

**IDENTIFICATION OF WIND INFLUENCED
ROOF VENTILATORS CHARACTERISTICS BASED
ON MEASUREMENT IN THE NZEB TEST FACILITY**

**TUULE JÕUL TÖÖTAVATE KATUSEVENTILAATORITE
KARAKTERISTIKUTE MÄÄRAMINE MÕÕTMISTE PÕHJAL
LIGINULLENERGIA TESTHOONES**

MASTER'S THESIS

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THESIS TASK

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Thesis topic:

(in English) *Identification of wind influenced roof ventilators characteristics based on measurement in the nZEB test facility.*

(in Estonian) *Tuule jõul töötavate katuseventilaatorite karakteristikute määramine mõõtmiste põhjal liginullenergia testhoones.*

Thesis main objectives:

1. To measure the performance of natural ventilation boosters under different wind conditions
2. To estimate hourly natural ventilation airflow rates due to stack effect in a detached house in typical Finnish climates
3. To develop algorithms for a simple tool to evaluate the annual temporal need for boosting natural ventilation to reach good air quality in a detached house in typical Finnish climates

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CONTENTS

PREFACE	7
List of abbreviations and symbols	8
INTRODUCTION.....	9
1 INDOOR AIR QUALITY ASSESSMENT AND NATURAL VENTILATION.....	11
1.1 Definitions	12
1.2 Methods for calculating ventilation air flow rates.....	12
1.3 Calculation of air flow rates in naturally ventilated buildings.....	13
1.3.1 Operating conditions calculation	13
1.3.2 Calculation for air flow rates	15
2 METHOD FOR TESTING.....	18
2.1 Measurement of the cowls	18
2.1.1 Measured room	18
2.1.2 Description of test installation	19
2.2 Evaluating the duct systems characteristics based on the measurement results	25
2.3 The cowl efficiency evaluation based on wind speed	27
2.3.1 Cowl effectiveness relation with wind speed with duct system connected to outside air	27
2.4 Validation of the cowl models with duct systems that are connected to the inside air.....	29
3 RESULTS	32
3.1 System characteristics based on measurement results	32
3.1.1 System characteristics for duct system connected to outside air.....	32
3.1.2 System characteristics for duct system connected to inside air.....	33
3.2 The results of cowl efficiency evaluation based on wind speed with duct system connected to outside air	35
3.2.1 The cowl efficiency relation to wind speed calculation results	35
3.2.2 Results of the validation of cowl with duct systems that are connected to the outside air.	42
3.3 Results of the validation of the cowl with duct systems that are connected to the inside air.	44
3.3.1 Validation on cowl number 1.....	44
3.3.2 Validation on cowl number 2.....	47
3.3.3 Validation on cowl number 3.....	51
3.3.4 Validation on cowl number 3.....	55
SUMMARY.....	60

EESTIKEELNE KOKKUVÕTE	62
LIST OF REFERENCES	64
APPENDICES	65

PREFACE

This thesis is initiated by the Finnish Cultural Foundation.

The thesis was conducted in Tallinn University of Technology (TalTech) and the TalTech nZEB test facility in Mäepealse Street in Tallinn.

For assisting and consulting the author would like to thank the supervisors Martin Thalfeldt (PhD) and Kimmo Lylykangas (PhD). Also author would like to thank: Alo Mikola (junior researcher) for consulting in designing the test installations, Karl-Villem Võsa (doctoral student-junior researcher) for assisting in setting up the data collection system, Peeter Linnas (laboratory engineer) for assisting while collecting measurements in nZEB test facility, Neeme Takis (Uniflex Systems OÜ) for helping with data collection in Uniscada system. Author would also like to thank the companies who donated the cowl for testing.

In this thesis the effect of cowl was assessed in Taltech nZEB test facility with four different cowls. The measurements were conducted in the spring of 2020. Measurements were carried out with two different test installations – one was connected to indoor air and one was connected to outside air. The cowl effectiveness was assessed with both systems and validated with measurement results.

Natural ventilation booster, ventilation, cowl, masters thesis.

List of abbreviations and symbols

nZEB – Near zero energy building

IEQ – Indoor Enviromental Quality

INTRODUCTION

Building ventilation has an important role in ensuring good indoor climate. In terms of air quality it is important that air is clean from pollutants, which could have harmful impacts on a humans health. As far as ventilation systems go building can be equipped with mechanical ventilation, natural ventilation or a hybrid system. Up until the mid 20th century natural ventilation was the most common ventilation system in all building in Finland.[1] Nowadays it is more common to use mechanical ventilation in buildings.

In Estonia it is difficult to meet energy efficiency requirements for new detached building if natural ventilation is used. It is difficult to ensure required airflow rates with natural ventilation system.

Because of the big interest in natural ventilation systems in Scandinavian countries this thesis was brought to life Finnish Cultural Foundation project K3 and it focuses on natural ventilation systems and the effectiveness of cowls for improving air flow rate. There has been few researched conducted to find the effect on cowls. In 2003 A. Revel and B.P. Huynh published a research where they tested turbine eductors in wind tunnel. In 2005 S.Irving, B.Ford and D.Etherige published a revision of the Applications Manual where they researched natural ventilation usage in non-domestic buildings. There has also been some studies in 20th century that researched natural ventilation and cowl effect.

This subject has become more relevant due to climate change. The need to use less energy and emit less CO₂ has become more important in society.

This subject has interest in other Scandinavian countries as well were they have built experimental buildings with natural ventilation. Natural ventilation systems are also interesting because of their very little energy consumption and small CO₂ footprint.

In this thesis tests for cowl were conducted and their effect for the airflow rates was analysed without the information of wind tunnel data. It was tried to characterize the cowl with field measurements and to find the connection between stack effect and cowl effect in total airflow in natural ventilation system.

For the test, a test installation was constructed in TalTech nZEB test facility where the airflow rates and pressure differences were measured in a period of time. From the measured data a function was formulated, which can be used for calculating airflow rates in the ducts in accordance of pressure differences, temperature and windspeed.

This thesis is divided into 3 parts. It starts with the explanation on how we assess indoor air quality, second part focuses on the method used to carry out the tests. The third part is covering the results of the tests and calculations.

1 INDOOR AIR QUALITY ASSESSMENT AND NATURAL VENTILATION

For assessing indoor air quality the following means need to be controlled: source control, ventilation, and possible filtration and/or air cleaning. [2]

- Source control is the non-human emissions control for maintaining good indoor air quality.[2]
- Ventilation – Design air flow rates are used for any type of ventilation system to ensure air purity from the left emissions by source control and other means.[2]
- Possible filtration and/or air cleaning – The required air purity level shall be determined by the building owner before the design process and engineer has to ensure that the system meets the demands.[2]

Depending from the needs of the building owner there has been specified default input values for different categories of indoor environment quality.

Category	Level of expectation
IEQ _I	High
IEQ _{II}	Medium
IEQ _{III}	Moderate
IEQ _{IV}	Low

Table 1.1 Categories of indoor environmental quality

[2]

The categories are related to the level of expectations the occupants may have. A normal level would be „Medium“. A higher level may be selected for the occupants with special needs (children, elderly, persons with disabilities, etc.). A lower level will not provide any health risk but decrease comfort. [2]

1.1 Definitions

In this thesis the following definitions are given in the following meaning.

- Cowl – Air terminal device with or without moving components, intended to be fitted on top of an exhaust duct, with aim, by creating negative pressure depending of the wind speed, to avoid reverse flow and to increase the extracted flow rate in presence of wind.
- Stack effect – airflow induced by pressure difference from temperature difference.

1.2 Methods for calculating ventilation air flow rates

Design parameters for indoor air quality shall be derived using one or more of the following methods:

- Method 1: Method based on perceived air quality;
- Method 2: Method using limit values for substance concentrations;
- Method 3: Method based on predefined ventilation air flow rates.

The pre-defined ventilation air flow rated shall be expressed by one or more of the following parameters:

- Total design ventilation for people and building components (q_{tot});
- Design ventilation per unit floor area (q_{m^2});
- Design ventilation per person (q_p);
- Design air change rate (ach);
- Design air flow rates by room and building type (q_{room}).

[2]

Ventilation air flow rates in naturally ventilated buildings shall be calculated based on building layout, location and weather conditions.

Natural ventilation rates can be calculated in accordance with EN 16798-7 or with dynamic thermal simulation tools.[2]

1.3 Calculation of air flow rates in naturally ventilated buildings

In this chapter the calculation of air flow rates according to European Standard EN 16798-7:2017 "Energy performance of buildings – Ventilation for buildings – Part 7: Calculation methods for the determination of air flow rates in buildings including infiltration (Modules M5-5)" is given.

1.3.1 Operating conditions calculation

1.3.1.1 Air density calculation

The air density at temperature T and neglecting atmospheric pressure variations is given by:

$$\rho_T = \frac{T_{ref}}{T} \rho_{a;ref} \quad (1.1)$$

where ρ_T – air density at temperature T , kg/m^3 .

T_{ref} – Reference temperature 293,15 K, K.

T – Given temperature, K.

$\rho_{a;ref}$ – air density at sea level, 293 K and dry air, kg/m^3 .

1.3.1.2 Reference wind speed at site

The meteorological wind speed at 10m is corrected as follows to obtain the reference wind speed at site at 10m height:

$$u_{site} = \frac{C_{rgh;10;site} \cdot C_{top;site}}{C_{rgh;met} \cdot C_{top;met}} u_{10} \quad (1.2)$$

where u_{site} – wind velocity at the zone level, m/s

$C_{rgh;10;site}$ – roughness coefficient at height of 10m depending on local environment of the building site.

$C_{top;site}$ – topography coefficient depending on the local environment of the building site at building height.

$C_{rgh;met}$ – roughness coefficient at height of 10 m depending on the local environment of the meteorological station.

$C_{top;met}$ – topography coefficient depending on the local environment of the meteorological station.

u_{10} – meteorological wind speed, m/s

The meteorological wind speed at 10 m is corrected as follows to obtain the reference wind speed at site at 10 m height:

$$u_{10;site} = \frac{C_{rgh;10;site} \cdot C_{top;10;site}}{C_{rgh;met} \cdot C_{top;met}} u_{10} \quad (1.3)$$

where $u_{10;site}$ – reference wind speed at site at 10 m height.

$C_{top;10;site}$ – topography coefficient depending on the local environment of the building site at height of 10 m.

$C_{rgh;site}$, $C_{top;site}$, $C_{rgh;10;site}$, $C_{top;10;site}$, $C_{rgh;met}$, $C_{top;met}$ shall be:

- Calculated according to ISO 15927-1, taking into account the roughness and the topography near the building site and the meteorological station; or
- Assess with default values given in EN 16798-7:2017 B.3.4.2

1.3.1.3 Pressure coefficients associated to an air flow path

The pressure coefficients shall be determined for each air flow path taking into account:

- Its height on the facade; and
- The facade exposure to wind

Pressure coefficients are given in EN 16798-7:2017 B.3.3.

1.3.1.4 Pressure difference at an air flow path

The pressure difference between the outside and the inside of air flow path "i" at its height above floor level is given by:

$$\Delta p_{path,i} = p_{e;path,i} - p_{z;path,i} \quad (1.4)$$

Where $\Delta p_{path,i}$ – pressure difference at air flow path "i" level, Pa.

$p_{e;path,i}$ – external pressure at the air flow path "i" level, Pa.

$p_{z;path,i}$ – Internal pressure at the air flow path "i" level, Pa.

$$p_{e;path,i} = \rho_{a,ref} \cdot \frac{T_{e,ref}}{T_e} \cdot (0,5 \cdot C_{p;path,i} \cdot u_{site}^2 - h_{path,i} \cdot g) \quad (1.5)$$

Where $T_{e,ref}$ – external absolute temperature at reference conditions, K.

T_e – external absolute temperature, K.

$C_{p;path,i}$ – wind pressure coefficient for air flow path "i".

$h_{path,i}$ – mid-height of the air flow path "I" relative to ventilation zone floor level, m.

g – acceleration of gravity, m/s².

$$p_{z;path,i} = p_{z;ref} - \rho_{a,ref} \cdot h_{path,i} \cdot g \cdot \frac{T_{e,ref}}{T_z} \quad (1.6)$$

Where $p_{z;ref}$ – internal reference pressure of the ventilation zone at the floor level, Pa.

T_z – ventilation zone temperature, K.

External pressure at floor level of the ventilation zone is taken equal to 0.

1.3.2 Calculation for air flow rates

The air flow rate through a passive duct is characterized by:

- Pressure loss at the internal air terminal device
- Pressure losses in ductwork
- Pressure loss in the cowl
- The useful height for stack effect

1.3.2.1 Pressure loss at internal air terminal devices

The pressure loss at an internal air terminal device shall be characterized taking into account the total air flow rate passing through the device:

$$\Delta p_{ATD} = -\text{sign}(q_{V;pdu}) \cdot \left(\frac{|q_{V;pdu}|}{C_{ATD}} \right)^{\frac{1}{n_{ATD}}} \quad (1.7)$$

Where Δp_{ATD} – pressure drop at an internal air terminal device, Pa.

$q_{V;pdu}$ – airflow through passive or hybrid duct, m³/h

C_{ATD} – airflow coefficient of air terminal device, m³/(h·Paⁿ)

n_{ATD} – flow exponent of air terminal devices.

Or, for externally mounted air transfer device, by the test results according to EN 13141-1 and EN 13141-2 if applicable.

The coefficient of the air terminal device may be calculated from the equivalent area A_{ATD} value, according to EN 13141-1 and EN 131-41-2, as follows:

$$C_{ATD} = \frac{3600}{10000} \cdot C_{D;ATD} \cdot A_{ATD} \cdot \left(\frac{2}{\rho_{a;ref}} \right)^{0,5} \cdot \left(\frac{1}{\Delta p_{ATD;ref}} \right)^{\frac{1}{n_{ATD}}} \quad (1.8)$$

Where $C_{D;ATD}$ – discharge coefficient for air terminal devices.

A_{ATD} – equivalent area of the air terminal device, cm².

$\Delta p_{ATD;ref}$ – reference pressure difference for an air terminal device, Pa.

1.3.2.2 Pressure loss in the ductwork

A method can be defined at national level to calculate pressure drop through the ductwork Δp_{pdu} from the inside space to the outside near the cowl or passive duct outlet.

The pressure drop of linear ducts, take-off and singularities shall be calculated.

1.3.2.3 Cowl characteristics and corrections according to roof angle position and height of the cowl

A cowl is characterized with 2 coefficients derived by tests performed according to EN 13141-5:

- Its pressure drop ζ_{cowl} in no-wind conditions; and
- Its pressure factor C_{cowl} which is a function of vertical wind approach angle, air speed in the duct and (for hybrid system) fan operation.

For hybrid systems, the pressure factor shall be determined taking into account the combined effects of wind and fan operation according to EN 13141-5.

The pressure factor taken at the roof outlet or cowl $C_{cowl;tot}$ is given by:

$$C_{cowl;tot} = C_{cowl} + C_{p;cowl;roof} + \Delta C_{cowl;height} \quad (1.9)$$

Where $C_{cowl;tot}$ – pressure at roof level taking into account the height of the cowl above the roof level.

C_{cowl} – pressure factor of the cowl.

$C_{p;cowl;roof}$ – pressure coefficient when the cowl is installed at roof height.

$\Delta C_{cowl;height}$ – correction of cowl pressure factor accounting for height above roof level.

EN 16798-7 B.3.3.5 and B.3.3.6 give default values for $C_{p;roof;cowl}$ and $\Delta C_{cowl;height}$ respectively.

The pressure drop at cowl is:

If $u_{site}=0$

$$\Delta p_{cowl} = -\frac{1}{2} \cdot \text{sign}(q_{V;pdu}) \cdot \zeta_{cowl} \cdot \rho_{a;ref} \cdot \left(\frac{|q_{V;pdu}|}{3600 \cdot A_{S;pdu}} \right)^2 \quad (1.10)$$

Where Δp_{cowl} – pressure drop at the cowl, Pa.

ζ_{cowl} – pressure loss coefficient of the cowl in no wind condition.

$A_{S;pdu}$ – cross-sectional area of the passive duct, m².

Else

$$\Delta p_{cowl} = -\frac{1}{2} \cdot \text{sign}(q_{V;pdu}) \cdot \zeta_{cowl} \cdot \rho_{a;ref} \cdot u_{site}^2 \quad (1.11)$$

1.3.2.4 Overall calculation

The following implicit formula shall be solved with $q_{V;pdu}$ as unknown:

$$\Delta p_{ATD} + \Delta p_{pdu} + \Delta p_{cowl} = p_{z;ref} + h_{pdu;st} \cdot g \cdot (\rho_{a,e} - \rho_{a,z}) \quad (1.12)$$

Where Δp_{pdu} – pressure drop through the ductwork, Pa.

$h_{pdu;st}$ – useful height for stack effect with passive duct, m.

$\rho_{a,e}$ – air density of external air, kg/m³.

$\rho_{a,z}$ – air density of ventilated zone air, kg/m³.

If $q_{V;pdu} \geq 0$

$$q_{v;pdu;in} = q_{V;pdu} \quad (1.13)$$

$$q_{v;pdu;out} = 0 \quad (1.14)$$

where $q_{v;pdu;in}$ – airflow entering through passive or hybrid duct, m³/h.

$q_{v;pdu;out}$ – airflow leaving through passive or hybrid duct, m³/h.

Else

$$q_{v;pdu;in} = 0 \quad (1.15)$$

$$q_{V;pdu;out} = q_{V;pdu} \quad (1.16)$$

In this thesis the aim was to try to evaluate the air volume flow, without the cowl coefficients and try to characterize it with field measurements and find the connection between stack effect and cowl effect in total airflow through natural ventilation system.

2 METHOD FOR TESTING

The method for this thesis consists of the cowls measurements and then evaluating the performance of the cowls based on measurement results. The method consists the following steps:

1. Measurements of the cowls with duct systems that are connected to outside air and with duct systems that are connected to the inside air.
2. Evaluating the duct systems characteristics based on the measurement results.
3. Cowl efficiency evaluation based on wind speed with the results of duct systems that were connected to outside air.
4. Validation of the cowls constructed models with measurement results from duct systems that were connected to inside air.

2.1 Measurement of the cowls

The measurements were carried out in a test facility in Tallinn, Estonia. Detailed description of the facility and the room is described in chapter 2.1.1. The tests were conducted with two different systems, detailed description of the test installation is in chapter 2.1.2

2.1.1 Measured room

The building that was used in the tests was TalTech nZEB test facility in Tallinn, Estonia. Building is located in Mäepealse street in Mustamäe district, oriented in East-West orientation with high landscaping to the South-East side across Lossi street and a 5 story high building to the North-West side about 20m from the test facility. The building is situated at the height of 27.00 m above sea level.

For the test one room from the building was used – room number 9 “Testruum”. The room has area of 30,7 m² and height of 3m. The room was already equipped with 28 100mm feed-throughs to the wall from previous test that had been carried out in the building what were used for the test installation and compensation air.

