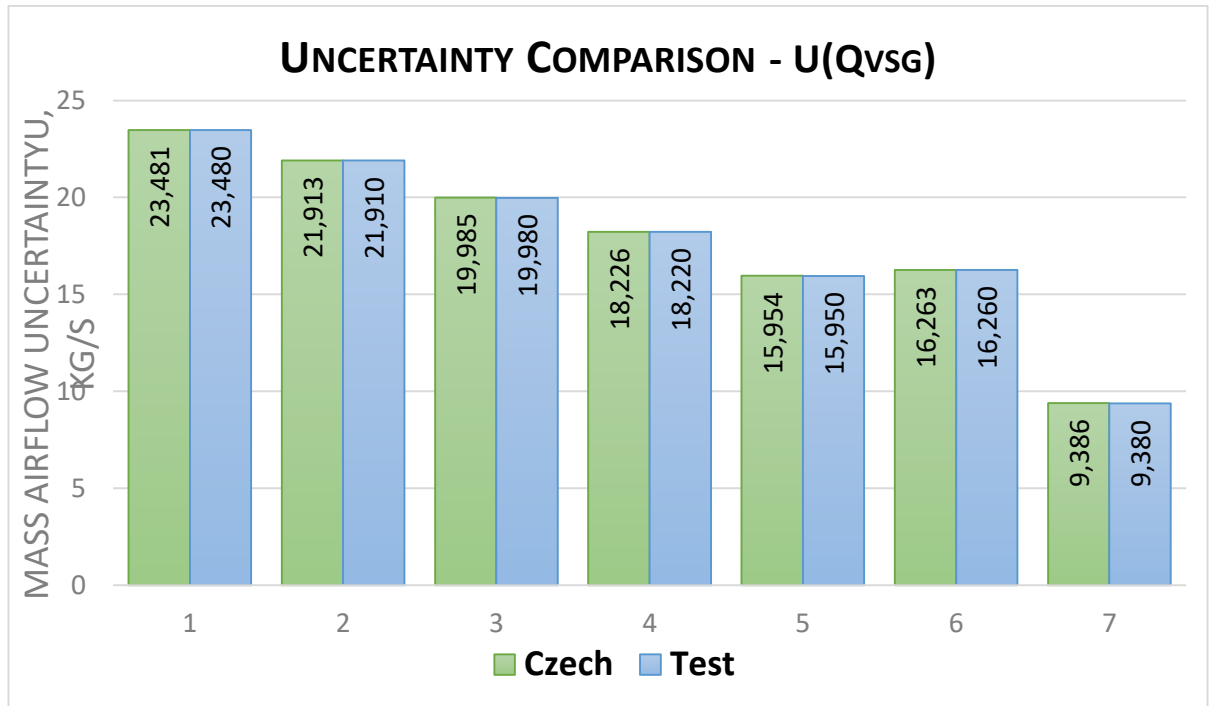


Figure 3.1.2. Mass Airflow Standard Uncertainty Comparison.

3. **Comparing Standard (Normalized) Air Pressure.** No significant differences were found during the test. Values calculated using precision methodology (section 2.2) are slightly lower than data obtained in referenced laboratory. Measured data is provided on the graph below (Figure 3.1.3).

