AALBORG UNIVERSITY
DENMARK

ELFORSK-PROJECT 351-020

PILOT PROJECT: MINIATURE SENSOR FOR RESISTANCE-LESS MEASUREMENT OF AIR VELOCITY

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Denne rapport udgør afrapporteringen af ELFORSK 2019 *351-020 Forprojekt: Miniatureføler til modstandsfri lufthastighedsmåling i ventilationskanaler* (Pilot project: Miniature sensor for resistanceless measurement of air velocity in ducts).
Forprojektet er gennemført af Statens Byggeforskningsinstitut ved Aalborg Universitet, København i tæt dialog med Princeton University, USA. Projektperioden var fra marts 2019 til november 2019.
Rapporten redegør for gennemførelsen og resultaterne af forprojektet. Resultaterne udgør en del af det materiale, som ligger til grund for en projektansøgning til ELFORSK 2020: *352-008 Fase 2: Miniatureføler til modstandsfri lufthastighedsmåling i ventilationskanaler*.

Dansk resume

Dette pilotprojekt introducerer en miniatureføler til modstandsfri måling af lufthastighed i ventilationskanaler. Føleren er baseret på Micro Electro-Mechanical System (MEMS), EFV - Elastic Filament Velocimetry. Formålet med pilotprojektet er at opnå eksperimentelt bevis for konceptet – at føleren kan anvendes til måling af lufthastighed i ventilationskanaler. Eksperimentelle undersøgelser og simuleringer ved anvendelse af computational fluid dynamics (CFD) er udført parallelt for at bestemme egenskaber og ydeevne for EFV-føleren. Resultaterne viste, at EFV-føleren er i stand til at måle lufthastigheder, og at føleren er i stand til at bestemme lufthastigheder under 0,1 m/s i et rør med en diameter på 1,14 mm og fra 0,4 m/s i en ventilationskanal med en diameter på 160 mm. Et unikt træk ved EFV-føleren er, at den er i stand til at måle turbulensintensitet. Tilstedeværelsen af føleren i en ventilationskanal medfører kun ubetydeligt tryktab sammenlignet med målekors, der typisk anvendes i ventilationssystemer.

Dansk konklusion

Resultaterne viser, at EFV-føleren er et lovende alternativ til måling af lufthastigheder i ventilationskanaler, uden at det medfører mærkbart tryktab i kanalsystemet. Specifikt konstateres:

- De eksperimentelle undersøgelser i laboratoriet har vist, at EFV-føleren er i stand til at måle lufthastigheder lavere end 0,1 m/s i et rør med en diameter på 1,14 mm og fra 0,4 m/s i en ventilationskanal med en diameter på 160 mm. Usikkerheden på de målte værdier er ± 0,025 m/s.
- CFD-simuleringerne indikerer, at et forøget gennemgående hul i selve EFV-føleren kan forbedre følerens egenskaber med hensyn til at måle lufthastigheder lavere end 0,4 m/s.
- Resultaterne viser, at EFV-føleren medfører et lavere tryktab i sammenligning med et traditionelt målekors, hvilket indikerer, at udskiftning af målekors med EFV-følere kan føre til en reduktion af energibehovet til ventilatordrift.
- De eksperimentelle undersøgelser har vist, at EFV-føleren er i stand til at måle turbulensintensitet, idet følerens responsfrekvens kan være 100 Hz.

Endvidere forventes det, at prisen for en EFV-føler vil være mindst 100-200 gange lavere end eksempelvis UltraLink. Den lave pris kan føre til en markant bredere anvendelse af følertypen, som derved kan bruges i algoritmer inden for kunstig intelligens til forbedring af komfort og reduktion af energibehovet i kommende ventilationssystemer.