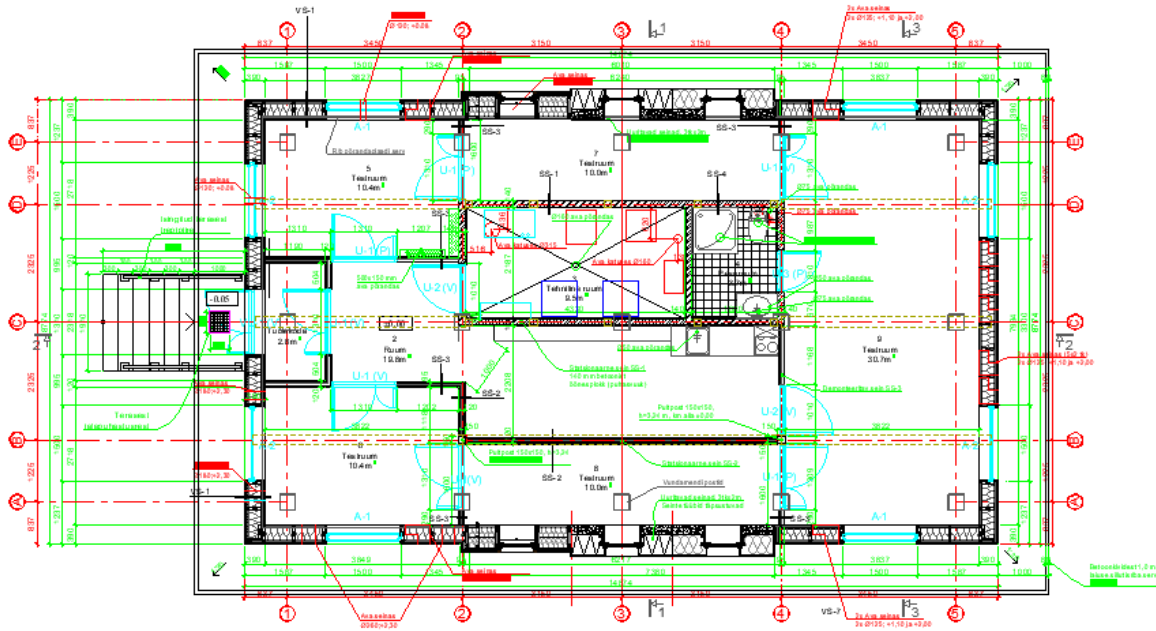


Figure 2.1 TalTech nZEB plan view (source: Nordecon Betoon OÜ, job nr: P-12-048)

Building is equipped with mechanical ventilation system that was turned off during the tests.

2.1.2 Description of test installation

2.1.2.1 Design of the installation

The design of the test installation is based on the European Standard prEN 13141-5:2019 "Ventilation for buildings – Performance testing of components/products for residential ventilation – Part 5: Cowls, assisted cowls and for outlet terminal devices", what was modified to suit field measurements while still remaining close to the standards typical installation example. The aerodynamic characteristics of the air terminal device was tested in a test installation as shown in Figure 2.2.

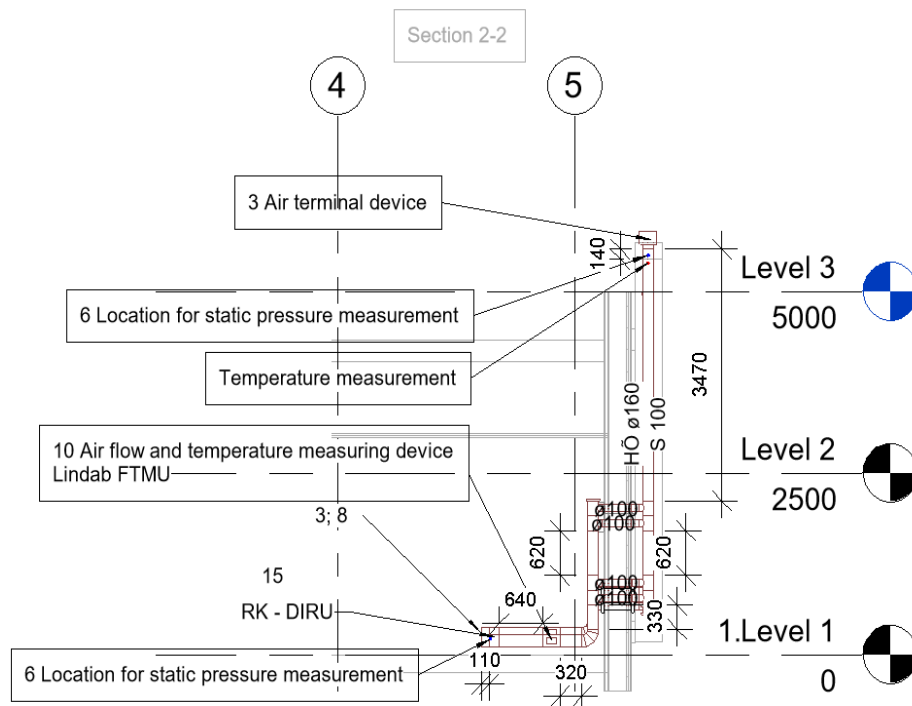
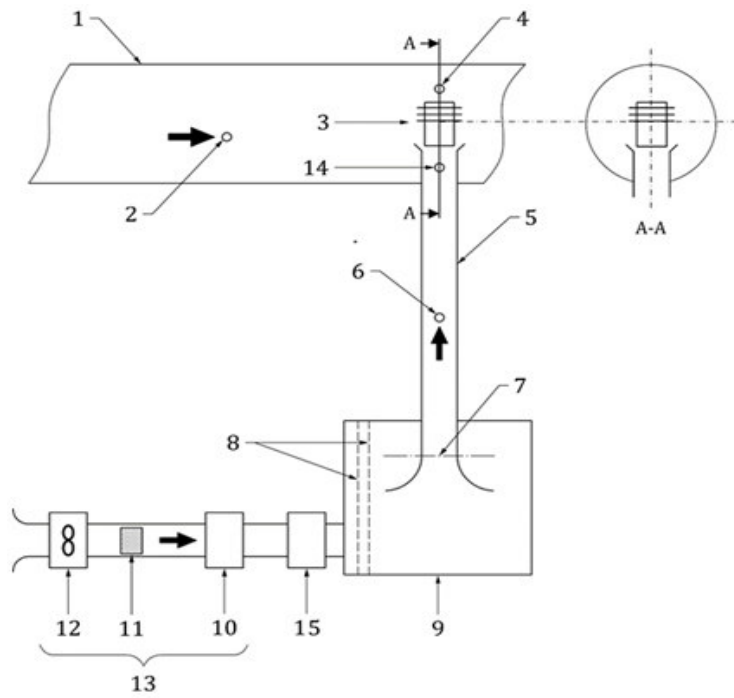


Figure 2.2 Typical test installation and constructed test installation

2.1.2.2 Construction of the installation

The test installation was constructed in TalTech nZEB test facility by the author. There was total of four chimneys constructed. Two of the chimneys were connected with the room of the building and two were not. The purpose for the two chimneys that were connected to the room was to evaluate the efficiency of the ventilation with stack effect and the two that were connected to outside air were constructed to assess the influence of the cowl to the airflow rate in the duct without the stack effect.

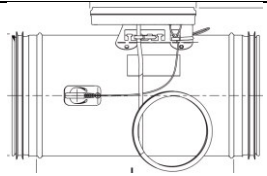


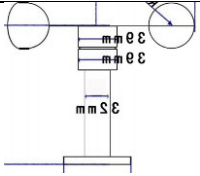


Figure 2.2 Test installations

The ducting used was 160mm diameter plastic Uponor Indoor ventilation duct were used to minimize pressure loss in ducting. Unfortunately some T-joints used were steel joints manufactured by ETS Nord because of the long waiting time for the supply of plastic T-joints. Regulators used were diaphragm type EST Nord KRI regulation dampers, air flow measurement were carried out with Lindab FTMU Ultrasonic measurement device. For the insulation for ducts of exhaust air Paroc Wired mat 80 AluCoat was used, installed thickness 100mm. Insulation joints were taped with aluminium tape. Insulated ducts were covered with moisture resistant plywood, with thickness 15mm and the joints were taped with vapor barrier tape and the seals between the plywood and ducts were sealed with acrylic sealant.

The insulation installed thickness was choosed to be 100mm because most of the chimneys in buildings are usually constructed inside the building, so the temperature drop in the duct will be minimal, therefor to replicate this aspect it was decided to keep the temperature drop to a minimal in the test installations. The tests showed that with outdoor temperature of +4 °C and inside air temperature +21 °C resulted in a temperature drop of 4 °C, which is acceptable.

Table 2.1 Measurement units used in the test installation

Measurement unit	Lindab FTMU Ultrasonic	Dwyer Magnasense differential pressure transmitter	Hobo TMCx-HD temperature sensors	Quingy QS-FS01
Description	Air flow and temperature measurement device	Differential pressure measurement device	Temperature measurement device	Wind speed measurement device
Illustration				
Measurement range	Velocity range: 0,2-15 m/s Temperature range: -10°C to +50°C	-50Pa to 50 Pa	-40°C to +50°C	0-30 m/s
Measurement uncertainty	Flow: $\pm 5\%$ or $\pm 1,6$ l/s	$\pm 1\%$	$\pm 0,25^\circ\text{C}$ from 0°C to 50°C	$\pm(0,3+0,03)$ m/s

For logging the measurements HOBO 4-channel analog data logger and Grant Industries 2020 series squirrel data logger with supported software were used. For wind speed logging Uniscada web based logger was used.

The installation process for the test installation with connection to the indoor environment was carried out as follows:

- The ventilated room was already equipped with fresh air valves, therefore wall feedthroughs were already in place for the test installation. Because the existing feedthroughs were 100mm diameter four feedthroughs were connected for one test installation for minimal pressure loss.

- After the feedthroughs were freed the outside part was extended to clear the existing solar panels that were installed on the wall of the building.
- Next the plywood chimney for covering the insulated ducts was placed on the wall, dimensions 395mm x 395mm x 5000 mm (Width x Depth x Height).
- Next step was building the ducting system and placing the temperature sensor and pressure measurement hose on the ducting under the insulation.
- After that the ducting was insulated and the joints taped with aluminium tape.
- Final step for outside part of the test installation was closing the plywood cover for the insulated ducts and sealing all joints with vapor barrier tape and sealing plywood and duct connection places with acrylic sealant.
- Next step was constructing the indoor part of the installation. The ducting was cut to length and installed indoor. The measurements are given in Appendix 1.

The installation process for the test installation without connection to the indoor environment was carried out as follows:

- The ducts were placed on the wall with standard duct placeholders.
- The airflow measurement unit was placed approximately 1m from the end of the ducting.
- A cover for the airflow measurement unit was constructed and placed over the measurement unit to protect it of outside elements.

All the cowls and roof hood were placed at the same height approximately same height with the wind measurement device.

For the compensation air 12 100mm fresh air valves were placed on the wall for minimal pressure drop for compensation air.

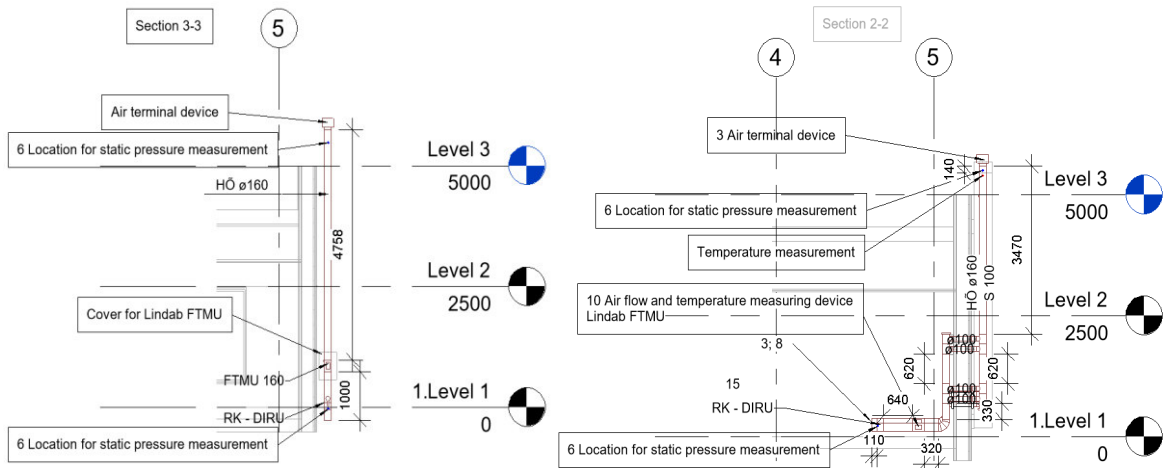


Figure 2.3 Duct system connected to outdoor air and duct system connected to inside air

Data was collected from all the test installations. Data collection points were determined based on European Standard prEN 13141-5:2019 "Ventilation for buildings – Performance testing of components/products for residential ventilation – Part 5: Cowls, assisted cowls and for outlet terminal devices". The measurement points are illustrated in the test installation in Figure 2.3.

Installations that were connected to inside air the airflow rate through duct, temperature drop along the test installation and the static pressure difference over the duct system were measured.

For the installations that were not connected to the room airflow through duct and pressure difference over the duct system were measured.

Logging interval for all measurements was 10 seconds.

The data was collected and exported from logging devices in a CSV format and imported to Microsoft Excel software for further processing

The quality of the construction satisfies the needs for the tests and ensures accurate measurements.

Possible improvements would be to consider another solution for the covering of the insulated ducts for easier installation and better waterproofing, using weather proof pressure differential measurement devices to use less length hoses for more accurate measurements and to use more wind speed measurement devices closer to the cowls.

2.1.2.3 Tested cowls

Cowls were acquired from Finnish manufactures as a donation. Cowls used for testing were:

1. Biolan Wind fan,
2. Rotoflex SZ-WK 150 ROTKR,
3. Domus classica Piipunhatta viirihattu
4. Kosken metalli kikka-vedon parentaja



Picture 2.1 Tested elements

2.2 Evaluating the duct systems characteristics based on the measurement results

Since the air flow through the ducts was relatively small, conventional pressure drop calculation may give us the wrong answer. Thus in these tests duct characteristics was found out with tests. The characteristics were composed for every ducting system with 4 different local pressure drop values. To regulate the local pressure drop values iris-type regulator damper was used. Regulator damper setpoint value for different characteristics were $k=0$, $k=4$, $k=8$, $k=8$ with 50mm wide tape across opening.



Figure 2.4 Regulator damper setpoints $K=0$, $K=4$, $K=8$, $K=8$ with tape

All the measurements were gathered together and sorted by the duct system and regulator damper k value. The values that were gathered directly from measuring were the air flow through ducting system, static pressure drop in ducting system, temperature of inside and outside air and wind speed. All the measurements were measured with 1 second interval and averaging to 10 seconds. To minimize measurement error and minimize sudden peaks of measurement the measurement values were averaged to 1 minute manually.

To find out duct characteristics air volume flow and total pressure drop are needed. The air volume flow was measured and therefor only pressure drop was needed. Total pressure drop is consisted of two elements – static pressure drop and dynamic pressure drop (also know as velocity pressure drop).

$$p_t = p_s + p_{dyn} \quad (2.1)$$

Where p_t – total pressure, Pa

p_s – static pressure, Pa

p_{dyn} – dynamic pressure, Pa

From the measured air flow rate dynamic pressure drop in system was calculated. Formula used to calculate dynamic pressure loss is (2.2).

$$p_{dyn} = \frac{\rho \cdot v^2}{2} \quad (2.2)$$

Where p_{dyn} – dynamic pressure drop, Pa

ρ – air density, kg/m³

v – air velocity, m/s

The total pressure drop was calculated by adding together measured static pressure and calculated dynamic pressure illustrated in formula (2.1).

Next step was to calculate the air volume flow and pressure to 0°C temperature to minimize measurement difference caused by temperature difference. For this calculation formulas (2.3) and (2.4) were used.

$$\frac{q_o}{q_r} = \frac{(273 + t_o)}{(273 + t_r)} \quad (2.3)$$

Where, q_o – operating volume flow, m³/s

q_r – reference volume flow, m³/s

t_o – operating temperature, °C

t_r – reference temperature, °C

$$\frac{dp_o}{dp_r} = \frac{(273 + t_o)}{(273 + t_r)} \quad (2.4)$$

Where, dp_o – operating pressure developed, Pa

dp_r – reference pressure developed, Pa

Next step was to compose an analytical function for all given duct system characteristics. For this excel add-in "Solver" was used. The generic formula for characteristic is $dP = \xi \dot{V}^n + C$, where dP – pressure drop, Pa, ξ – system local pressure drop constant, \dot{V} – air volume flow, l/s, n – constant, C – constant. With the help of excel solver the values of " ξ ", " n " and " C " were found that would give the smallest residual with the measured pressure drop. Since the duct characteristics formula has to start in the point $[0;0]$, the constant C in the function will be considered as measurement systematic error.

For example the duct system that is not connected with the indoor air. The composed formula was $dP = 0,0035 \dot{V}^2 + 0,4971$. As mentioned earlier the pressure drop is 0 Pa the air volume flow has to be 0 l/s, therefor the constant C will be ignored. The fitted line has formula $dP = 0,0035 \dot{V}^2$.

Same calculation was conducted for all different duct system characteristics – $k=0$, $k=4$, $k=8$, $k=8$ with 50mm wide tape across opening.

The same method was used to create system characteristics for the duct system that is connected to the inside air.

The results of the calculation can be seen at chapter 3.1.

2.3 The cowl efficiency evaluation based on wind speed

To measure the effect of the cowl the duct system connected to outside air was used to measure pressure drop and airflow rates created by the cowl at different wind speeds.

2.3.1 Cowl effectiveness relation with wind speed with duct system connected to outside air

The first step was creating a formula that makes air volume flow or pressure drop relative to wind speed. The formula that was chosen was $v_{wind} = a \dot{V} \text{ (or } dP)^n + C$, where v_{wind} – wind speed, m/s, a – constant, $\dot{V} \text{ (or } dP)$ – air volume flow, l/s (or total pressure drop, Pa), C – constant, n – constant. This was done for every system characteristics that was measured ($K=0$, $K=4$, $K=8$, $K=8$ with tape).

This equation was solved similar to duct system characteristics – with excel solver the equation constants were calculated, so that the residual would be minimum. And the constant C would be considered as the minimum wind speed that the cowl is effective.

For regulator damper position $k=8$ with tape the formula was constructed between pressure drop and wind speed. The reason was that the formula created with excel solver is more accurate than with air volume flow.

Combining the duct system characteristics equation and wind speed equation the values for pressure drop and air volume flow rate were calculated at reference wind speeds. The wind speed formula was solved with reference wind speed and calculated air volume flow (or pressure drop) as a result. The calculated result was the input for system characteristics equation and pressure drop (of air volume flow) was found. By combining these two equations the cowls effect was discovered for every system characteristics at reference wind speeds.