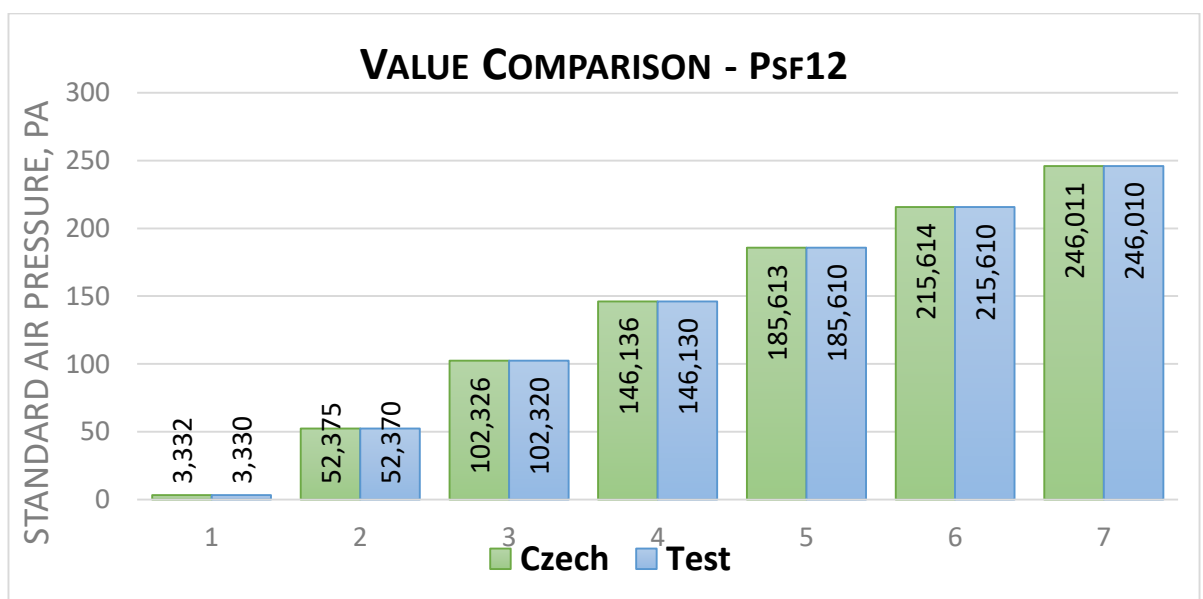
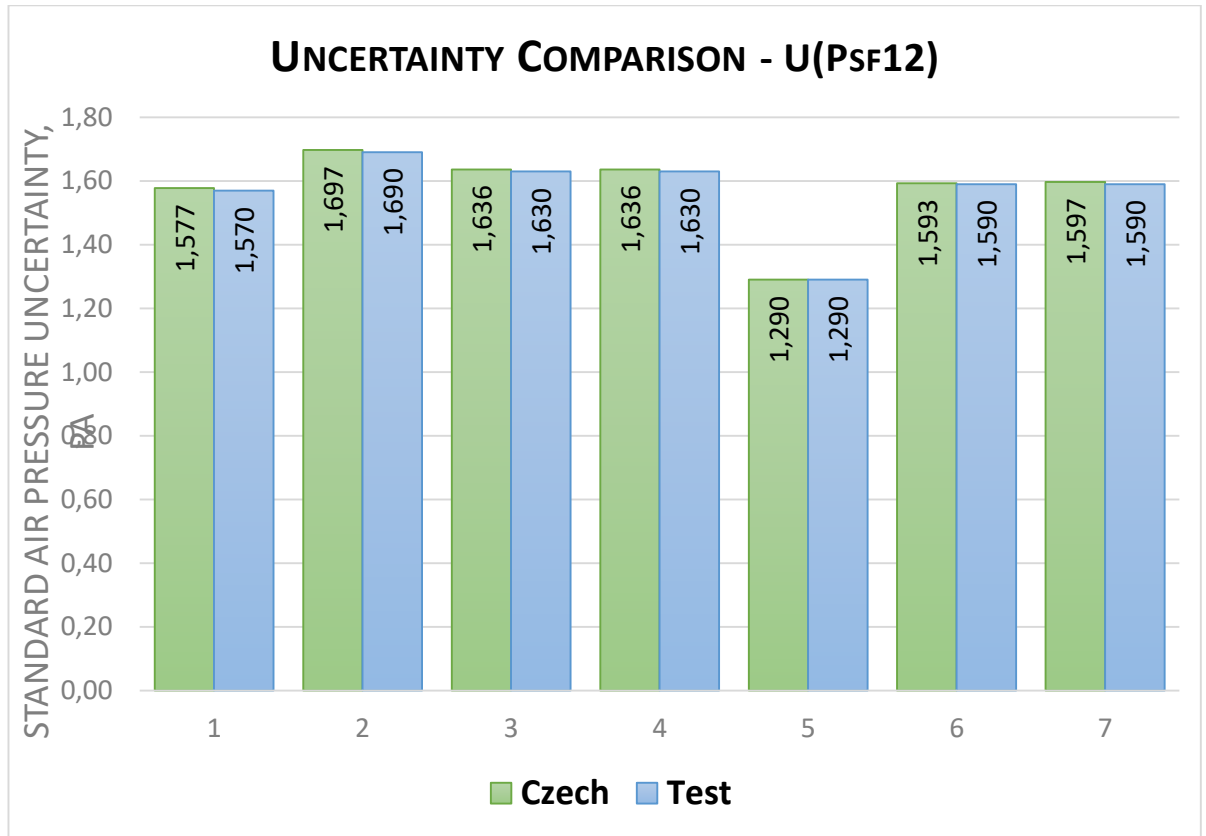


Figure 3.1.3. Standard Air Pressure Comparison.

4. **Comparing Uncertainty of Standard Air Pressure.** As in the previous tests, comparison did not give information about big parameter values differences. Although, it is noticeable that uncertainty calculated by precision methodology (section 2.2) is slightly lower than referenced, which means that the measured values are more precise. Data is provided on the graph below (Figure 3.1.4).



**Figure 3.1.4.** Standard Air Pressure Uncertainty Comparison.

To obtain the possible precision deviation, we decided to compare the difference of the measured values with number **0,01**, due to the fact that number accuracy for these two parameters is determined within two decimal places (according to reviewed standards and methodologies). Each difference value is taken as a precision number (**0,01**) percentage. Results of such comparison are provided on the graph below (Figure 3.1.5).