Abstract

This pilot project introduces a miniature sensor for measuring air velocity in ventilation ducts. The sensor is based on Micro Electro-Mechanical System (MEMS), so-called EFV – Elastic Filament Velocimetry. The objective of the pilot project is to achieve experimental proof-of concept of the sensor for measuring the air velocity in ventilation ducts. Experimental investigations and simulations using computational fluid dynamics (CFD) were performed in parallel in order to determine the characteristics and the performance of the EFV-sensor. The results showed that the EFV-sensor is capable of measuring the air velocities, and that the sensor is capable of determining air velocities below 0.1 m/s in a pipe with a diameter of 1.14 mm and from 0.4 m/s in a ventilation duct with a diameter of 160 mm. A unique feature of the EFV-sensor is that it is capable of measuring turbulence intensity. The presence of the sensor in a ventilation duct creates insignificant pressure drop compared to measuring crosses commonly used in ventilation systems.

1. Introduction

Determination of airflow rates in ventilation ducts is necessary in order to achieve efficient control of ventilation systems aiming at improving the indoor climate and reducing the energy use for mechanical ventilation. Furthermore, monitoring of airflow rates makes it possible to uncover inadequate and inefficient performance of the ventilation system. To determine the airflow rate in a duct, one of the available methods is to explore the velocity field. With this method, the average air velocity in the duct is determined and the average airflow rate is calculated considering the cross-sectional area of the duct. The determination of airflow rates depends on the number of measurement points and their location in the duct together with the accuracy of the measuring devices used. Recommendations on airflow measurements are found e.g. in ASHRAE Standard 41 [1].

Currently, a measuring cross is commonly used to measure the airflow rate in ventilation ducts. The device consists of crossed self-averaging probes, measuring the dynamic pressure from which the airflow rate is calculated. The measuring cross measures the dynamic pressure at a number of fixed points in the cross-sectional area of the duct. However, the capability of the measuring crosses is usually limited to air velocities higher than 1.0 m/s. At lower air velocities the uncertainty increase. Furthermore, measuring crosses and other devices mounted or extend into the duct disturb the airflow causing an additional pressure drop in the distribution system. Pressure drops increase the energy use for fan operation and therefore, it is important that the measuring devices create minimal disturbance to the airflow. An alternative solution to measuring crosses is UltraLink. UltraLink consists of a sensor body and two airflow sensors mounted on the sensor body. UltraLink measures the average air velocity with an angled ultrasonic beam. The device is accurate even in low air velocities [2] and due to its construction and geometry, it creates insignificant pressure drop. However, UltraLink, like measuring crosses, requires that the air velocity profile at the measurement plane in the duct is fully developed, which consequently may limit the use of the device.

Measuring the turbulence intensity opens up the possibility for an alternative method for the determination of the airflow rate. However, turbulent flows exhibit very high frequency that require measuring devices with high time and spatial resolution for appropriate characterization. The measuring devices commonly used in ventilation systems, such as measuring crosses or UltraLink, have a frequency response that is much too slow to be used for measuring turbulence. Optical methods used for research purposes, such as laser Doppler velocimetry (LDV) or particle image velocimetry (PIV), can be used for turbulence measurements, but the methods are, however, costly and not aimed at general use.

This pilot project introduces an innovative miniature sensor for measuring air velocity. The sensor used is a modified research prototype developed at Princeton University, USA.

2. Objective

The objective of this pilot project is to achieve experimental proof-of concept of the functionality of a newly developed miniature EFV-sensor for measuring air velocity in ventilation ducts. Specific focus points are:

- Modification of the EFV-sensor for sensing airflow in ventilation ducts
- Investigation of the capability of the EFV-sensor for measuring air velocities in ducts
- Investigation and comparison of the pressure drop in a ventilation duct due to the presence of an EFV-sensor and a measuring cross, respectively
- Potential further modifications in terms of sensor design.

3. Description of the EFV-sensor

The EFV-sensor is a strain-based sensor that uses free-standing, electrically conductive nanoribbons suspended between silicon supports. Drag from the passing flow deflects the nanoribbons and induces an axial strain within the material. The strain leads to a resistance change of the nanoribbons, which is measurable through a simple Wheatstone bridge circuit, and can be directly correlated with the flow velocity.