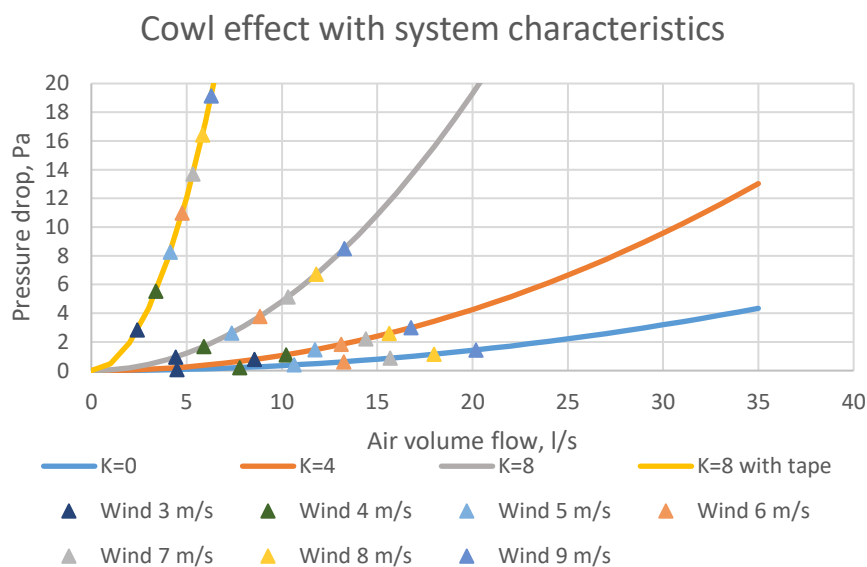


Figure 2.5 Illustration of the results of combining system characteristics and wind speed formulas.

Next step was to create analytical formulas so that the results could be calculated at any given wind speed. The input for this calculation were the results of system characteristics equation and wind speed equation system illustrated in Figure 2.5. This was carried out using excel solver and the formulas generic shape was $dP=dP_0-\beta\dot{V}^2$, where dP – pressure drop, Pa, dP_0 – maximum static pressure drop generated by the cowl at given wind speeds, Pa, β – constant, \dot{V} – air volume flow, l/s. By using solver dP_0 and “ β ” were given values, with the constraint that residual with calculated value has to be minimal. The calculated formulas are given in chapter 3.

To be able to transfer these wind speeds analytical formulas to desired wind speed, analytical formulas for constants dP_0 and β were compiled with simple excel scatter table and trendline option.

2.4 Validation of the cowl models with duct systems that are connected to the inside air

Next part of testing and analysis was to evaluate how effective is the cowl with systems that are connected to indoor air and therefore have stack effect airflow through the system.

To evaluate the effect that the cowl has on improving the ventilation in a room the measured airflows were compared to the airflows that the cowl initiates.

In the system where there is a natural ventilation there are two forces that cause the airflow. First one is the cowl as we have evaluated before and the second is the flow caused by thermal forces. The simplification was done that anything else in the building does not create pressure difference (e.g. windows and doors were not open). For the validation the principle on how to add together the stack effect and the cowl effect had to be found. The connection is illustrated in the figure below.

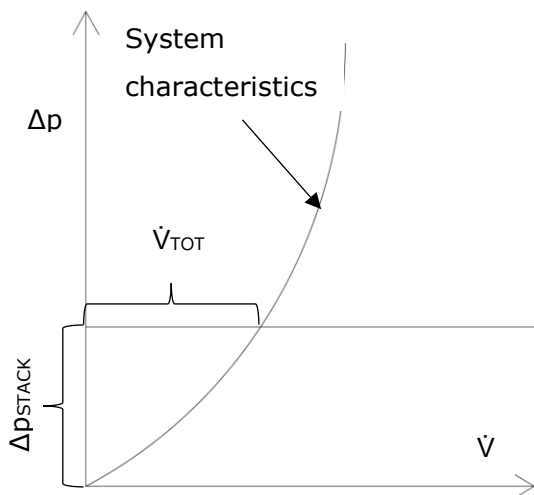


Figure 2.6 Stack effect

The equation for stack effect for nonhorizontal duct with different temperatures for inside and outside air can be calculated by using the equation (2.5).

$$\Delta p_{se} = g \cdot (\rho_a - \rho) \cdot (z_2 - z_1) \quad (2.5)$$

Where Δp_{se} – stack effect, Pa

z_2 and z_1 – elevation from datum in direction of airflow, m

- ρ_a – density of ambient air, kg/m³
- ρ – density of air within duct, kg/m³
- g – 9,81 – gravity acceleration, m/s²

For the stack effect calculation, the average temperature between measured temperature between Lindab FTMU and thermal probe before the cowl was used.

From the calculated pressure drop due to stack effect the airflow was calculated using the duct system characteristics equation composed earlier.

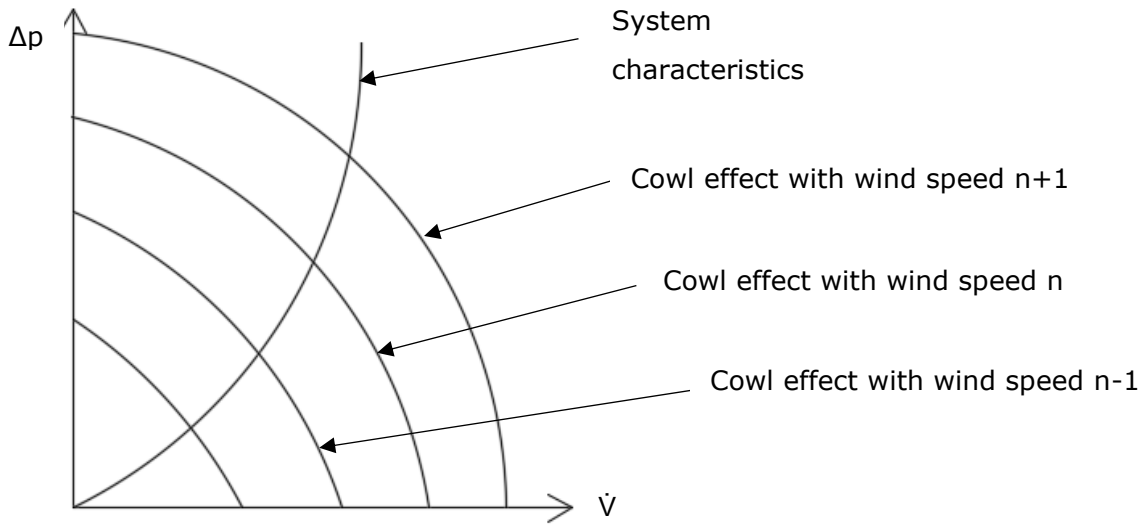


Figure 2.7 Cowl effect with different wind speeds

Airflow through the system resulted by the two mentioned forces can be calculated by adding together the pressure generated as if two ventilators are connected in a series, and the airflow can be found by using the system characteristics analytical formulas.

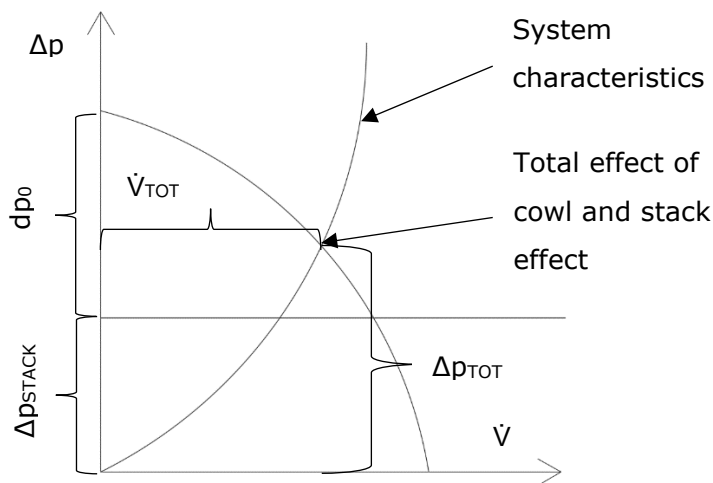


Figure 2.8 Result of stack effect and cowl effect

For the validation the measured airflow rate and calculated airflow rate were compared.

The results of the validation can be found in chapter 3.

3 RESULTS

3.1 System characteristics based on measurement results

3.1.1 System characteristics for duct system connected to outside air

Characteristics measurements with duct systems connected to the outside air for each different characteristics are given in Figure 3.1 **Törge! Ei leia viiteallikat.** and Figure 3.2 **Törge! Ei leia viiteallikat.**. The analytical formulas for the characteristics line are:

- $K=0, dP=0,0035 \dot{V}^2 + 0,4971$
- $K=4, dP=0,0106 \dot{V}^2 + 0,2856$
- $K=8, dP=0,0482 \dot{V}^2 + 1,5469$
- $K=8 \text{ with tape}, dP=0,4823 \dot{V}^2 + 1,2573$

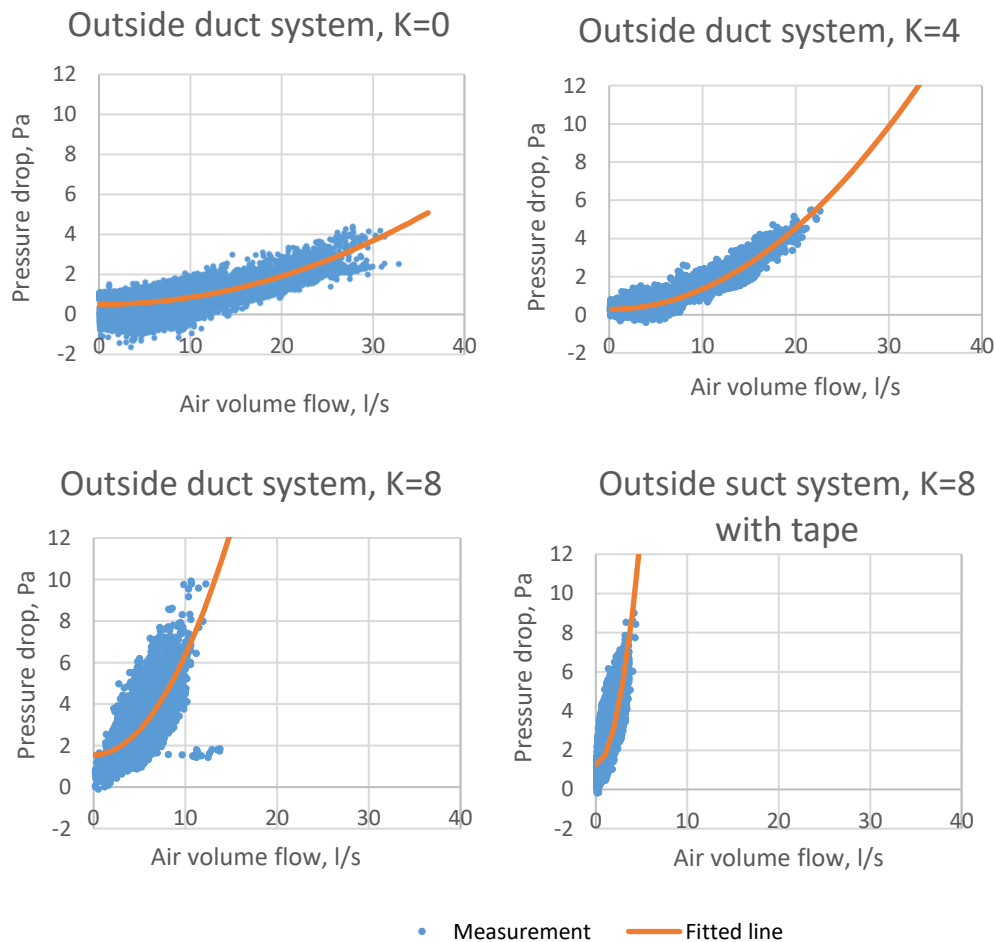


Figure 3.1 Duct system connected to outside air system characteristics.

As said in the chapter 2.2 the constant „C“ was considered as a measurement systematic error and therefor neglected.

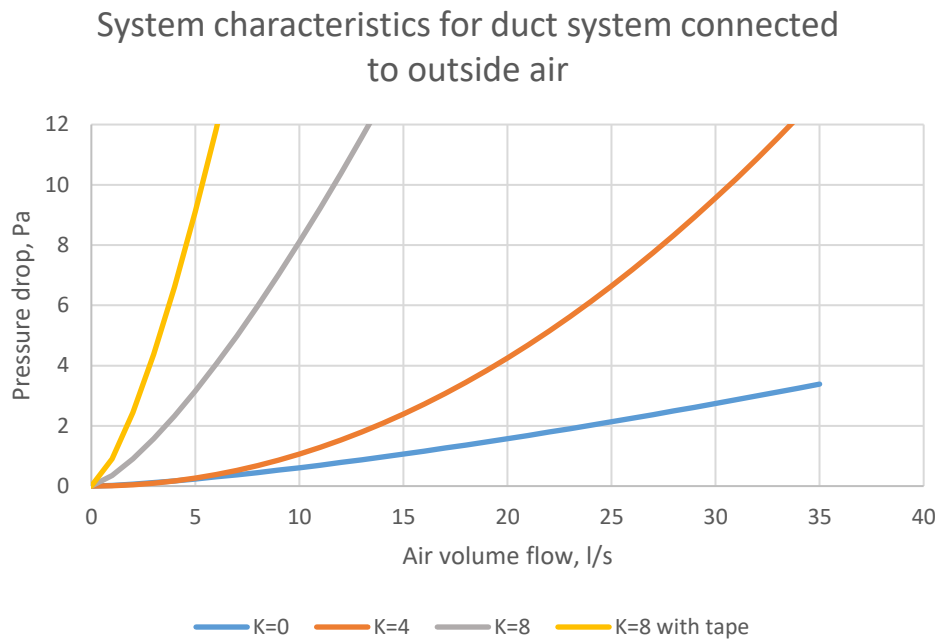


Figure 3.2 System characteristics for duct system connected to outside air.

3.1.2 System characteristics for duct system connected to inside air

Characteristics measurements with duct systems connected to the inside air for each different characteristics are given in Figure 3.3 and Figure 3.4. The analytical formulas for the characteristics line are:

- $K=0, dP=0,0090 \dot{V}^2 + 1,6198$
- $K=4, dP=0,0126 \dot{V}^2 + 1,0628$
- $K=8, dP=0,08175 \dot{V}^2 + 0,1783$
- $K=8 \text{ with tape}, dP=2,5461 \dot{V}^2 + 0,8139$

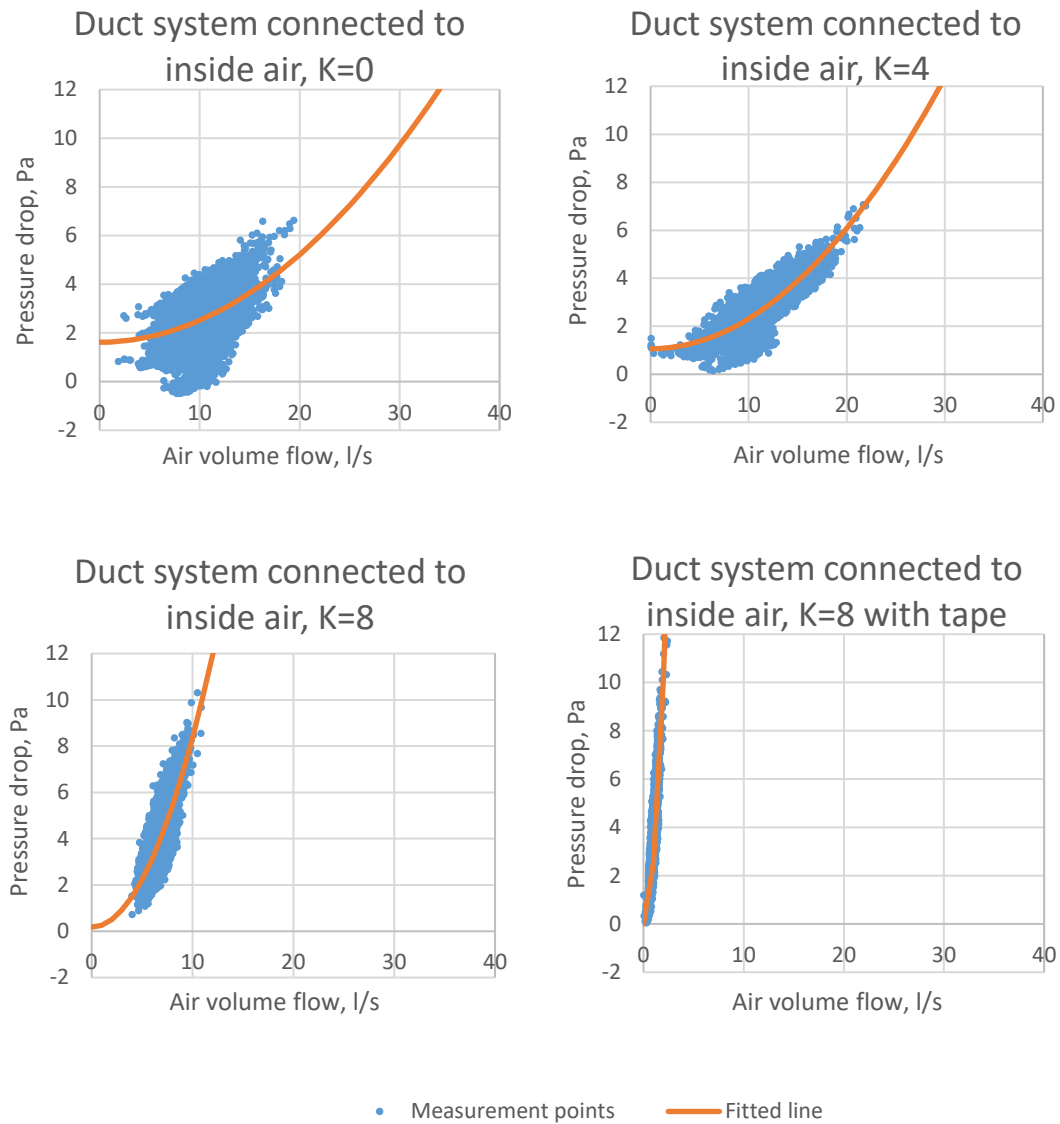


Figure 3.3 Duct system connected to inside air system characteristics.

As said in the chapter 2.2 the constant „C“ was considered as a measurement systematic error and therefore neglected.