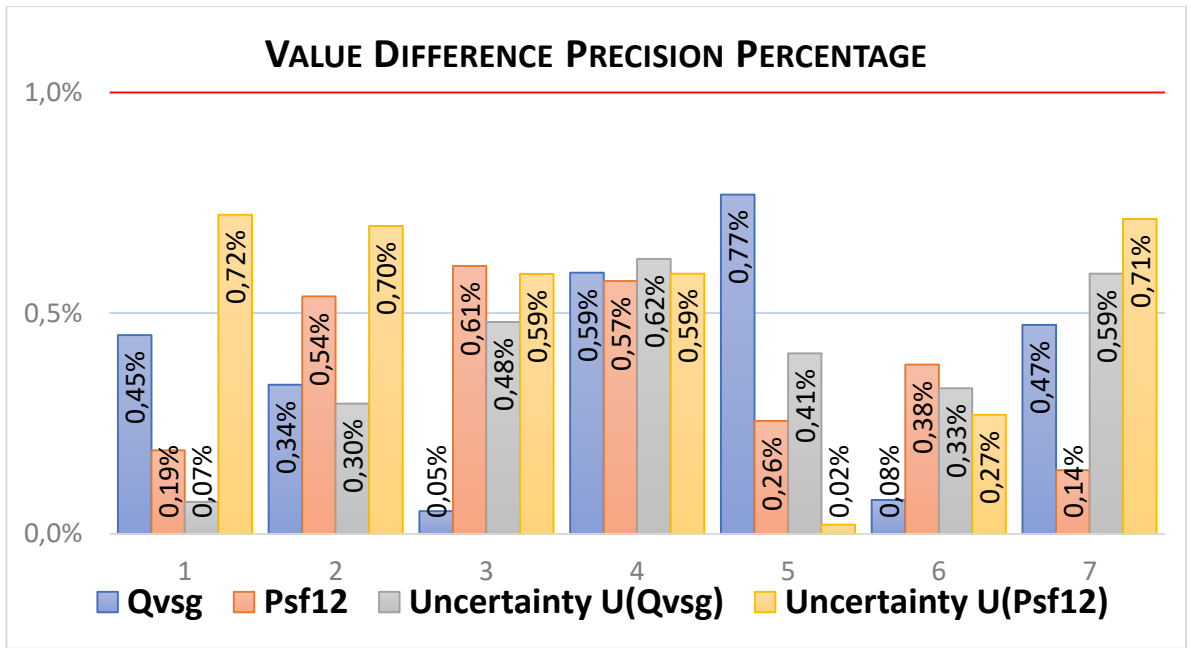


Figure 3.1.5. Value Difference Precision Percentage

None of the percentage values does exceed the critical influence of the difference percentile on the result, remaining behind the value of 1% (or, other words, 0,01). This fact guarantees that data calculated according to the precision methodology and installation methods is correct.

In addition, we decided to calculate the percentage of the mean difference value, which can summarize the total measured data inconsistency in comparison to referenced laboratory data. Mean values characteristics are presented on the graph below (Figure 3.1.6). Result difference percentage is lower than 0,5%, which confirms the correctness of developed methodology.

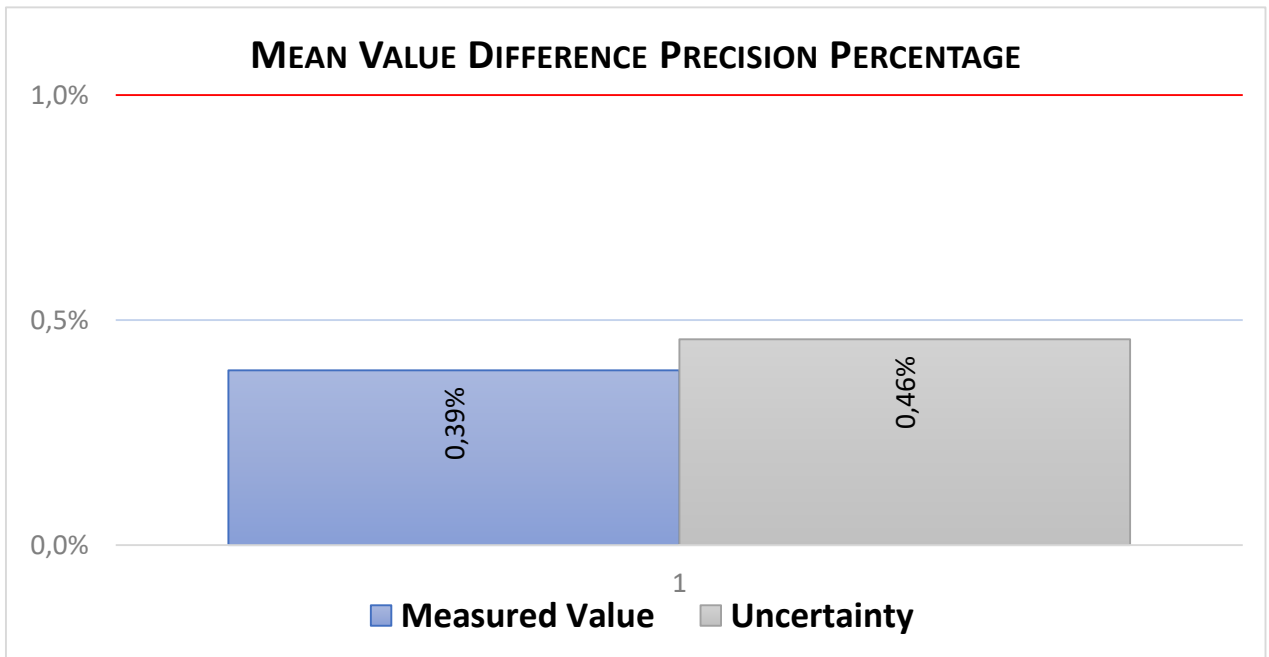


Figure 3.1.6. Mean Value Difference Precision Percentage

### 3.2. Automation validation

To check whether the solution is more automated, it was decided to compare the old and new solution in case of resources saving, among which the most important is time. We are providing comparisons and benefits of the new approach in the list below.