The sensor used in this project is a prototype developed at Princeton University. The sensor has 22 nanoribbons and the nanoscale dimensions of the sensing elements (0.5 mm length, 6.5 µm width and 150 nm thickness) result in viscously dominated drag force, while enabling high sensitivity to gases. Furthermore, the nanoscale dimensions allow a linear relationship between the airflow forcing on the wires and the flow velocity. The construction and form of the sensor is similar to the design of a nanoscale hot-wire, while the operation of the sensor is similar to that of a strain gauge [3], which yields a cost effective efficient measuring device.

A layout of the EFV-sensor (chip) is shown in Figure 1. Red circle highlights the through-hole of the sensor. The dimensions of the rectangular through-hole, which is spanned by the 22 sensing nanoribbons, is 1.0 mm x 0.5 mm x 0.5 mm. The EFV-sensor is mounted on the edge of a stick with dimensions of 80 mm x 6 mm x 2 mm, which is designed to be mounted to a larger printed circuit board (PCB). The stick has the same sized through-hole. Figure 2 presents an overview of the considered measuring device, EFV-sensor, stick and PCB.

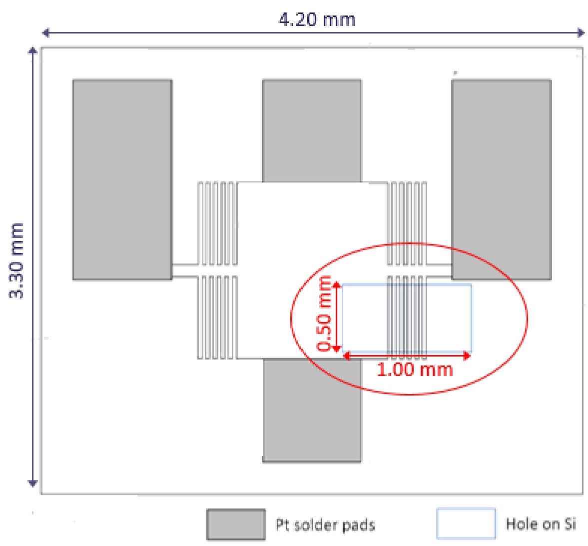

Figure 1: EFV chip – Top down view.

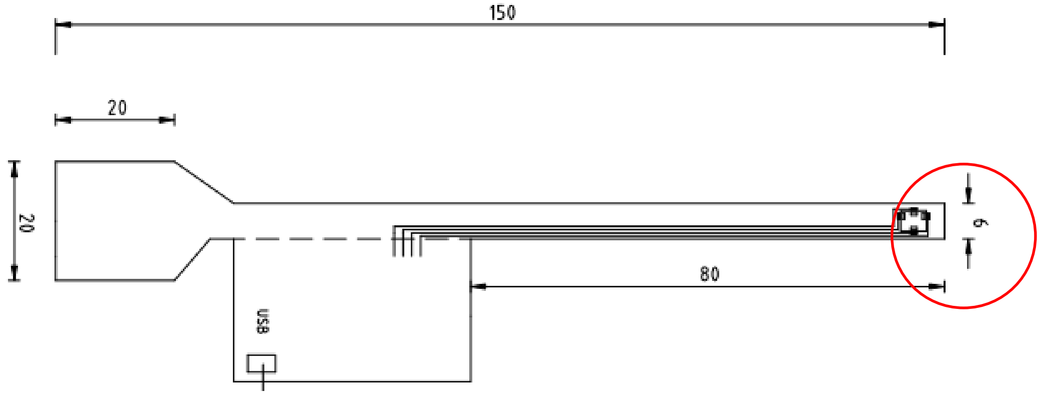

Figure 2: EFV chip (highlighted with the red circle), stick and PCB; unit: millimeter.