System characteristics of duct system connected to outside air

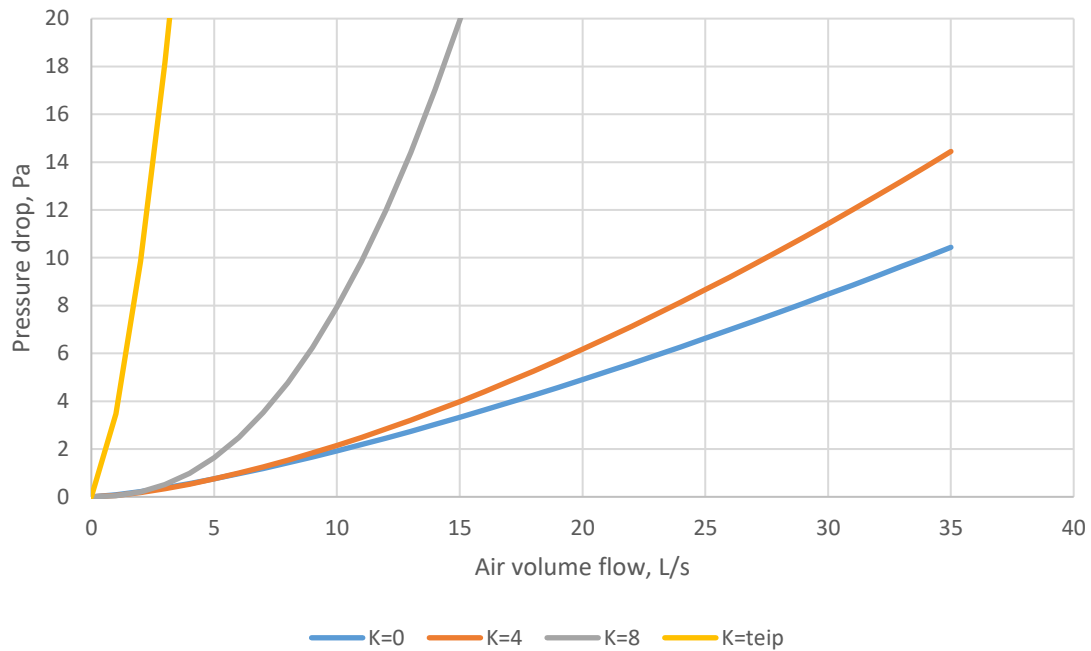


Figure 3.4 System characteristics for duct system connected to inside air.

3.2 The results of cowl efficiency evaluation based on wind speed with duct system connected to outside air

3.2.1 The cowl efficiency relation to wind speed calculation results

In the first part of this chapter the calculation steps for element number 1 are shown and later the results for all elements are given.

Element number 1 efficiency based on wind speed was evaluated according to chapter 2.3.1 and the results are described in Figure 3.5. The analytical formulas for the fitted lines are:

- $k=0; v_{wind}=0,1177 \dot{V}^{1,3546} + 2,0978$
- $k=4; v_{wind} = 0,0797 \dot{V}^{1,6730} + 0,8699$
- $k=8; v_{wind} = 0,6777 \dot{V}$
- $k=8 \text{ with tape}; v_{wind} = 0,3680 \text{ dP} + 1,9577$

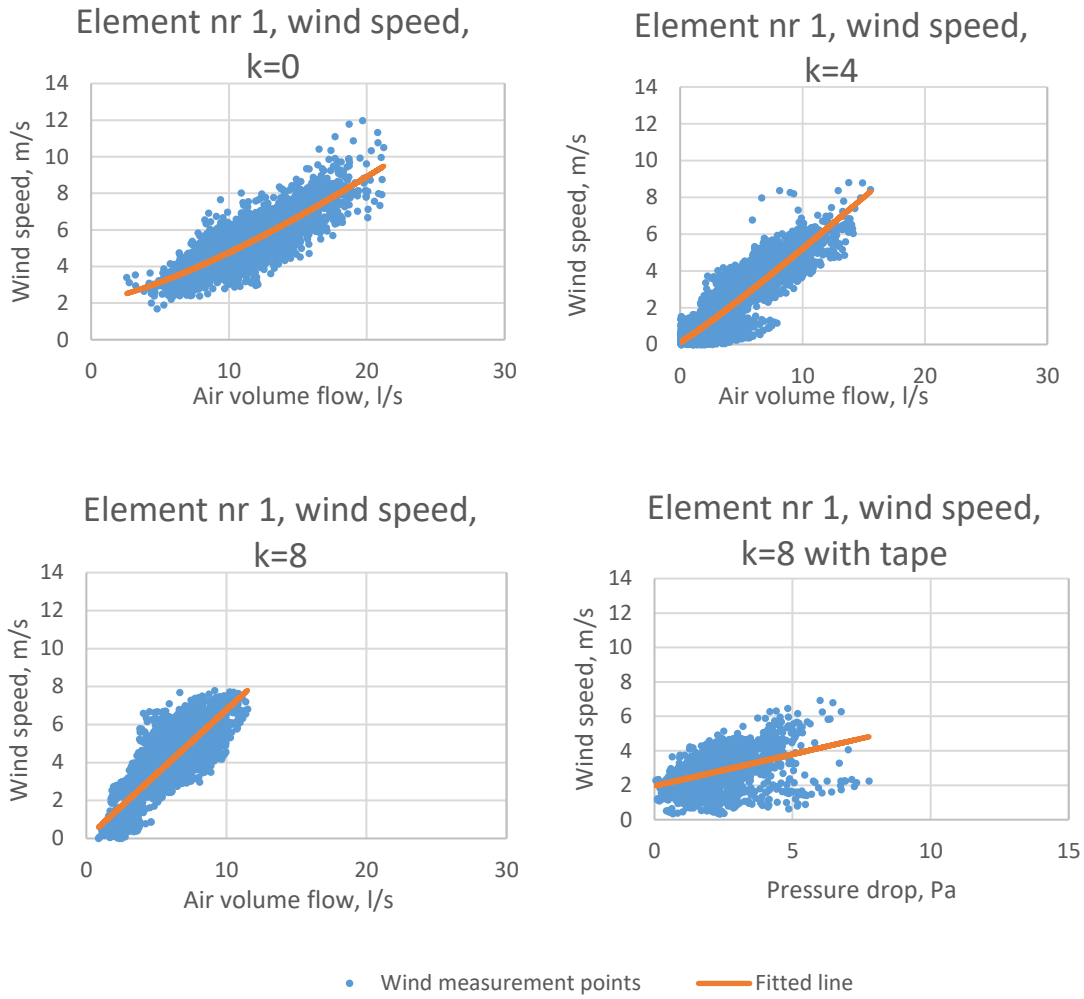


Figure 3.5 Element number 1 measured wind speeds relation to air flow and pressure drop. With the analytical wind formulas given before and system characteristics given in chapter 3.1.1 the air volume flow and pressure drop were calculated for element number 1 in reference wind speeds.

Table 3.1 Air volume flow rates and pressure drop at reference wind speeds

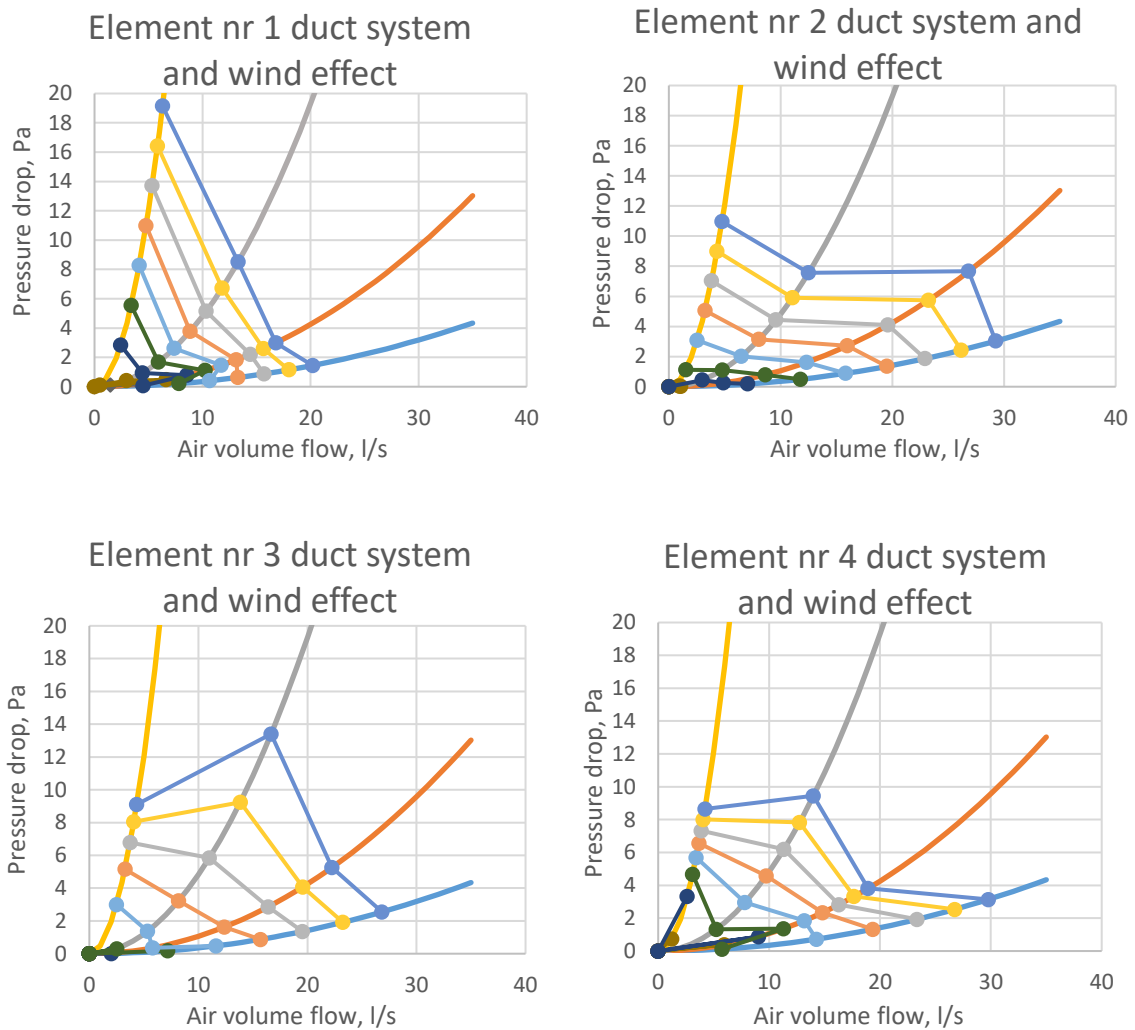


Figure 3.6 The cowl effect relative to wind speed in duct system connected to outside air. At this point of data processing it became clear that the wind direction has an impact on the results. Therefore wind direction measurements were gathered from the local weather station in Tallinn-Harku. The measurements were hourly averaged, therefore in this thesis the hourly values were averaged across the measured timespan.

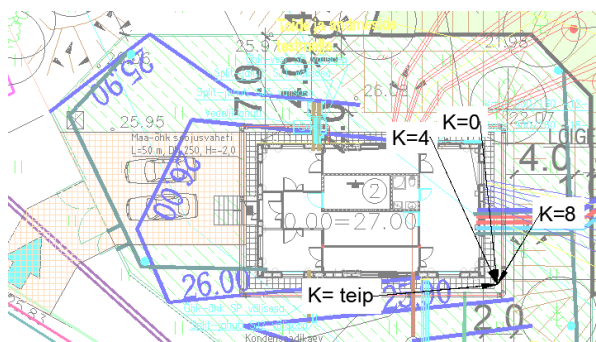


Figure 3.7 Wind direction testing element number 1 connected to duct system connected to outside air.

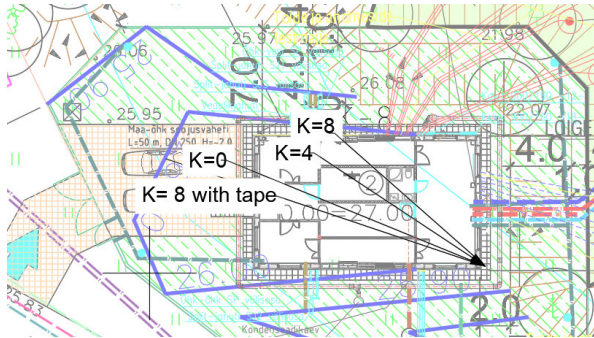


Figure 3.8 Wind direction intesting element number 2 connected to duct system connected to outside air

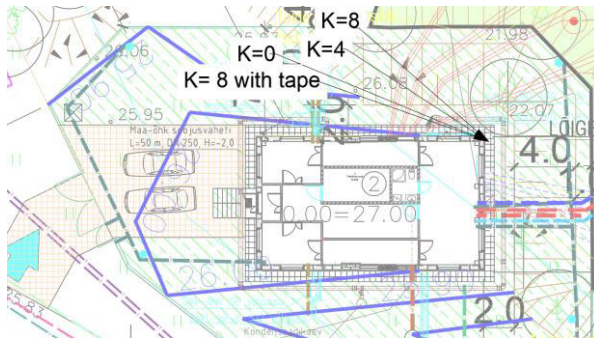


Figure 3.9 Wind direction intesting element number 3 connected to duct system connected to outside air.

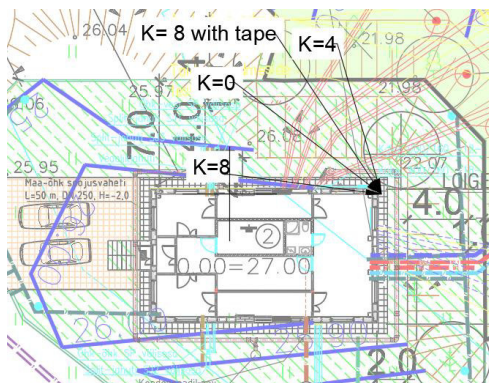


Figure 3.10 Wind direction intesting element number 4 connected to duct system connected to outside air

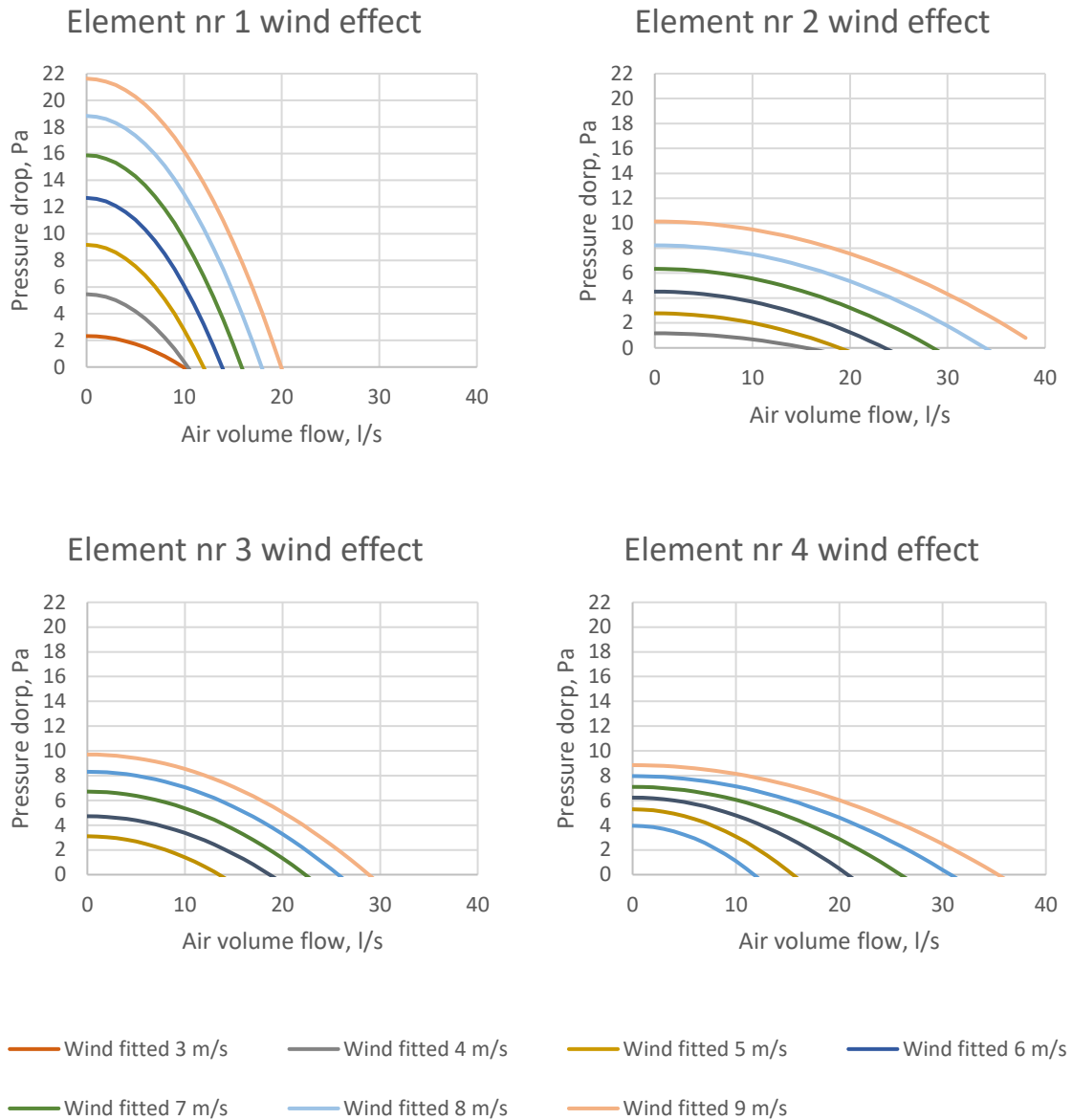


Figure 3.11 Cowls effect with analytical wind speed formulas

The results for analytical formulas for dp_0 and β are given in Figure 3.12 to Figure 3.15.