#### Automation benefits:

- ✓ **Software configuration automation.** One of the main differences, if to compare to previous solution, is to store much more data in project file, such as plane size values, nozzles been opened, data grid visible columns and their order, fan frequency configurations, etc. Such change eases the way of installation configuring and saves the time of laboratory technician work.
- ✓ **Project description automation.** Previous solution did not offer a possibility to leave comments to created project, technician had to spend extra time to recall what configurations were in this project.
- ✓ **Sharing automation.** Previous solution did not provide a possibility to share project data and required the usage of third-party applications.
- ✓ **Working area automation.** Previous application was capable to work only with generalized installation type and only with one ventilation chamber, additional calculations had to be performed by technician. Additionally, due to the laboratory expansion old software couldn't process new ventilation chamber data.
- ✓ **Data grid automation.** Previous solution did let to change data grid and usually there was a lot of redundant information in data grid; technician time could be taken if it was necessary to scroll through the data on the grid to find a key value of parameter.
- ✓ **Calculation automation.** Previously some calculations were made manually by technician and after were included into documentation. Now technician is capable to obtain all the specter of data regarding chosen installation automatically.
- ✓ **Fan control automation.** Technician has to do it manually, although such change requires time. Old software did not have an option to change fan speed programmatically, however new software implements such function. It provides fan speed controller and displays fan speed as well, again saving the time of the technician.
- ✓ **Real-time data automation.** Technician could watch real-time data in the previous software, however later the number of real-time values had to be increased. Such demand led to the problem when technician should watch the application screen and sensor's display screen (to handle the incoming data) at the same time. It led to failure of

measurement procedure and to need of measurement restart. New software displays all required values on the application screen, and risk of mentioned failure became lower.

- ✓ **Measurements timing automation.** In the new software technician can choose how many measurements should be completed within certain amount of time that provides time saving facility. Previous solution didn't provide an option for timing modifications, measurements were executed with the same timing and for same amount of time.
- ✓ **Export automation.** Previous solution did not have an opportunity to export data, technician had to copy-paste it into Excel file. With the new software technician can specify what data should be exported and export it to the report Excel document. Such option provides time saving.
- ✓ **Installation scheme automation.** Previously the technician should have kept in mind what installation is assembled at the moment of measurement. New software displays chosen installation and shows measured values on installation scheme in real-time.
- ✓ **Input data automation.** Old software had hardcoded calibration points values which could be configured only by a programmer. In current software technician can change the calibration points directly in the application, which leads to financial and time-saving solution.

In addition, we decided to draw up a table of actions of the laboratory technician, describing the approximate time of execution of each of its actions before and after the introduction of the process automation technique. In addition, the time of execution of one measurement by the old and the new program and the accuracy of the result obtained will be compared. Results are provided in Table 3.2.1.

Table 3.2.1

**Execution time comparison**

Action	Old time of execution	New time of execution	Time saving
Software configuration	<i>10 min</i>	<i>0,5 min</i>	<i>9,5 min</i>
Project description writing	Was not implemented previously, although technician had to recollect the information about the project.	<i>1 min</i>	<i>2 min</i>



	Because part of description was stored in the name of the project, we can say that such process took about <b>3 min.</b>		
Sharing the project	Was not implemented, had to be done manually. Average time is <b>1 min.</b>	<b>0,5 min</b>	<b>0,5 min</b>
Working area configuration	Was not implemented fully, technician had to take about <b>35 min</b> to reconfigure sensors and actuators or do any manual calculations.	<b>1 min</b>	<b>34 min</b>
Data grid operations	Grid data overflow was taking technician's time for choosing the data for look up or export. Took about <b>7 min.</b> Such operation was executed each measurement cycle.	With enhanced data grid configuration, it takes <b>2 min</b> to configure data grid and no time is required furthermore.	<b>5 min</b>
Post-calculation	<b>10 min</b>	<b>0 min</b>	<b>10 min</b>
Fan control	<b>0,5 min per single action</b>	<b>0,1 min per single action</b>	<b>0,4 min per action</b>
Real-time data observation	Not all the data was in the application, took about <b>0,2 min per observation.</b>	<b>0 min</b>	<b>0,2 min per observation</b>
Measurements completion	<b>1 min per single measurement.</b>	Time can vary, however same result can be achieved in <b>0,5 min per single measurement.</b>	<b>0,5 min per single measurement</b>
Data export	Was not implemented, technician was performing copy-paste	<b>0,5 min</b>	<b>9,5 min</b>

	procedure and manual writing. Whole procedure took about <b>10 min.</b>		
Installation scheme displaying	Was not implemented, for technician it took about <b>0,5 min</b> to recall the installation configuration.	<b>0 min</b>	<b>0,5 min</b>
Input data setting	Was not implemented, laboratory had to contact with programmer for changes. Time taken: <b>24 hours (1140 min).</b>	<b>20 min once a year</b>	<b>1120 min once a year</b>

The obtained results can guarantee that new solution provides gigantic time-saving possibility comparing to the previous one. There are a few values that are included into consideration:

- The average number of measurements being done per daily session: **20**.
- The average number of fan control actions (frequency changing): **30**.
- The average number of sensors real-time data observations: **90**.

If not take into account time of calibration points input (due to the fact that it happens one time in a year), the total time benefit per measuring daily session is around **111 minutes**, which equals almost of 2 hours of work day. Totally new application usage saves about **23%** of maximum time per fully loaded daily session (assuming that the working day is 8 hours). This is a significant improvement and a massive breakthrough in measuring operations.