At the current stage of sensor development and at the experimental studies, the prototype of the sensor was connected to a PC via a standard USB. The sensor requires only 400 uA (2 mW) and takes all of the power from the USB connector. The entire research circuit consumes less than 100 mW. The circuit includes internal filters and power management components to ensure a stable signal, and it also has an integrated 16-bit A/D converter, which sends the data through a standard USB port. The measurement range of the A/D converter is 3.3 V, while the resolution is ≈ 50.4 uV. The bandwidth of the EFV-sensor is 100 kHz and the measured outputs are automatically temperature compensated.

4. Methodology

A. Experimental studies at Princeton University, USA

The capability of the EFV-sensor to measure low air velocities, up to 0.2 m/s, was examined at Princeton University using the test facility shown in Figure 3. A NE-1000 Single Syringe Pump with dispensing accuracy of ± 1 % was used to regulate the airflow that was directed through a section of calibrated smooth pipe. The used pipe with a diameter of 1.14 mm interfaced directly with the sensor through-hole of 0.5 mm^2, therefore airflow exiting the system was passing over the sensing elements, inducing a strain and a measurable resistance change.

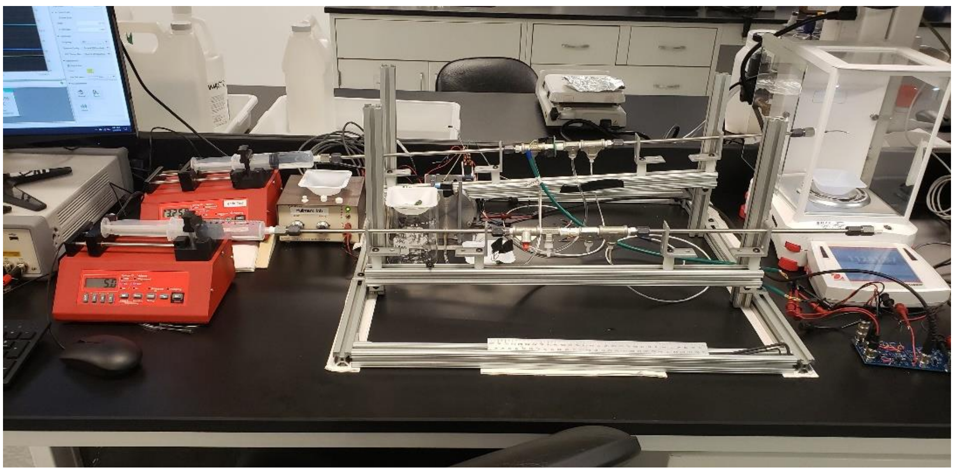

Figure 3: Experiment set-up used at Princeton University to evaluate the EFV-sensor.

B. Experimental studies at SBi, Aalborg University

Laboratory studies were conducted at Aalborg University/Statens Byggeforskningsinstitut (SBi) in order to evaluate the capability of the EFV-sensor to measure air velocities in ventilation ducts. Furthermore, laboratory studies were conducted in order to investigate the pressure drop in a ventilation duct due to the presence of the EFV-sensor and compared to two different types of measuring crosses.

For each purpose, one test rig was designed and constructed. In both test rigs, the airflow rate was regulated using UltraLink FTCU (Ø160), which consisted of a sensor body attached to a damper body. The minimum uncertainty of airflow measurements using UltraLink FTCU, depending on the length of the straight duct upstream as well as the placement of the first airflow sensor, was ± 5 % of the measured value or 1.6 L/s (≈ 0.08 m/s), based on which of these two values were the greatest. In these laboratory studies, UltraLink FTCU was installed following the technical suggestions to achieve the minimum uncertainty in order to measure airflow rates ranging from 4 L/s to 141 L/s (≈ 0.2 m/s to 7.0 m/s).

The test rig presented in Figure 4 was used to evaluate the capability of the EFV-sensor to measure air velocities in ventilation ducts. Apart from UltraLink FTCU, the test rig consisted of a fan, a silencer, a bend and galvanized ducts of 160 mm diameter; all the components had similar diameter. The EFV-sensor was installed in a vertical duct of 2.0 m length, having a distance from the bend of 1.15 m (Figure 4). The center of the sensor through-hole, spanned by the sensing elements, was positioned approximately at 70 mm from the duct wall, while the airflow was always perpendicular to the sensing elements. The measurements were conducted under fully developed airflow conditions.