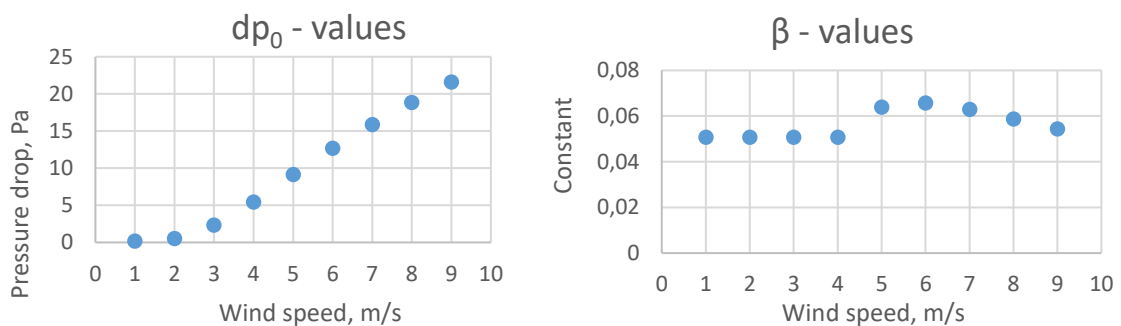


Figure 3.12 Maximum pressure drop dp_0 and constant β values for element nr 1

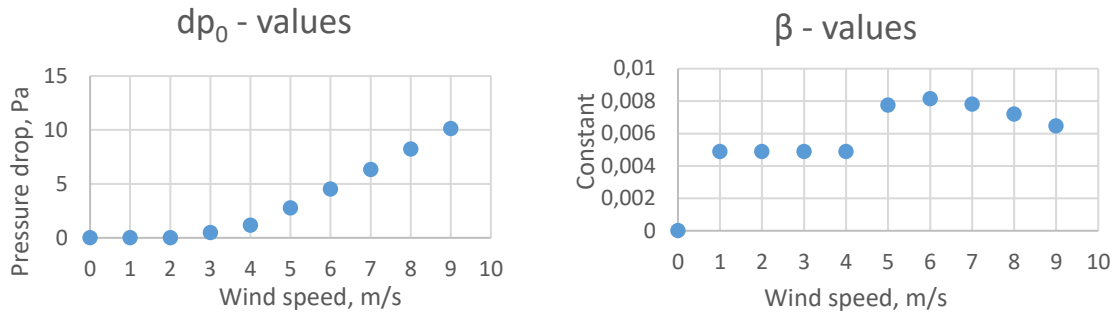


Figure 3.13 Maximum pressure drop dP_0 and constant β values for element nr 2

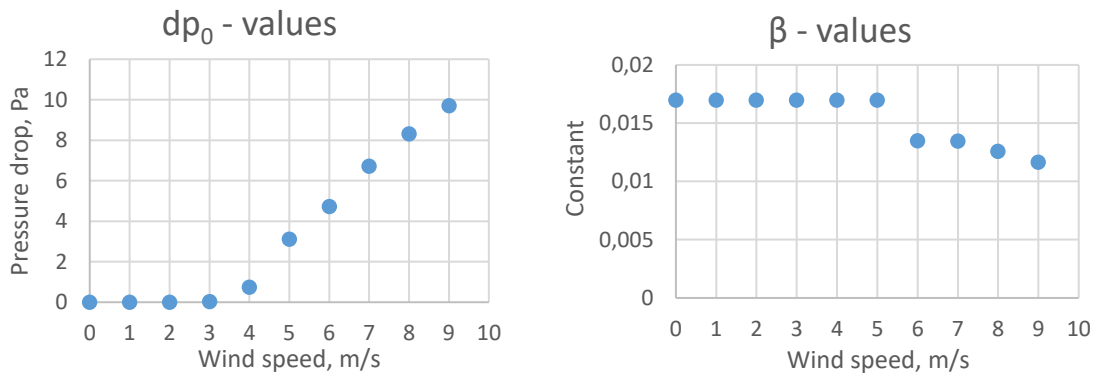


Figure 3.14 Maximum pressure drop dP_0 and constant β values for element nr 3

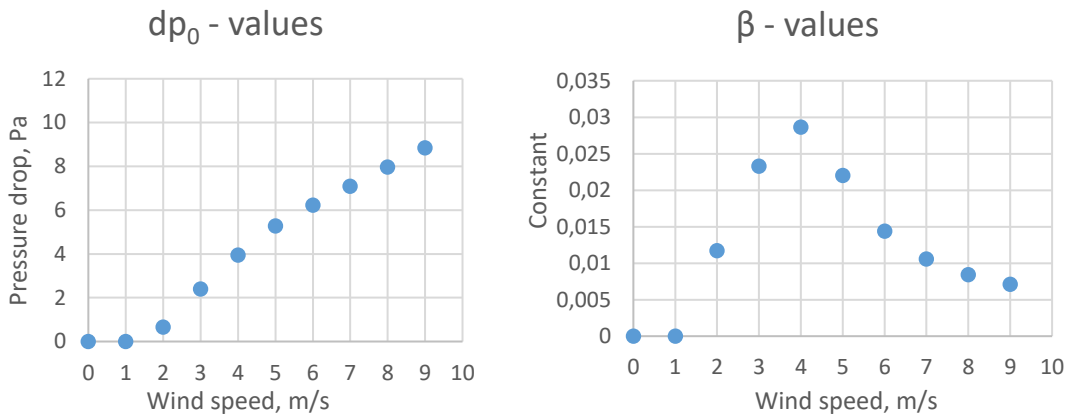


Figure 3.15 Maximum pressure drop dP_0 and constant β values for element nr 4

To calculate dP_0 and β values precisely for any wind speed analytical formulas for calculating these values were formed with a simple excel trendline command. While calculating dP_0 and β it is important to use very specific formula because the values are quite small and averaging the formulas can easily lead to wrong final answer.

Table 3.2 Element number 1 maximum pressure drop value equations

Wind speed, m/s	dP ₀
0-1	0
1-9	$dP_0 = -0,0582990268 v_{wind}^3 + 0,9928705385 v_{wind}^2 - 1,9529452951 v_{wind} + 1,0715046862$

Table 3.3 Element number 1 constant β value equations

Wind speed, m/s	β
0-4	0,05066
4-9	$\beta = 0,0006133256 v_{wind}^3 - 0,0139551921 v_{wind}^2 + 0,1005762575 v_{wind} - 0,1674260927$

Table 3.4 Element number 2 maximum pressure drop value equations

Wind speed, m/s	dP ₀
0-1	0
1-9	$dP_0 = 0,0012083000 v_{wind}^5 - 0,0316506605 v_{wind}^4 + 0,2877789760 v_{wind}^3 - 0,9097525169 v_{wind}^2 + 1,2133769992 v_{wind} - 0,5679944751$

Table 3.5 Element number 2 constant β value equations

Wind speed, m/s	β
0-4	0,004882
4-9	$\beta = -0,0000320380 v_{wind}^4 + 0,0009547647 v_{wind}^3 - 0,0106718195 v_{wind}^2 + 0,0524653687 v_{wind} - 0,0871297715$

Table 3.6 Element number 3 maximum pressure drop value equations

Wind speed, m/s	dP ₀
0-3	0
3-9	$dP_0 = 0,0149764711 v_{wind}^4 - 0,4009871313 v_{wind}^3 + 3,8433278918 v_{wind}^2 - 13,7548828278 v_{wind} + 16,2693963945$

Table 3.7 Element number 3 constant β value equations

Wind speed, m/s	β
0-5	0,01699
5-9	$\beta = 0,000214536811511 v_{wind}^4 - 0,006296782327084 v_{wind}^3 + 0,068513171229519 v_{wind}^2 - 0,328072427462423 v_{wind} + 0,597534841850911$

Table 3.8 Element number 4 maximum pressure drop value equations

Wind speed, m/s	dP_0
0-1	0
1-9	$dP_0 = -0,0018482312 v_{wind}^5 + 0,0535067443 v_{wind}^4 - 0,5774267986 v_{wind}^3 + 2,7754698370 v_{wind}^2 - 4,3365147607 v_{wind} + 2,0810795995$

Table 3.9 Element number 4 constant β value equations

Wind speed, m/s	β
0-1	0
1-4	$-0,0010118433 v_{wind}^3 + 0,0060001379 v_{wind}^2 + 0,0007866306 v_{wind} - 0,0057749252$
4-9	$\beta = 0,0000676453 v_{wind}^5 - 0,0023177045 v_{wind}^4 + 0,0311586840 v_{wind}^3 - 0,2041511251 v_{wind}^2 + 0,643154060 v_{wind} - 0,7476745651$

3.2.2 Results of the validation of cowl with duct systems that are connected to the outside air.

To validate the accuracy of the created model the results were compared to the original measurement results of the element. The results are given in Figure 3.16.

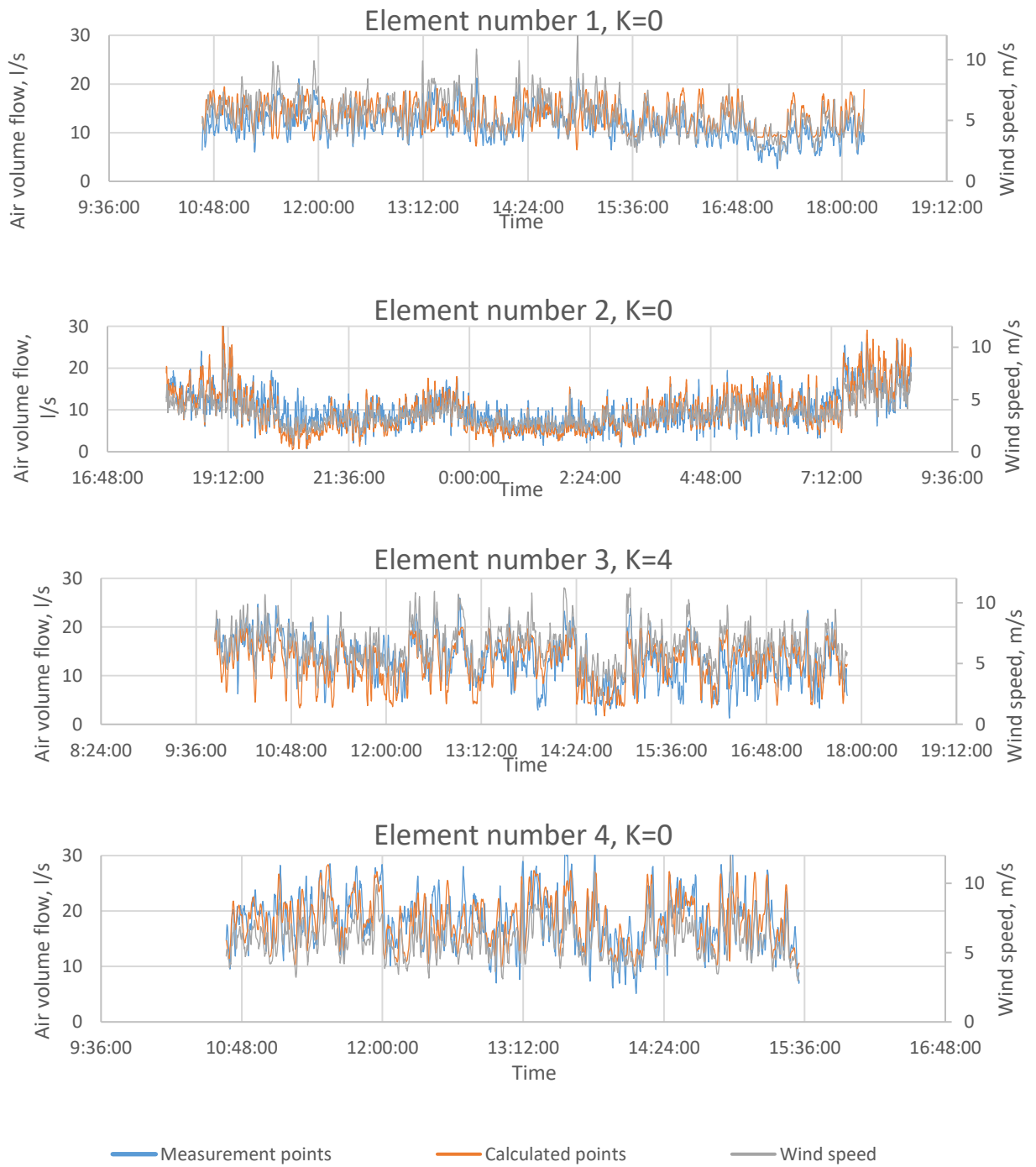


Figure 3.16 Calculated and measured airflow rates with duct system that is connected to outside air.

On average the calculated results were 109% of the measured results, which is acceptable.

3.3 Results of the validation of the cowl with duct systems that are connected to the inside air.

3.3.1 Validation on cowl number 1

As described in chapter 2.4 the measured and calculated airflow rates were analysed to see if the test were correct and the results are similar. The following figures illustrate each tested cowl validation results.

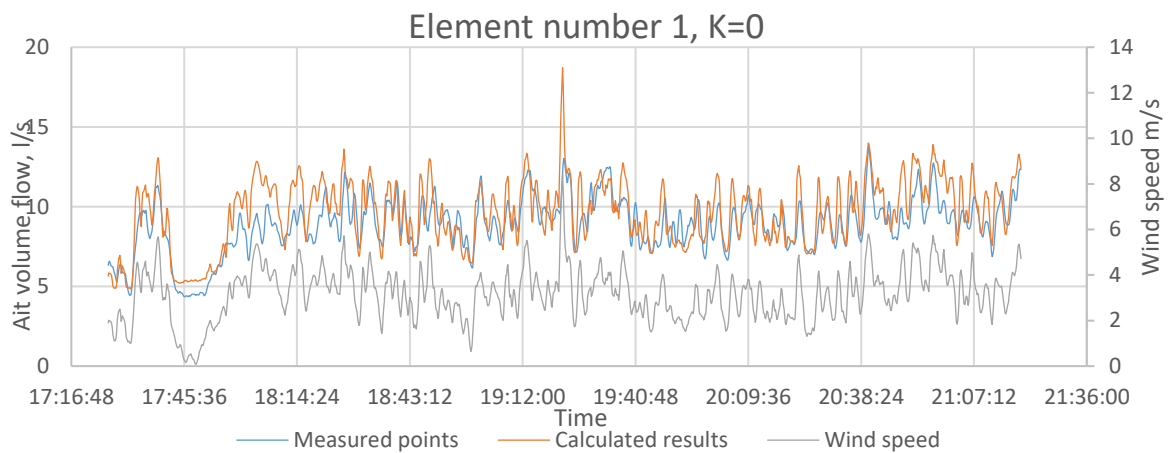


Figure 3.17 Element number 1 K=0 measured and calculated air flow rates and measured wind speed.

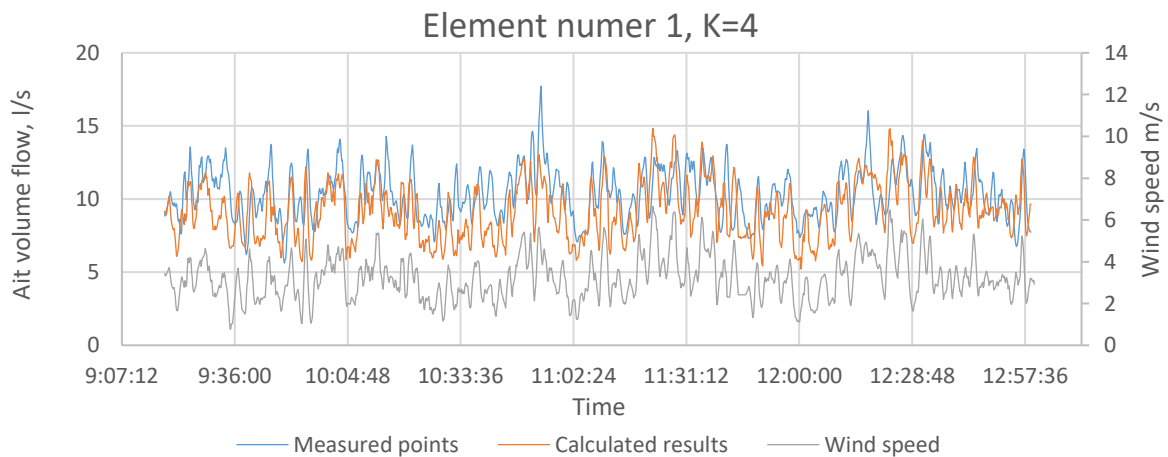


Figure 3.18 Element number 1 K=4 measured and calculated air flow rates and measured wind speed.

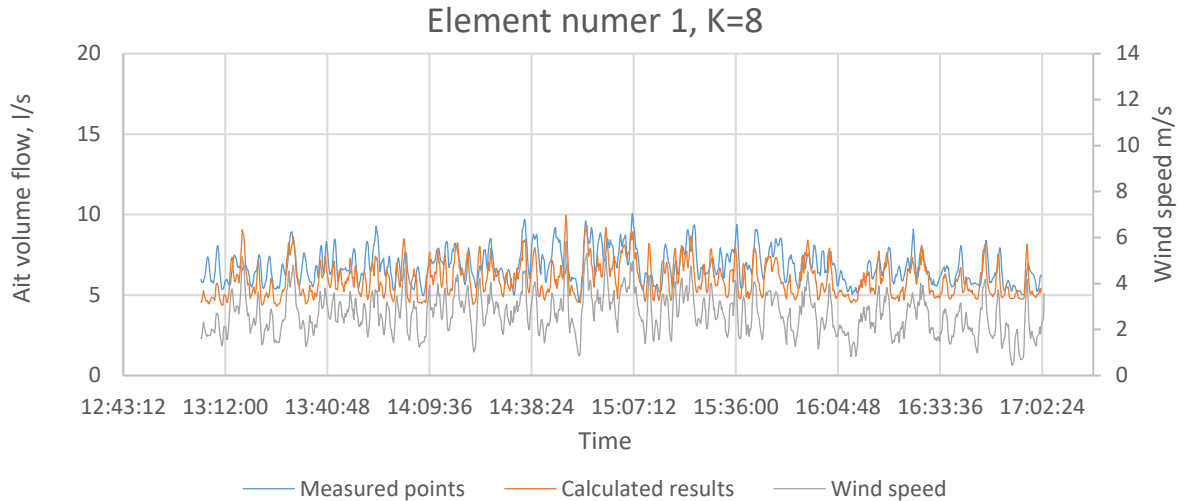


Figure 3.19 Element number 1 K=8 measured and calculated air flow rates and measured wind speed.

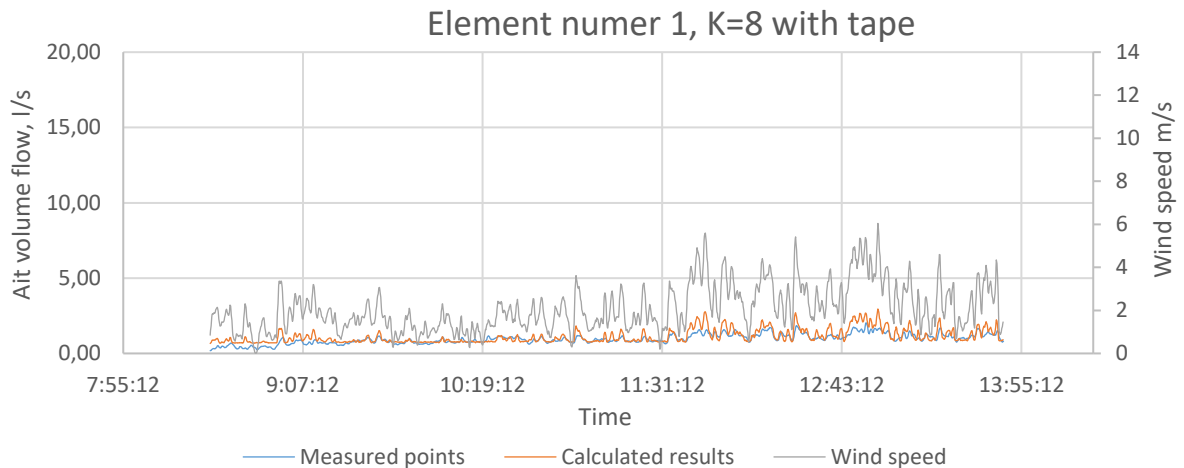


Figure 3.20 Element number 1 K=8 with tape measured and calculated air flow rates and measured wind speed.

On average over all the measured points the calculated results were 103% of the measured airflow, with the closest results were with K=0 with 109% and the biggest difference was with K=8 with tape with 122%. The measurements differed from 122% to 89%. Measurement with K=8 with tape was conducted with low wind speeds and the cowl effect at low wind speeds is difficult to calculate.