## CONCLUSIONS

The task of this thesis paper was to study the problems of insufficient accuracy of the computed data, as well as the problem of insufficient automation of software used in the laboratory. The problem of inaccuracy raised due to the fact that Siventa UAB laboratory utilized old standards in their calculations for ventilation devices, it did not give the necessary level of accuracy and did not give its estimation. The second part of the problem was that the laboratory needed a greater level of accreditation, so that the equipment tested by it could have a great consumer opportunity. As Siventa cooperates with Salda, a company that supplies ventilation equipment, such changes were required by Salda as well.

During the cooperation with mentioned companies, the environment for testing ventilation equipment, its configuration, as well as the measurement methods, was well reviewed and studied. The problem of raising the accreditation level was solved by implementing corresponding standards, such as LST EN ISO 5801:2009 and EA-4/02. This demand was required and introduced new parameter, which describes how precise was the measurement done. It is called uncertainty. During the materials study it was understood the usage of standard and extended uncertainties and their importance for customers. However, techniques for installations calculations has to be developed and tested, in order to work well. Such calculations, although based on standards, still require additional computations; they are unique for each laboratory and for each installation configuration. Developed precision methodology takes into account the most important aspects of standards, simplifying some calculations that do not have much influence on result. The methodology is different from others and is easy to use due to such simplifying. Besides, it provides guideline for similar calculations related to air parameters. We calculated sensitivity coefficients, standard deviations and uncertainties for each parameter and measured value. To make results more precise, standard deviation was taking into account for each value (used for value correction). Such approach was found in uncertainty calculation, however it was applied only to uncertainty parameters but not to the values by themselves.

Additionally, we solved the problem of data handling automation. The solution was to create a new application which would use the developed calculation technique and will save the time of technician working with this software. To create such application, we considered several laboratories and review their software. We created our own application, partly removing manual control from technician, providing full range of calculated parameters and measured values, flexible interface, possibility to change calibration data, operate with air chamber plane sizes directly from the programme, make Excel report exports, make measurements timed, fast and precise.

Final tests proved the efficiency of developed approaches. The result values and their uncertainties were tested in Siventa laboratory and compared with the test results of accredited

laboratory Air-lab s.r.o in Czech Republic. There were used same conditions for testing, and results proved the correctness of calculated data and the efficiency of developed methodology. Theoretically, results are even more precise, however practically it was not possible to check yet.

Automation increase led to 23% time-saving, which is a very significant result. Such programme provides a big range of time saving features, and its analogs can be used in other laboratories.

Generally, it should be said that all the tasks were achieved and completed, results are much more than satisfactory. By now the developed software is actively used by Siventa for more than year and has very positive reviews.

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Conferences participation:

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2. 2017-06-11 – Siauliu Universitetas 12 – osios konferencijos - *Automation of Handling of the Ventilation Chamber Data*.

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## **ADDITIONS**

**Skaičiavimo metodika Nr. 002**

**7.2.1. Oro tankio  $\rho_7$  standartinės neapibrėžties skaičiavimas**

Oro tankio formulė:

$$\rho_7 = \frac{p_a + p_{e7} - 0,378 \cdot h_{u7} (610,8 + 44,442 \cdot T_7 + 1,4133 \cdot T_7^2 + 0,02768 \cdot T_7^3 + 2,5567 \cdot 10^{-4} \cdot T_7^4 + 2,8917 \cdot 10^{-6} \cdot T_7^5)}{78394,05 + 287 \cdot T_7} \quad (7.1.1)$$

čia:  $p_a$  - atmosferinis slėgis laboratorijoje (Pa);

$p_{e7}$  - manometrinis slėgis pjūvyje 7 (Pa), prieš tūtą;

$h_{u7}$  - santykinė drėgmė pjūvyje 7, prieš tūtą;

$T_7$  - temperatūra pjūvyje 7 (°C), prieš tūtą.

$p_a$ ,  $p_{e7}$  ir  $T_7$  - matuojami dydžiai; jų standartinė neapibrėžtis nustatoma pagal **Skaičiavimo metodiką 001** (Neapibrėžties apskaičiavimo algoritmas, kai atliekamas paprastas 1 parametro matavimas kalibruota matavimo priemone).

**Jautrio koeficientai**, skaičiuojant oro tankio  $\rho_7$  neapibrėžtį:

Išverstinės	Jautrio koeficientų formulės
$c_{\rho_7-pa} = \frac{df(\rho_7)}{dp_a}$	$c_{\rho_7-pa} = c_{\rho_7-pe7} = \frac{1}{78394,05 + 287 \cdot T_7}$
$c_{\rho_7-pe7} = \frac{df(\rho_7)}{dp_{e7}}$	
$c_{\rho_7-T7} = \frac{df(\rho_7)}{dT_7}$	$c_{\rho_7-T7} = \frac{(-0,378) \cdot h_{u7} (44,442 + 2,8266 \cdot T_7 + 0,08304 \cdot T_7^2)}{78394,05 + 287 \cdot T_7} - \frac{287(p_a + p_{e7} - 0,378 \cdot h_{u7} (610,8 + 44,442 \cdot T_7 + 1,4133 \cdot T_7^2 + 0,02768 \cdot T_7^3))}{(78394,05 + 287 \cdot T_7)^2}$
$c_{\rho_7-hu7} = \frac{df(\rho_7)}{dh_{u7}}$	$c_{\rho_7-hu7} = \frac{-230,8824 - 16,799076 \cdot T_7 - 0,5342274 \cdot T_7^2 - 0,010463 \cdot T_7^3 - 0,966433 \cdot 10^{-4} \cdot T_7^4}{78394,05 + 287 \cdot T_7}$