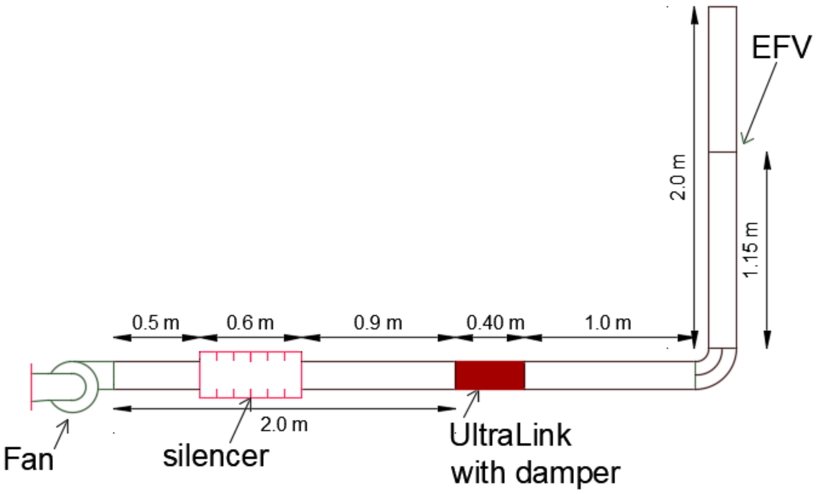

Figure 4: Test rig constructed to evaluate the capability of the EFV-sensor in ventilation ducts

The test rig shown in Figure 5 was designed and constructed to investigate the pressure drop characteristics in a ventilation duct due to different measuring devices mounted. Apart from UltraLink FTCU, the test rig consisted of a fan, a silencer, straight galvanized ducts of 160 mm diameter and the considered device (EFV-sensor or measuring cross); all the components had similar diameter.

Four scenarios were examined, pressure drop in the duct system with and without the EFV-sensor and with two different types of measuring crosses (Type A and Type B). The EFV-sensor extended to the middle of the duct. Figure 5 show the location of the investigated measuring devices.

Pressure taps were soldered to the ducts to measure the pressure drop. The measurement points remained identical for all study cases, and they were placed far away from other potential disturbances (Figure 5). At the measurement locations, the air velocity profile was fully developed. The pressure measurements were conducted using the TESTO 480 differential pressure sensor with accuracy of ± (0.3 Pa + 1 % of measured value) and resolution of 0.1 Pa.

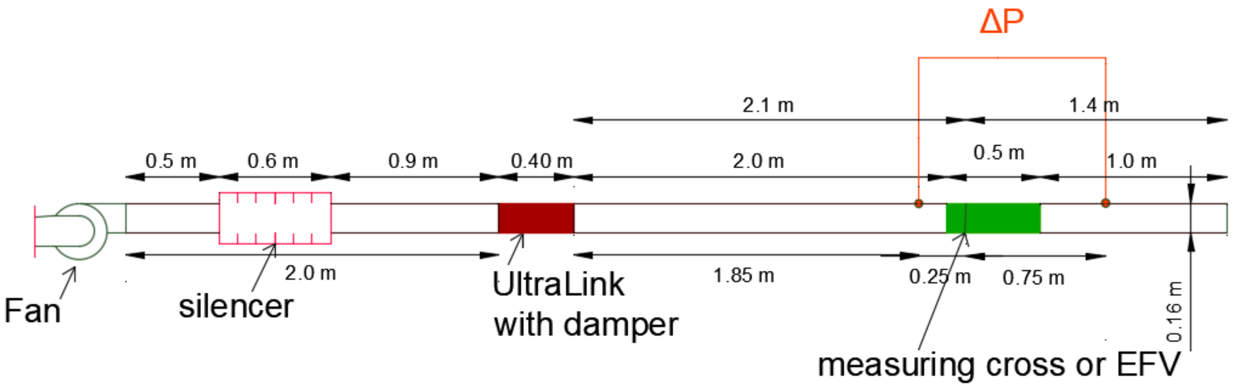

Figure 5: Test rig constructed to investigate the pressure drop in a ventilation duct