For absolute values the differences were:

- K=0,
 - Measured average air volume flow – 8,9 l/s
 - Calculated average air volume flow – 9,6 l/s
 - Stack effect – 16,7 l/s
 - Cowl – -7,8 l/s
- K=4
 - Measured average air volume flow – 10,4 l/s
 - Calculated average air volume flow – 9,2 l/s
 - Stack effect – 13,6 l/s
 - Cowl – -3,2 l/s
- K=8
 - Measured average air volume flow – 6,8 l/s
 - Calculated average air volume flow – 6,0 l/s
 - Stack effect – 5,8 l/s
 - Cowl – 0,2 l/s
- K=8 with tape
 - Measured average air volume flow – 1,0 l/s
 - Calculated average air volume flow – 1,1 l/s
 - Stack effect – 0,9 l/s
 - Cowl – 0,1 l/s

For more extensive evaluation the measured and calculated results were plotted on one chart. If the calculated and measured values would match the plot should show a correlation between two data sets (fitted line equation should have 1x as the first component).

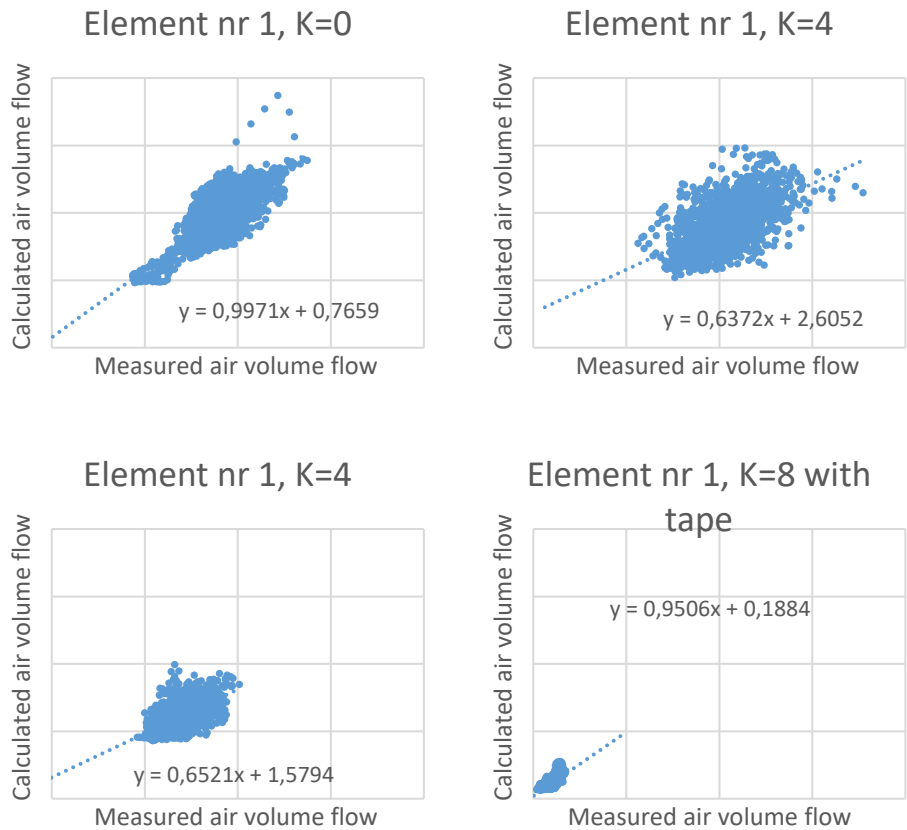


Figure 3.21 Element number 1 measurements relative to calculated results.

As is seen from the plotted results the calculated and measured results differ from each other significantly with K=4, K=8 and K=8 with tape. Most likely it is caused by wind direction influence to cowl characteristics calculation. Nevertheless, the in Figure 3.17 to Figure 3.20 we can see that the calculated and measured airflows are not too far off, therefore the model is still usable to evaluate the effect of the cowl in the measured room over a period of time.

3.3.2 Validation on cowl number 2

As described in chapter 2.4 the measured and calculated airflow rates were analysed to see if the test were correct and the results are similar. The following figures illustrate each tested cowl validation results.

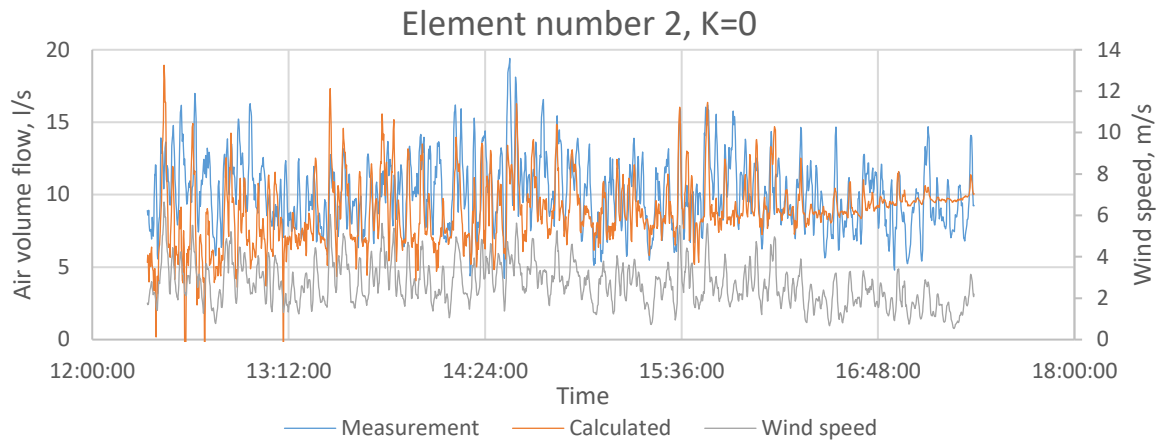


Figure 3.22 Element number 2 K=0 measured and calculated air flow rates and measured wind speed.

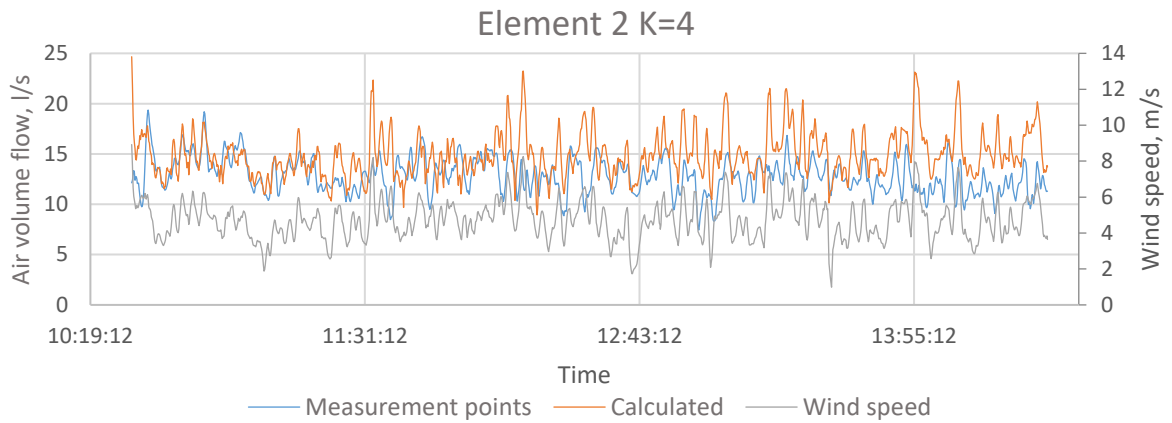


Figure 3.23 Element number 2 K=4 measured and calculated air flow rates and measured wind speed.

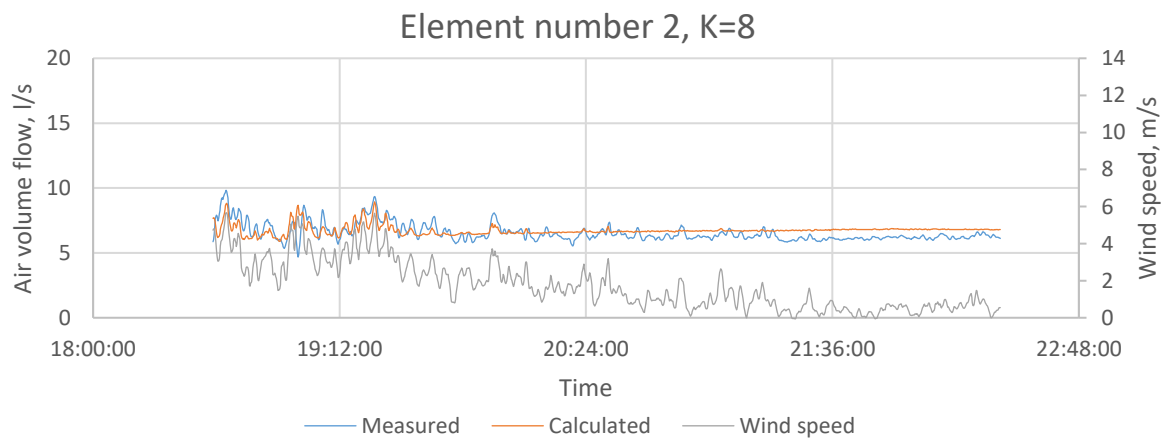


Figure 3.24 Element number 2 K=8 measured and calculated air flow rates and measured wind speed.

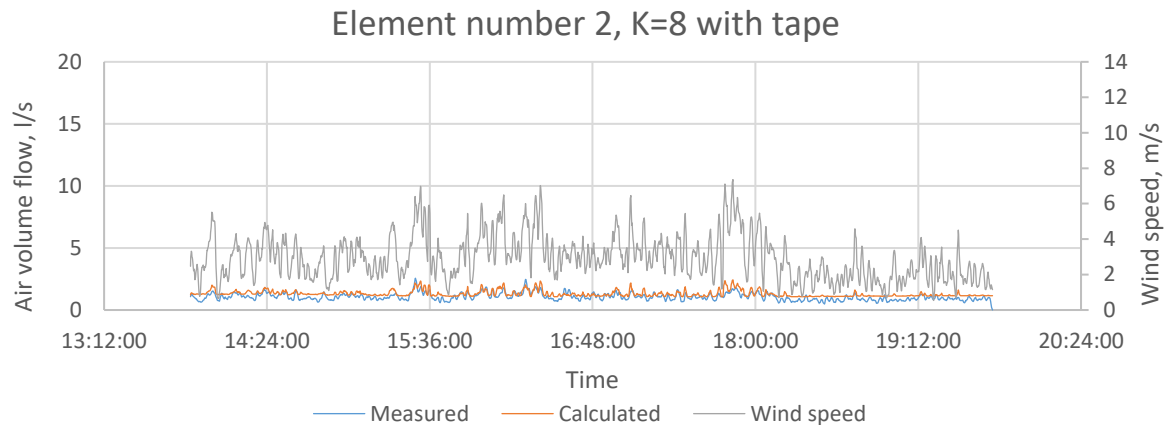


Figure 3.25 Element number 2 K=8 with tape measured and calculated air flow rates and measured wind speed.

On average the calculated results were 112% of the measured airflow, with the closest results were with K=8 with 104% and the biggest difference was with K=8 with tape with 137%. The measurements differed from 137% to 90%. Measurement with K=8 with tape was conducted with low wind speeds and the cowl effect at low wind speeds is difficult to calculate. There is also possibility that the wind direction had a big influence to cowl characteristics calculation.

For absolute values the differences were:

- K=0,
 - Measured average air volume flow – 10,1 l/s
 - Calculated average air volume flow – 8,8 l/s
 - Stack effect – 1,7 l/s
 - Cowl – 7,1 l/s
- K=4
 - Measured average air volume flow – 12,8 l/s
 - Calculated average air volume flow – 14,9 l/s
 - Stack effect – 12,4 l/s
 - Cowl – 2,5 l/s
- K=8
 - Measured average air volume flow – 6,6 l/s

- Calculated average air volume flow – 6,7 l/s
 - Stack effect – 6,7 l/s
 - Cowl – 0 l/s
- K=8 with tape
 - Measured average air volume flow – 1,1 l/s
 - Calculated average air volume flow – 1,3 l/s
 - Stack effect – 1,1 l/s
 - Cowl – 0,2 l/s

For more extensive evaluation the measured and calculated results were plotted on one chart. If the calculated and measured values would match the plot should show a correlation between two data sets (fitted line equation should have 1x as the first component).

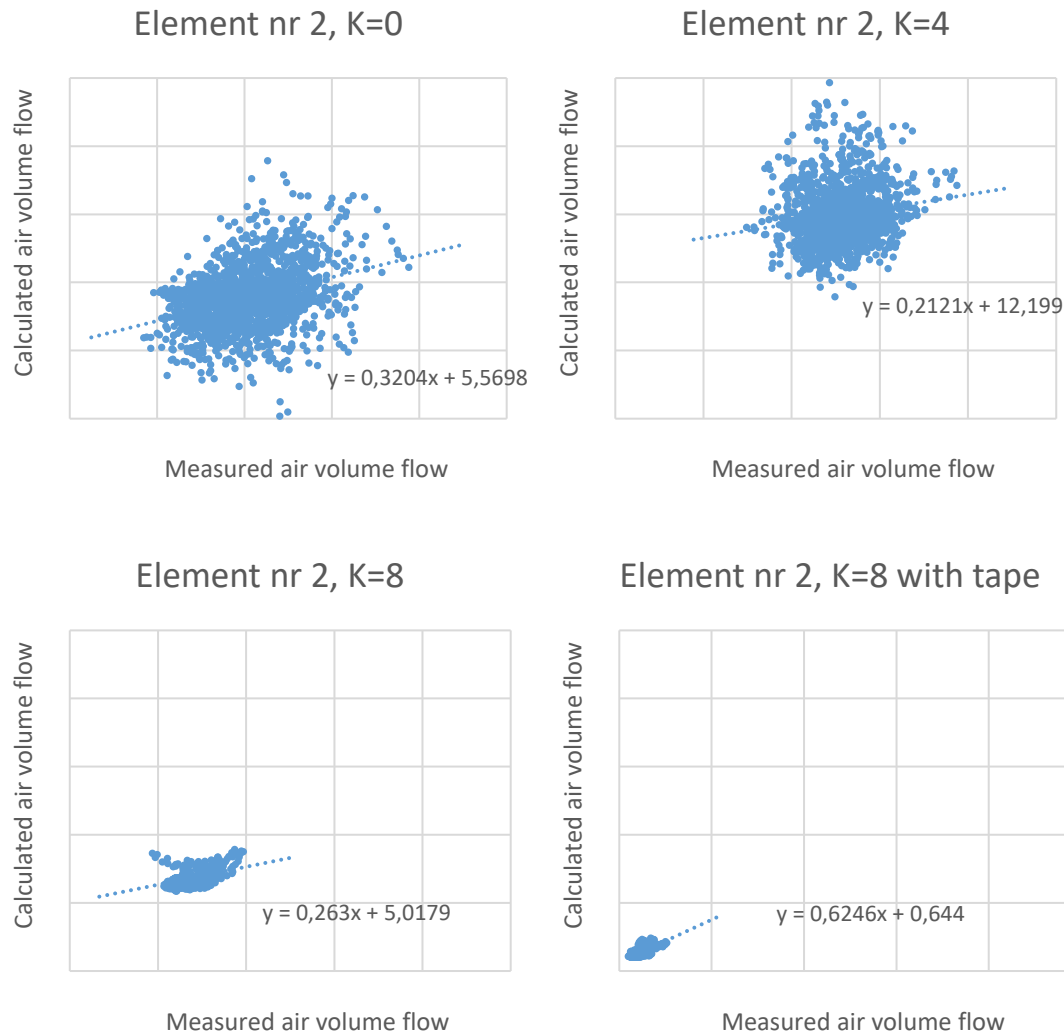


Figure 3.26 Element number 2 measurements relative to calculated results.

As is seen from the plotted results the calculated and measured results differ from each other significantly. Most likely it is caused by wind direction influence to cowl effect calculation. Also it is seen from Figure 3.22 to Figure 3.25 that the calculated airflow was around the measured airflow but there is no exact match. Therefore it can be said that to estimate roughly the airflow with cowl number 2 the model can be used, but for accurate calculation this model can not be used.

3.3.3 Validation on cowl number 3

As described in chapter 2.4 the measured and calculated airflow rates were analysed to see if the test were correct and the results are similar. The following figures illustrate each tested cowl validation results.

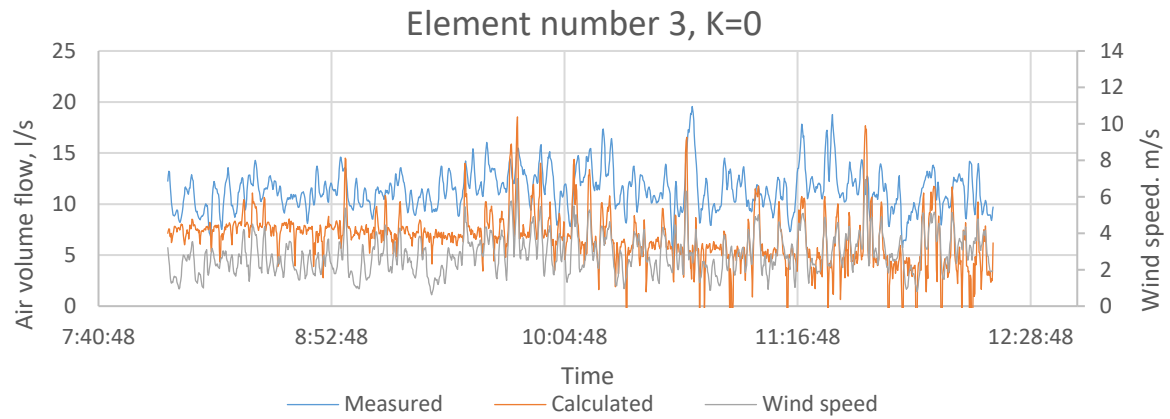


Figure 3.27 Element number 3 K=0 measured and calculated air flow rates and measured wind speed.

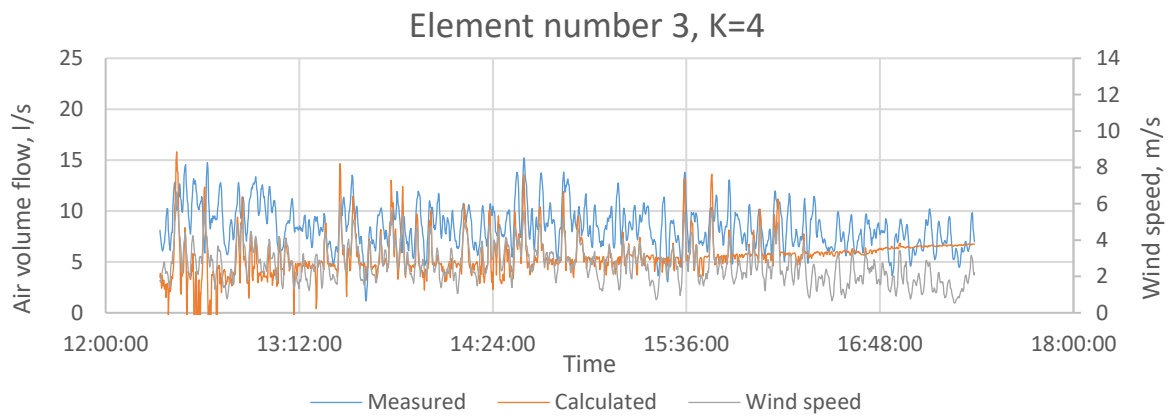


Figure 3.28 Element number 3 K=4 measured and calculated air flow rates and measured wind speed.