Oro tankio  $\rho_7$  standartinė neapibrėžtis:

$u(\rho_7) = \sqrt{(c_{\rho_7-pa} \cdot u(p_a))^2 + (c_{\rho_7-pe7} \cdot u(p_{e7}))^2 + (c_{\rho_7-T7} \cdot u(T_7))^2 + (c_{\rho_7-hu7} \cdot u(h_{u7}))^2}$	<b>(7.2.1)</b>
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### 7.2.2. Oro masės srauto $q_m$ (kg/s) standartinės neapibrėžties skaičiavimas

Formulė:

$$q_m = \varepsilon \frac{\pi}{4} \sqrt{2\rho_7 \Delta p} \sum_{i=1}^n (\alpha_i d_i^2)$$

Oro spūdumo faktoriaus  $\varepsilon$  neapibrėžtį neįvertiname, kadangi esant nedideliems slėgių skirtumams, jo įtaka yra nereikšminga.

Skersmenų  $d_i$  standartinės neapibrėžtys įvedamos į programą;

Slėgio kritimo  $\Delta p$  standartinė neapibrėžtis apskaičiuojamos pagal **Skaičiavimo metodiką 001**.

i-tosios tūtos srauto koeficiento  $\alpha_i$  išplėstinė neapibrėžtis - 1,2 proc. nuo  $\alpha_i$ , tada  $u(\alpha_i) = 0,006 \cdot \alpha_i$  [ISO EN LST 5801].

Jautrio koeficientai, skaičiuojant oro masės srauto  $q_m$  neapibrėžtį:

Išverstinės	Jautrio koeficientų formulės	Pastaba
$c_{q_m-\rho_7} = \frac{df(q_m)}{d\rho_7}$	$c_{q_m-\rho_7} = \frac{\varepsilon\pi}{8\sqrt{\rho_7}} \sqrt{2\Delta p} \sum_{i=1}^n (\alpha_i d_i^2)$	
$c_{q_m-\Delta p} = \frac{df(q_m)}{d\Delta p}$	$c_{q_m-\Delta p} = \frac{\varepsilon\pi}{8\sqrt{\Delta p}} \sqrt{2\rho_7} \sum_{i=1}^n (\alpha_i d_i^2)$	

$c_{qm\_ai} = \frac{df(q_m)}{d\alpha_i}$	$c_{qm\_ai} = \frac{\varepsilon\pi d_i^2}{4} \sqrt{2\rho_7\Delta p}$	Kiekvienos atidarytos i-tosios tūtos
$c_{qm\_di} = \frac{df(q_m)}{dd_i}$	$c_{qm\_ai} = \frac{\varepsilon\pi\alpha_i d_i}{2} \sqrt{2\rho_7\Delta p}$	Kiekvienos atidarytos i-tosios tūtos

Oro masės srauto  $q_m$  (kg/s) standartinė neapibrėžtis:

$u(q_m) = \sqrt{(c_{qm\_p7} \cdot u(\rho_7))^2 + (c_{qm\_dp} \cdot u(\Delta p))^2 + \sum_{i=1}^N [(c_{qm\_ai} \cdot 0,006 \cdot \alpha_i)^2 + (c_{qm\_di} \cdot u(d_i))^2]}$	<b>(7.2.3)</b>
<p><math>N</math> - atidarytų tūtų skaičius          Formulėje tiek narių po sumos ženklu, kiek atidarytų tūtų          Masės srauto standartinė neapibrėžtis išreikšta kg/s</p>	

### 7.2.3. Oro masės srauto $q_m$ (kg/s) išplėstinės neapibrėžties skaičiavimas

Pasikliovimo lygis - 95%, daugiklis  $k = 2$ :

$U(q_m) = 2 \cdot u(q_m)$	<b>(7.2.4)</b>

**Rezultatas:**  $q_m \pm U(q_m)$  kg/s

### Ventiliatoriaus slėgio skaičiavimas

Nustatomi bandomo ventiliatoriaus parametrai:

- Ventiliatoriaus slėgis ir statinis slėgis;

- Ventilatoriaus statinė oro galia ir oro galia;
- Ventilatoriaus naudingumas.

## 8. Ventilatorius pajungamas A instaliacija (free inle, free outlet)

Papildomai matuojami parametrai naudojami skaičiavime:

- slėgis  $p_{e3}$ , Pa;
- temperatūra  $T_3$ , °C;
- atmosferinis slėgis  $p_a$ , Pa;

### 8.1. Ventilatoriaus slėgių skaičiavimo algoritmai

#### 8.1.1. Ventilatoriaus statinis slėgis $p_{sfA}$ (A instaliacija)

$p_{sfA} = -p_{esg1} = -p_{esg3}$ $p_{esg3} = p_{e3} + \frac{1}{2} \frac{q_m^2}{A_3^2 \rho_3}$	<b>(8.1.1)</b>
<p>čia: <math>p_{esg1}</math> - stagnacinis manometrinis slėgis ventilatoriaus įėjime (inlete), Pa.  <math>p_{esg3}</math> - stagnacinis manometrinis slėgis kameroje, Pa (pjūvyje 3).  <math>q_m</math> - nustatytas oro masės srautas, kg/s;  <math>A_3</math> - kameros skerspjūvio plotas 3 pjūvyje, m<sup>2</sup> (reikšmė ir standartinė neapibrėžtis įvesti į programą);</p>	

$\rho_3$  - oro tankis kameros 3 pjūvyje.

$\rho_3$  - oro tankis kameros 3 pjūvyje:

$$\rho_3 = \frac{p_a + p_{e3} - 0,378 \cdot h_{u7} (610,8 + 44,442 \cdot T_3 + 1,4133 \cdot T_3^2 + 0,02768 \cdot T_3^3 + 2,5567 \cdot 10^{-4} \cdot T_3^4 + 2,8917 \cdot 10^{-6} \cdot T_3^5)}{78394,05 + 287 \cdot T_3} \quad (8.1.2)$$

čia:  $p_a$  - atmosferinis slėgis laboratorijoje (Pa);

$p_{e3}$  - manometrinis slėgis kameros pjūvyje 3 (Pa);

$h_{u7}$  - santykinis drėgnis pjūvyje 7, prieš tūtą (laikome, kad  $T_3 \approx T_7$ , todėl santykinis drėgnis kameros pjūviuose 7 ir 3 yra vienodas  $h_{u3} \approx h_{u7}$ );

$T_3$  - temperatūra pjūvyje 3 (°C).

### 8.1.2. Oro tankio $\rho_3$ standartinės neapibrėžties skaičiavimas

$p_a$ ,  $p_{e3}$  ir  $T_3$  - matuojami dydžiai; jų standartinė neapibrėžtis nustatoma pagal **Skaičiavimo metodiką 001** (Neapibrėžties apskaičiavimo algoritmas, kai atliekamas paprastas 1 parametro matavimas kalibruota matavimo priemone).

**Jautrio koeficientai**, skaičiuojant oro tankio  $\rho_3$  neapibrėžtį:

Išverstinės	Jautrio koeficientų formulės
$c_{\rho_3-pa} = \frac{df(\rho_3)}{dp_a}$	

$c_{\rho_3_{pe7}} = \frac{df(\rho_3)}{dp_{e3}}$	$c_{\rho_3_{pa}} = c_{\rho_3_{pe3}} = \frac{1}{78394,05 + 287 \cdot T_3}$
$c_{\rho_3_{T3}} = \frac{df(\rho_3)}{dT_3}$	$c_{\rho_3_{T3}} = \frac{(-0,378) \cdot h_{u7} (44,442 + 2,8266 \cdot T_3 + 0,08304 \cdot T_3^2)}{78394,05 + 287 \cdot T_3} - \frac{287(p_a + p_{e3} - 0,378 \cdot h_{u7} (610,8 + 44,442 \cdot T_3 + 1,4133 \cdot T_3^2 + 0,02768 \cdot T_3^3))}{(78394,05 + 287 \cdot T_3)^2}$
$c_{\rho_3_{hu}} = \frac{df(\rho_3)}{dh_{u3}}$	$c_{\rho_3_{hu3}} = \frac{-230,8824 - 16,799076 \cdot T_3 - 0,5342274 \cdot T_3^2 - 0,010463 \cdot T_3^3 - 0,966433 \cdot 10^{-4} \cdot T_3^4}{78394,05 + 287 \cdot T_3}$

Oro tankio  $\rho_3$  standartinė neapibrėžtis:

$u(\rho_3) = \sqrt{(c_{\rho_3_{pa}} \cdot u(p_a))^2 + (c_{\rho_3_{pe3}} \cdot u(p_{e3}))^2 + (c_{\rho_3_{T3}} \cdot u(T_3))^2 + (c_{\rho_3_{hu3}} \cdot u(h_{u7}))^2}$	<b>(8.1.3)</b>
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### 8.1.3. Ventilatoriaus statinio slėgio $p_{sfA}$ standartinės neapibrėžties skaičiavimas

Formulė  $p_{sfA} = -p_{esg1} = -p_{esg3}$

$$p_{sfA} = -p_{e3} - \frac{1}{2} \frac{q_m^2}{A_3^2 \rho_3}$$

Jautrio koeficientai, skaičiuojant  $p_{sfA}$  arba  $p_{esg3}$  neapibrėžtį:

Išverstinės	Jautrio koeficientų formulės	Pastaba
$c_{p_{sfA}_{pe3}} = \frac{df(p_{sfA})}{dp_{e3}}$	$c_{p_{sfA}_{pe3}} = -1$	

$c_{p_{sfA}-q_m} = \frac{df(p_{sfA})}{dq_m}$	$c_{p_{sfA}-q_m} = -\frac{q_m}{A_3^2 \rho_3}$	
$c_{p_{sfA}-A_3} = \frac{df(p_{sfA})}{dA_3}$	$c_{p_{sfA}-A_3} = -\frac{q_m^2}{A_3^3 \rho_3}$	
$c_{p_{sfA}-\rho_3} = \frac{df(p_{sfA})}{d\rho_3}$	$c_{p_{sfA}-\rho_3} = \frac{q_m^2}{2A_3^2 \rho_3^2}$	