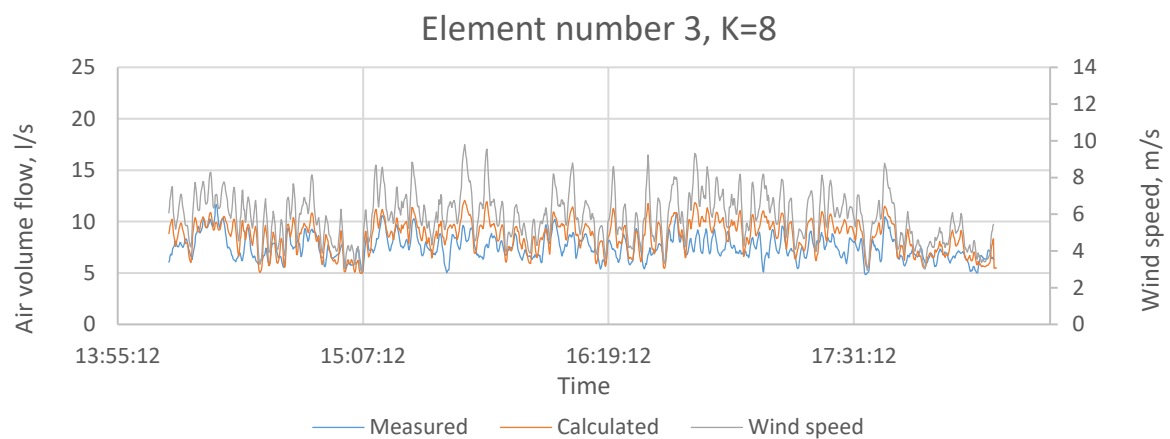


Figure 3.29 Element number 3 K=8 measured and calculated air flow rates and measured wind speed.

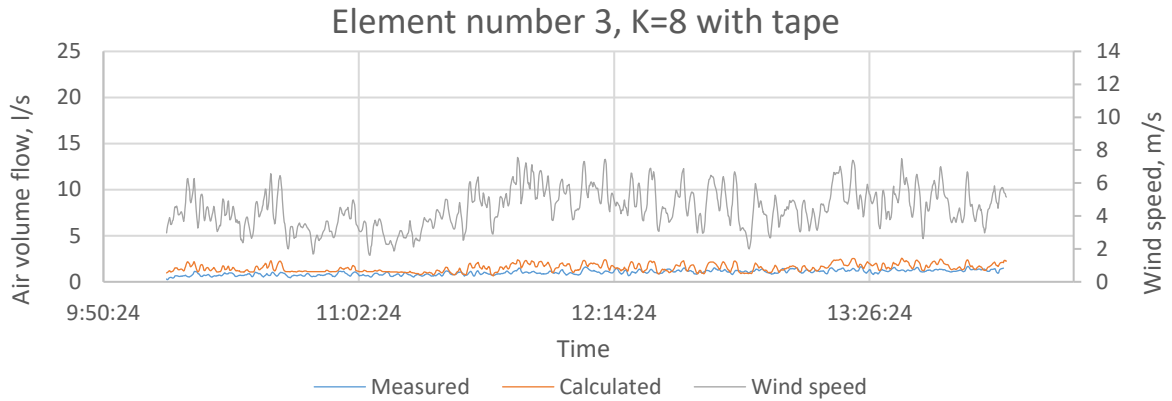


Figure 3.30 Element number 3 K=8 with tape measured and calculated air flow rates and measured wind speed.

On average the calculated results were 100% of the measured airflow, with the closest results were with K=8 with 115% and the biggest difference was with K=8 with tape with 157%. The measurements differed from 157% to 59%. The average calculated result in this cowl can not be considered true, because K=0 and K=4 measurements were significantly under the measured value (59% and 69%) and K=8 and K=8 with tape were significantly over the measured value (115% and 157%).

For absolute values the differences were:

- K=0,
 - Measured average air volume flow – 11,4 l/s
 - Calculated average air volume flow – 6,6 l/s
 - Stack effect – 9,4 l/s
 - Cowl – -2,8 l/s
- K=4
 - Measured average air volume flow – 8,5 l/s
 - Calculated average air volume flow – 5,6 l/s
 - Stack effect – 7,3 l/s
 - Cowl – -1,7l/s

- K=8
 - Measured average air volume flow – 7,5 l/s
 - Calculated average air volume flow – 8,6 l/s
 - Stack effect – 5,8 l/s
 - Cowl – 2,8 l/s
- K=8 with tape
 - Measured average air volume flow – 1,0 l/s
 - Calculated average air volume flow – 1,5 l/s
 - Stack effect – 1,0 l/s
 - Cowl – 0,5 l/s

For more extensive evaluation the measured and calculated results were plotted on one chart. If the calculated and measured values would match the plot should show a correlation between two data sets (fitted line equation should have 1x as the first component).

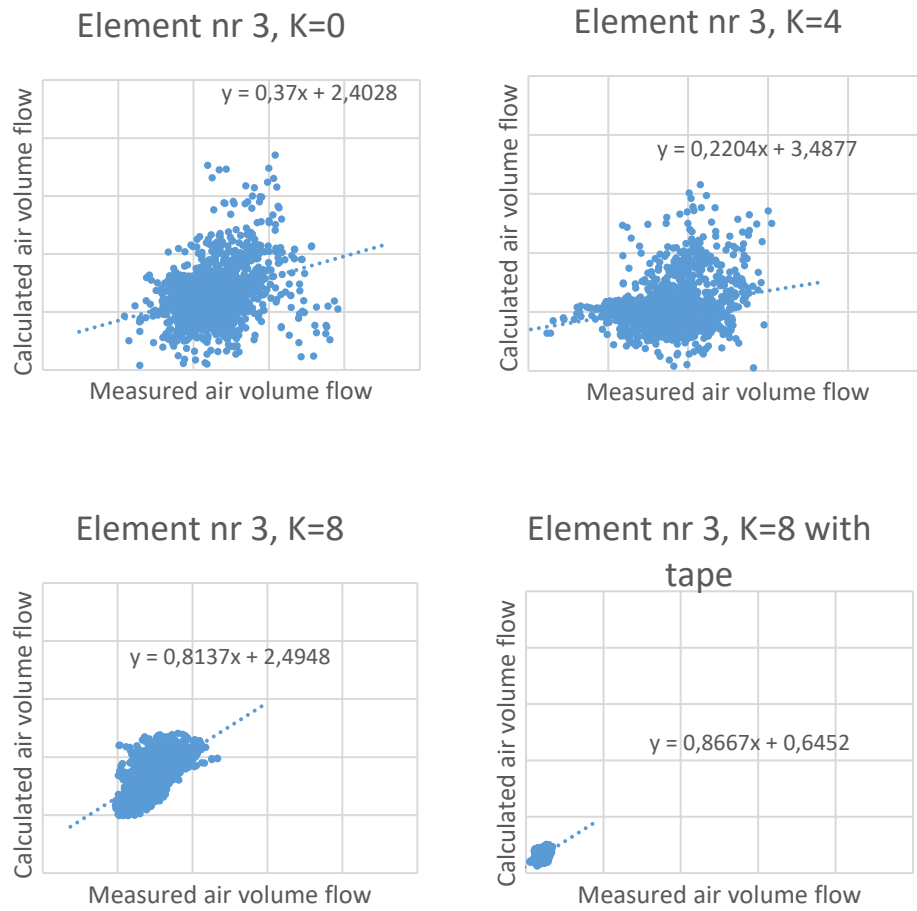


Figure 3.31 Element number 3 measurements relative to calculated results.

As is seen from the plotted results the calculated and measured results differ from each other significantly. Most likely it is caused by wind direction influence to cowl effect calculation. Also it is seen from Figure 3.27 to Figure 3.30 that the calculated airflow was around the measured airflow but there is no exact match. Therefore it can be said that to estimate the airflow with cowl number 2 the model can be used, but for accurate calculation this model can not be used.

3.3.4 Validation on cowl number 3

As described in chapter 2.4 the measured and calculated airflow rates were analysed to see if the test were correct and the results are similar. The following figures illustrate each tested cowl validation results.

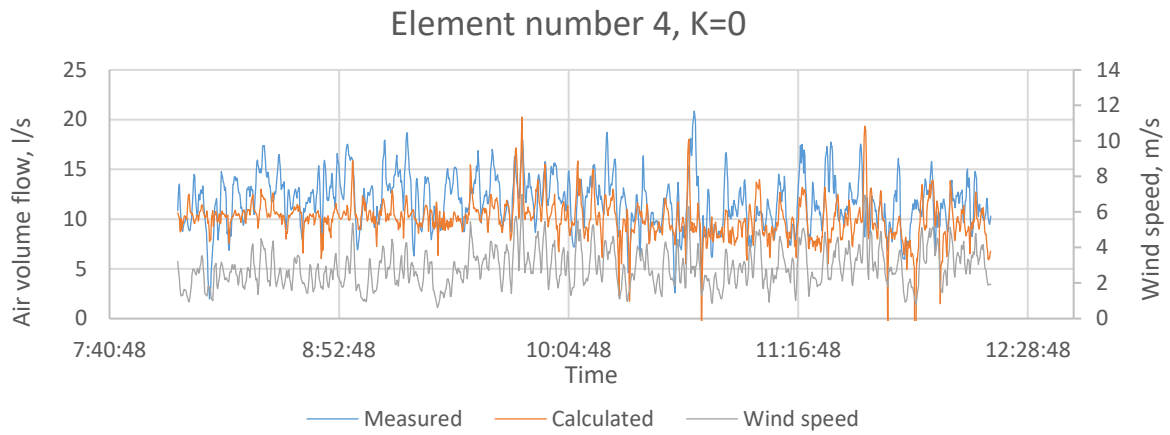


Figure 3.32 Element number 4 K=0 measured and calculated air flow rates and measured wind speed.

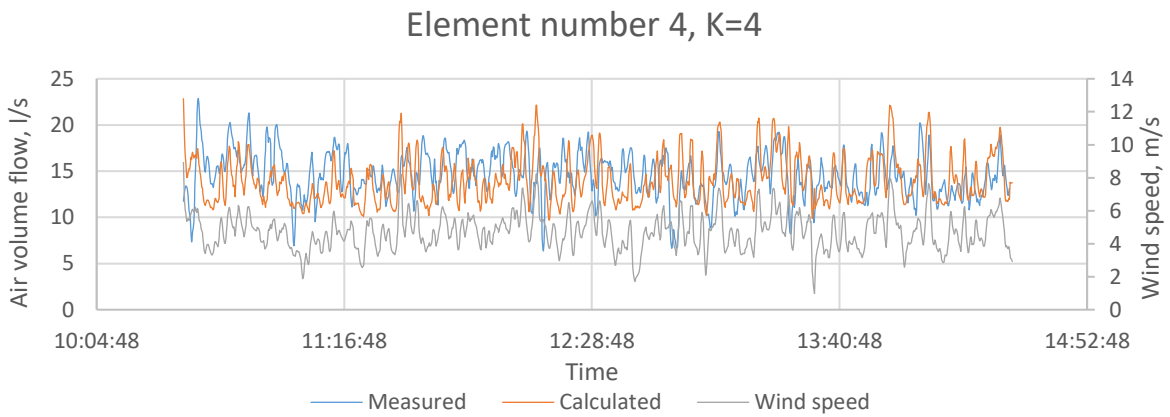


Figure 3.33 Element number 4 K=4 measured and calculated air flow rates and measured wind speed.

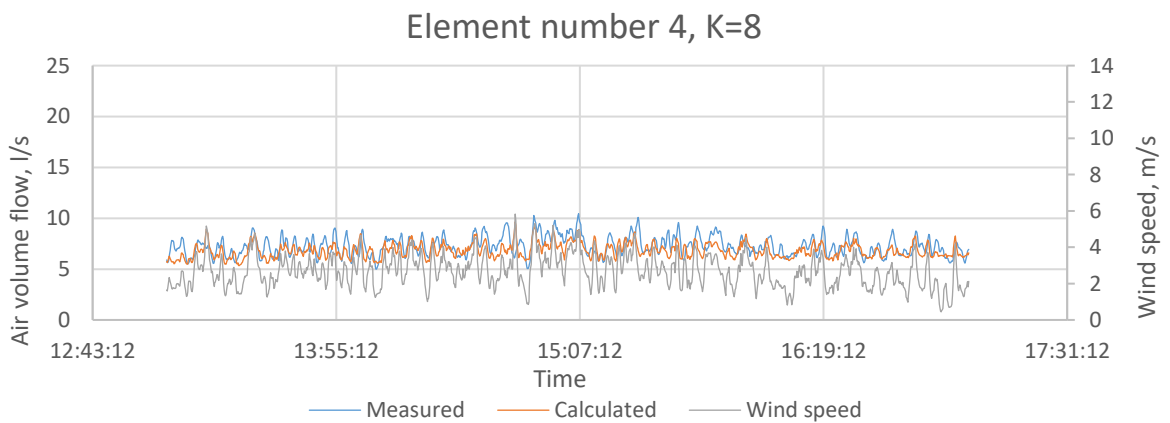


Figure 3.34 Element number 4 K=8 measured and calculated air flow rates and measured wind speed.

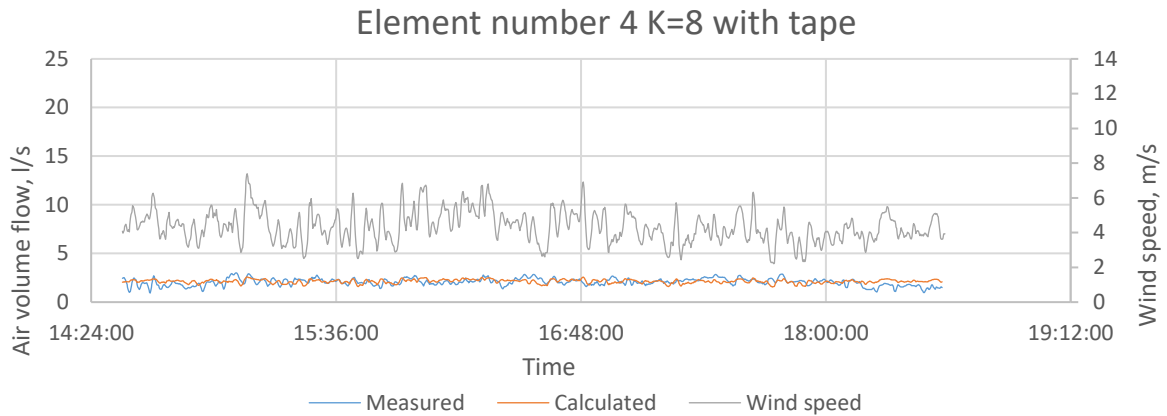


Figure 3.35 Element number 4 K=8 with tape measured and calculated air flow rates and measured wind speed.

On average the calculated results were 97% of the measured airflow, with the closest results were with K=4 with 98% and the biggest difference was with K=0 with 89%. The measurements differed from 107% to 89%.

For absolute values the differences were:

- K=0,
 - Measured average air volume flow – 11,8 l/s
 - Calculated average air volume flow – 10,0 l/s
 - Stack effect – 9,1 l/s
 - Cowl – 0,9 l/s
- K=4
 - Measured average air volume flow – 14,6 l/s
 - Calculated average air volume flow – 14,0 l/s
 - Stack effect – 12,1 l/s
 - Cowl – 1,9 l/s
- K=8
 - Measured average air volume flow – 7,3 l/s
 - Calculated average air volume flow – 6,8 l/s
 - Stack effect – 5,9 l/s

- Cowl – 0,9 l/s
- K=8 with tape
 - Measured average air volume flow – 2,06 l/s
 - Calculated average air volume flow – 2,13 l/s
 - Stack effect – 1,3 l/s
 - Cowl – 0,8 l/s

For more extensive evaluation the measured and calculated results were plotted on one chart. If the calculated and measured values would match the plot should show a correlation between two data sets (fitted line equation should have 1x as the first component).

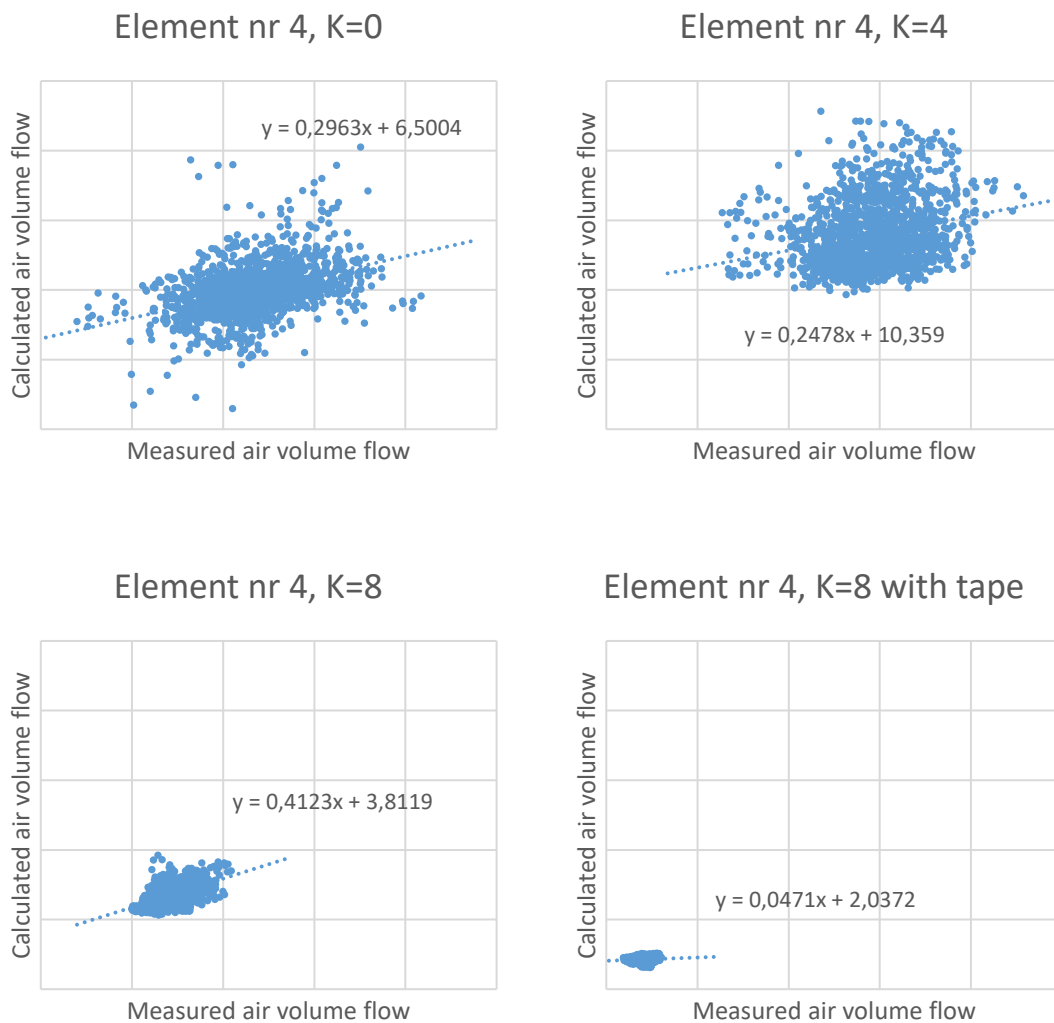


Figure 3.36 Element number 4 measurements relative to calculated results.