$p_{sfA}$  standartinė neapibrėžtis

$u(p_{sfA}) = \sqrt{(c_{p_{sfA}-p_{e3}} \cdot u(p_{e3}))^2 + (c_{p_{sfA}-q_m} \cdot u(q_m))^2 + (c_{p_{sfA}-A_3} \cdot u(A_3))^2 + (c_{p_{sfA}-\rho_3} \cdot u(\rho_3))^2}$	<b>(8.1.4)</b>
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#### 8.1.4. Ventilatoriaus statinio slėgio $p_{sfA}$ išplėstinės neapibrėžties skaičiavimas

Pasiklovimo lygis - 95%, daugiklis  $k = 2$ :

$U(p_{sfA}) = 2 \cdot u(p_{sfA})$	<b>(8.1.5)</b>
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**Rezultatas:**

$p_{sfA} \pm U(p_{sfA})$  Pa.



### 8.1.5. Ventilatoriaus slėgis $p_{fA}$ (A instaliacija)

$p_{fA} = \frac{1}{2\rho_2} \frac{q_m^2}{A_2^2} f_{M2} - p_{esg1}$	<b>(8.1.8)</b>
$p_{esg1} = p_{esg3} = p_{sfA}$ ( $p_{sfA}$ reikšmė ir standartinė neapibrėžtis nustatyta)	
<p>čia: <math>p_{esg1}</math> - stagnacinis manometrinis slėgis ventilatoriaus įėjime (inlete), Pa.</p> <p><math>p_{esg3}</math> - stagnacinis manometrinis slėgis kameroje, Pa (pjūvyje 3).</p> <p><math>q_m</math> - nustatytas oro masės srautas, kg/s;</p> <p><math>A_2</math> - kameros skerspjūvio plotas 2 pjūvyje, m<sup>2</sup> (reikšmė ir standartinė neapibrėžtis įvesdami prieš bandymą);</p> <p><math>\rho_2</math> - oro tankis kameros 2 pjūvyje.</p>	

### 8.1.5. $\rho_2$ - oro tankis ventilatoriaus uotlet pjūvyje:

$\rho_2 = \frac{p_a - 0,378 \cdot h_{u7} (610,8 + 44,442 \cdot T_2 + 1,4133 \cdot T_2^2 + 0,02768 \cdot T_2^3 + 2,5567 \cdot 10^{-4} \cdot T_2^4 + 2,8917 \cdot 10^{-6} \cdot T_2^5)}{78394,05 + 287 \cdot T_2}$	<b>(8.1.6)</b>

čia: Ventilatoriaus uotlet galas laisvas -  $p_2 = p_a$ ;  $p_a$  - atmosferinis slėgis laboratorijoje (Pa);

$h_{u7}$  - santykinis drėgnis pjūvyje 7, prieš tūtą (laikome, kad  $T_2 \approx T_7$ , todėl santykinis drėgnis kameros pjūviuose 7 ir 2 yra vienodas  $h_{u2} \approx h_{u7}$ );

temperatūra pjūvyje 2  $T_2 = T_3$  (°C).

### 8.1.6. Oro tankio $\rho_2$ standartinės neapibrėžties skaičiavimas (ventiliatoriaus outlet pjūvyje)

Jautrio koeficientai, skaičiuojant oro tankio  $\rho_2$  neapibrėžtį:

Išverstinės	Jautrio koeficientų formulės
$c_{\rho_2-pa} = \frac{df(\rho_2)}{dp_a}$	$c_{\rho_2-pa} = \frac{1}{78394,05 + 287 \cdot T_2}$
$c_{\rho_2-T_2} = \frac{df(\rho_2)}{dT_2}$	$c_{\rho_2-T_2} = \frac{(-0,378) \cdot h_{u7} (44,442 + 2,8266 \cdot T_2 + 0,08304 \cdot T_2^2)}{78394,05 + 287 \cdot T_2} - \frac{287(p_a + p_{e2} - 0,378 \cdot h_{u7} (610,8 + 44,442 \cdot T_2 + 1,4133 \cdot T_2^2 + 0,02768 \cdot T_2^3))}{(78394,05 + 287 \cdot T_2)^2}$
$c_{\rho_2-h_{u2}} = \frac{df(\rho_2)}{dh_{u2}}$	$c_{\rho_2-h_{u2}} = \frac{-230,8824 - 16,799076 \cdot T_2 - 0,5342274 \cdot T_2^2 - 0,010463 \cdot T_2^3 - 0,966433 \cdot 10^{-4} \cdot T_2^4}{78394,05 + 287 \cdot T_2}$

Oro tankio  $\rho_2$  standartinė neapibrėžtis:

$u(\rho_2) = \sqrt{(c_{\rho_2-pa} \cdot u(p_a))^2 + (c_{\rho_2-T_2} \cdot u(T_2))^2 + (c_{\rho_2-h_{u2}} \cdot u(h_{u7}))^2}$	<b>(8.1.7)</b>
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fm2

Ma2?

$p_a$ ,  $p_{e7}$  ir  $T_7$  - matuojami dydžiai; jų standartinė neapibrėžtis nustatoma pagal **Skaičiavimo metodiką 001** (Neapibrėžties apskaičiavimo algoritmas, kai atliekamas paprastas 1 parametro matavimas kalibruota matavimo priemone).