As is seen from the plotted results the calculated and measured results differ from each other significantly. Most likely it is caused by wind direction influence to cowl effect calculation. Also it is seen from Figure 3.32 to Figure 3.35 that the calculated airflow was around the measured airflow but there is no exact match. Therefore it can be said that to estimate the airflow with cowl number 4 the model can be used, but for accurate calculation this model can not be used.

SUMMARY

The aim for this thesis was to evaluate the tested cowl efficiency with field measurements. The second aim was to find the connection how to calculate the total airflow caused by stack effect and the cowl. The main goal of this thesis was to develop usable model to use in the design process of natural ventilation systems.

The first step was to design and construct the test installations. The design was based on European Standard prEN 13141-5:2019 "Ventilation for buildings – Performance testing of components/products for residential ventilation – Part 5: Cowls, assisted cowls and for outlet terminal devices", the test installation described in the standard was modified to suit field measurements. Construction of the test installation was done by the author of this thesis in Tallinn University of Technology nZEB test facility in Tallinn, Estonia.

There was constructed four chimneys – two connected to indoor air and two connected to outdoor air. With the test installations connected to outside air the characteristics for tested cowls was found by measuring airflow, pressure drop through the test installation and wind speed in system that was not influenced by stack effect.

To validate the composed characteristics the results were compared with measurements from the test installation connected to inside air. The stack effect was calculated using temperature difference between exhaust air and outside air. To find the total airflow through the natural ventilation system the stack effect and cowl effect was added together. It was found that to add together stack effect and cowl effect the pressure difference from stack effect and the maximum pressure drop for the cowl at the calculated wind speed have to be added together and by solving equation system between duct system characteristics and cowl effect at calculated wind speed the total air flow and pressure drop can be found. It was found that in some cases the cowl was a pressure drop in the system and had a negative effect on the air flow rate. This was seen with low wind speeds.

From the validation it was found that the calculated results were significantly different from the measurement results. For element number 1 the calculated results differed from 122% to 89%, element number 2 had differences between 137% to 90%, element number 3 had differences between 157% and 59% and element number 4 had differences between 107% and 89%.

To evaluate the validation results more a simple chart was created where the measured and calculated airflows were compared. If the calculated results would

match the measurement result exactly the results should form a correlation on the chart, this can be also expressed by the trendline equation having constant 1 in front of the variable x .

As it can be seen from the results do not match with measurement results very well. The reason behind this is probably that the cowl characteristics calculation had wrong input data caused by wind directions influence on the open end of the test installation. Therefore the conclusion can be made that cowl characteristics has to be evaluated in closed conditions in wind tunnels to get more accurate results. At the same time as it was seen from the comparison of the absolute average air flow values the cowl had little positive effect together with stack effect in our measurements. For future research the cowl effect to total air flow could be measured over longer period of time and with different stack effect to get a more accurate result for the cowl effect and also the cowl characteristics should be evaluated based on wind tunnel testing.

EESTIKEELNE KOKKUVÕTE

Lõputöö eesmärgiks oli hinnata testitud heitõhuotsikute tõhusust välimõõtmisega. Lisaks uuriti temperatuuri erinevusest tingitud õhuvahetuse ja heitõhuotsiku tööst tingitud õhuvahetuse liitumist, eesmärgiga välja töötada mudel mida kasutada loomuliku ventilatsiooni süsteemide projekteerimisel õhuvoolu hulkade hindamiseks.

Kõigepealt projekteeriti ja ehitati testinstallatsioon. Projekteerimise aluseks oli Euroopa Standard prEN 13141-5:2009 „Hoonete ventilatsioon – Elamute ventilatsiooniseadmete ja -komponentide katsetamine – Osa 5: Otskatted ja väljaviskeotsikud“. Standardis kirjeldatud tüüpne testinstallatsioon projekteeriti sobivaks välimõõtmistele. Testinstallatsioon ehitati autori poolt Tallinna Tehnikaülikooli liginullenergia testhoonesse, mis asub Tallinnas.

Kokku ehitati 4 erinevat heitõhu korstnend – kaks ühenduses hoone siseõhuga, kaks välisõhuga.

Testinstallatsiooni, mis oli ühendatud välisõhuga kasutati heitõhuotsikute töö iseloomustamiseks mõõtes süsteemis õhuvoolu hulka, rõhulangu ja objektil olnud tuule kiirust. Installatsiooni eesmärk oli määrata heitõhuotsikute tööd süsteemis, kus puudub temperatuuri erinevusest tingitud õhuvool.

Koostatud iseloomustuse valideerimiseks võrreldi karakteristikku abil arvatud õhuvooluhulki mõõdetud õhuvooluhulkadega süsteemis mis oli ühendatud hoone siseõhuga. Temperatuuri erinevusest tingitud õhuvahetus arvutati kasutades heitõhu temperatuuri ja ruumiõhu temperatuuri erinevust. Kogu vooluhulga leidmiseks tuli kokku liita temperatuuri erinevusest ja heitõhu otsiku poolt tingitud õhuvahetus. Leiti, et selleks tuleb kokku liita temperatuuri erinevusest tingitud rõhkude erinevus süsteemi otstes ja maksimaalne heitõhuotsiku poolt tekitatud rõhulang süsteemis ja seejärel lahendada võrrandsüsteem ventilatsioonisüsteemi karakteristikku ja heitõhuotsiku karakteristikku valemitega. Tulemustest selgus et madalatel tuule kiirustel tekitas heitõhuotsik süsteemis lisarõhukadu ja mõjutas ruumi õhuvahetust negatiivselt.

Valideerimisest selgus, et arvatud tulemused erinesid olulisel määral mõõtmistulemustes. Elemendi number 1 puhul oli arvatud vooluhulgad vahemikus 89% kuni 122% mõõdetud tulemustest, elemendi number 2 puhul 90% kuni 137%, elemendi 3 puhul 59% kuni 157% ja elemendi number 4 puhul 89% kuni 107%.

Saadud karakteristikute edasiseks valideerimiseks koostati lihtne graafik kus võrreldi arvatud vooluhulki ja mõõdetud vooluhulki. Kui arvatud ja mõõdetud vooluhulgad

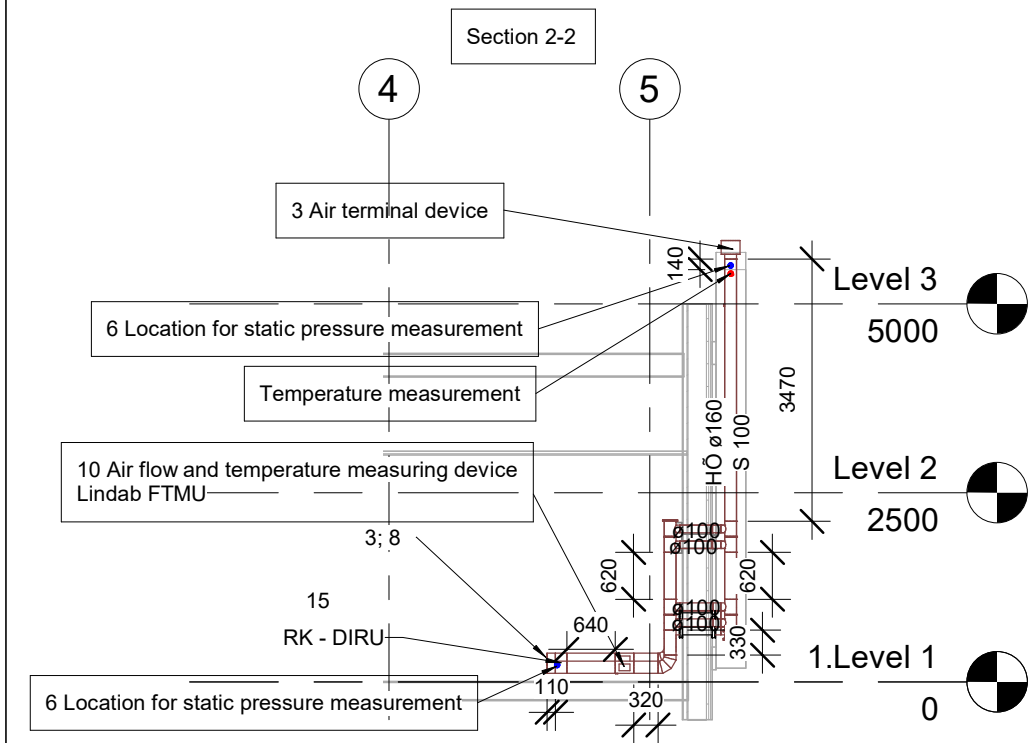
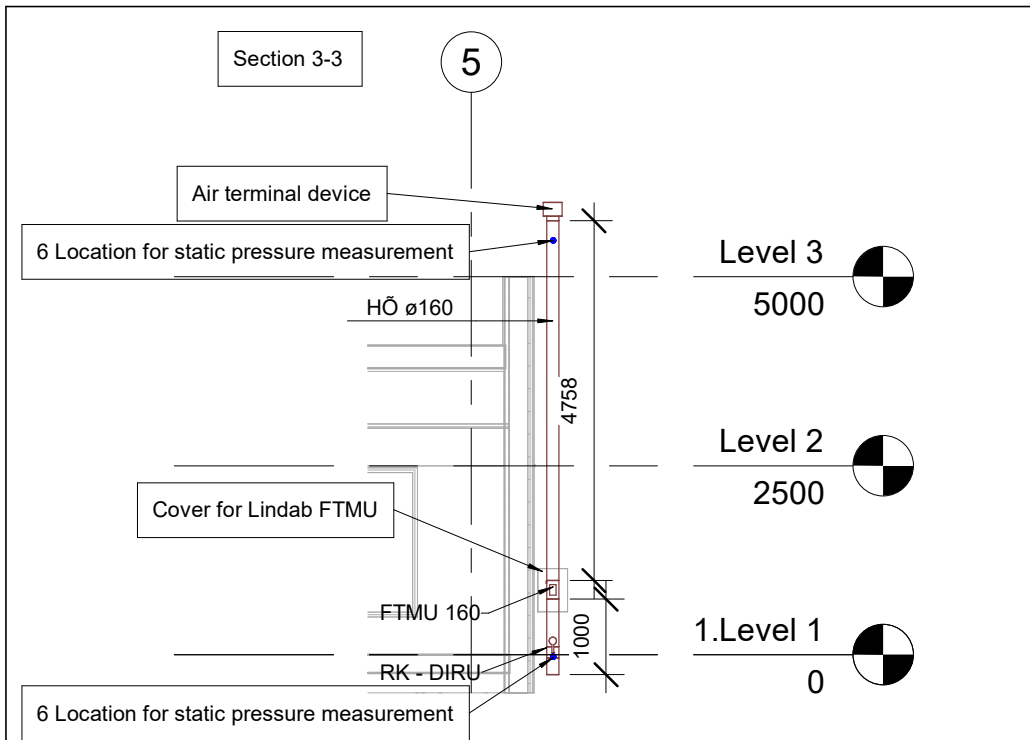
langevad kokku, peaks graafikult paistma korrelatsioon, seda saab ka valjendada kasutades trendijoone valemit, kus lineaarse funktsiooni puhul peaks muutuja „x“ kordaja olema 1.

Graafikutelt selgub, siis tulemused ei ühti omavahel hästi. Tõenäoliselt seisneb probleem selles, et heitõhuotsiku karakteristiku arvutamise lähteandmeteks olnud mõõtmised olid mõjutatud olulisel määral tuule suuna mõjust test installatsiooni vabale otsale. Seepeale saame järeldada, et heitõhuotsiku karakteristikut on vaja siiski määrata välistele elementidele suletud tingimustes tuuletunnelis, et saada täpsemad tulemused. Teisalt, nagu selgus vooluhulkade absoluutväärtuste analüüsist heitõhuotsiku positiivne mõju kogu vooluhulgale väike. Edasiseks uurimiseks tuleks määrata heitõhuotsiku mõju pikema perioodi jooksul ja erinevate temperatuurierinevusest tingitud õhuvahetuse väärtustega, et saada täpsem tulemus heitõhuotsiku efektiivsuse kohta ja otsikute efektiivsus tuleks määrata tuuletunnelis.

LIST OF REFERENCES

- [1] L. Kuuluvainen, B.-R. Lindberg, K. Lylykangas, J. Mikkola, J. Sainio, and M. Vuolle, "Painovoimainen ilmanvaihto opas," 2018.
- [2] "EVS-EN 16798-1:2019 Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoust." p. 84, 2019.

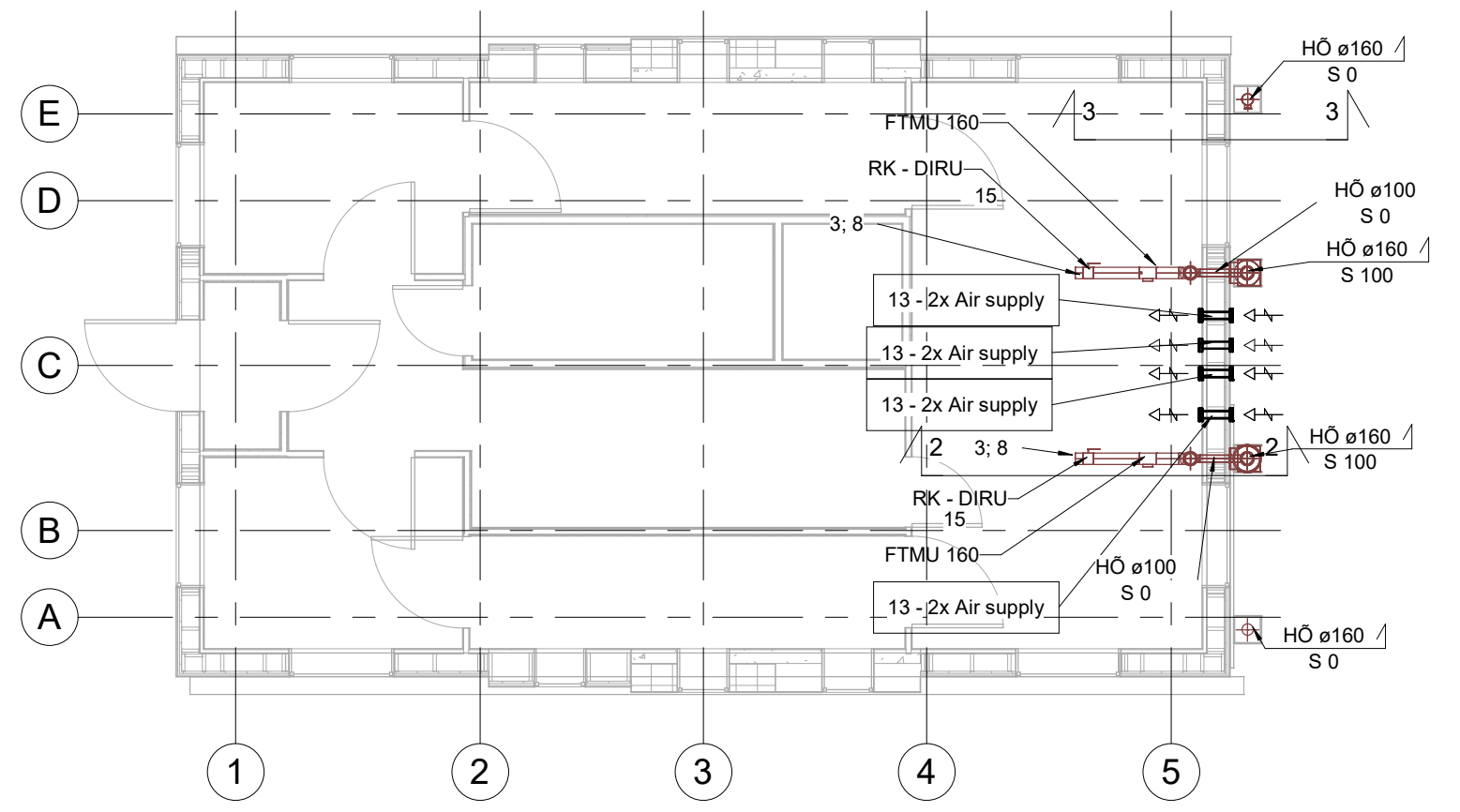
APPENDICES



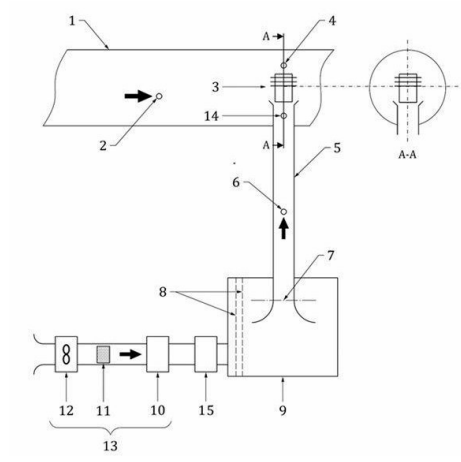
Ventilation system element tags		
Element	Abbreviation	Explanation
○ →		Supply air device
○ ←		Extract air device
⊠	RK	Pressure regulator

Ventilation system legend		
Symbol	Abbreviation	Explanation
—	VV	Exhaust

Ventilation system tags	
Tag	Explanation
KI - 125 20.0 l/s	Air terminal model - connection size Air flow
ø250 S 50	Duct size Insulation thickness (Duct moves down and/or up)



Typical example of a test installation (prEN 13141-5:2019)



- Legend:
1. Wind tunnel (tuuletunnel)
 2. Location for wind speed measurement (Tuule kiiruse mõõtja)
 3. Air terminal device (Ventilatsiooni otsik)
 4. Location for static pressure measurement (Staatilise rõhu andur)
 5. Test duct (Testi toru)
 6. location for static pressure measurement (Staatilise rõhu andur)
 7. Location of sealing for preliminary suction test (Õhutiheduse testiks toru sulgemise koht)
 8. Flow setting screens (Vooluhulga reguleerimine)
 9. Plenum chamber (Rõhualandus kamber)
 10. Air flow measuring device (Õhu vooluhulga mõõtja)
 11. Flow straightener (Voolusuunajad)
 12. Fan with flow rate adjusting device (Ventilaator vooluhulga reguleerijaga)
 13. Air Supply (Kompensatsiooniõhk)
 14. Location for static pressure at the bottom of the device (Staatilise rõhu andur katuseotsiku all)
 15. Pressure regulation device (Rõhu reguleerimise seade)

Object TalTech Testing facility			
Sheet KV-5-05			
Appendix 1 - Test installation for air terminal device			
Projekti juht Martin Thalfeldt	Stage TP	Date 05.01.2020	Scale 1:100
Projekteerija Tanel Papp	Project ID 001		