B.1 Examination conditions

The capability of the EFV-sensor to measure air velocities in ventilation ducts was evaluated for average air velocities expected in real applications; ranging from 0.2 m/s to 7.0 m/s. In each considered case, 3-min measurements were conducted under steady state conditions. The log interval of UltraLink FTCU was 1 sec, corresponding to 180 datapoints. While the high frequency response of the EFV-sensor (100 kHz) resulted in 18000 datapoints.

Note that an average air velocity of 0.2 m/s in a duct of 160 mm diameter results in airflow rate of 4 L/s. This low airflow rate satisfies the requirements for mechanical ventilation in low polluted office rooms of 10 m^2 during unoccupied hours [5]. Regarding the upper limit of the velocity range considered it was selected just to evaluate the sensor measuring range.

The pressure drop investigation was conducted for average air velocities in the duct ranging from 3.0 m/s to 7.0 m/s. The uncertainty of the pressure measurements was calculated on the base of repeated measurements under the same air velocities. Each measurement lasted 5 min with a log time interval of 1 sec.

C. CFD simulations

As this study presents the first case the EFV technology was used in a free-flowing condition, CFD simulations were performed to evaluate free-flow influences, and to suggest changes in terms of sensor design in order to improve the capabilities of the EFV-sensor to measure low air velocities in ventilation ducts. Therefore, the main target of these CFD simulations was to investigate the effect of the support body of the EFV-sensor on the airflow conditions developed around it, with focus on the area around the sensing elements.

The CFD simulations were performed using the grid-based, cell-centered finite volume CFD solver ANSYS Fluent 17.1. The experiment set-up presented in Figure 5 was modelled. Two EFV-sensors were modelled using the “cut material” operation, making it possible to ignore what happens insight the body of the object. The EFV-sensors were placed symmetrically in the duct with a diameter of 160 mm (Figure 6) at 4.1 m downstream of the duct inlet and 1.5 m upstream of the duct outlet. The distance between the center of the through-hole of each EFV-sensor and the duct wall was 8 mm.

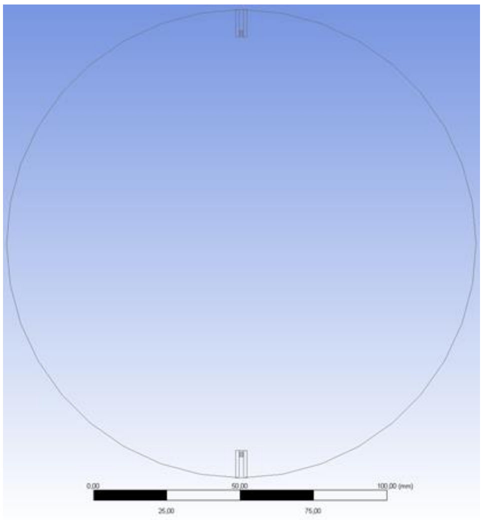

Figure 6: Location of the EFV-sensors in the ventilation duct; cross section view

The model domain was discretized with tetrahedron dominated elements. Both maximum face size and maximum tet size were set at 10 mm. In order to get efficient numerical solution and to save computational time, a fine mesh was developed only in the vicinity of the two sensors (Figure 7). Both minimum size and proximity minimum size were set to 10^{-4} mm. The number of volumes generated was of the order ~ 1.5 x 10^{6}. The average skewness was equal to 0.21, while the maximum aspect ratio was 18.8. Figure 7 shows the face of discretized elements in the cross section of the duct where the two EFV-sensors were modelled as well as the fine mesh developed in the through-hole, which had dimensions of 1.0 mm x 0.5 mm x 0.5 mm.

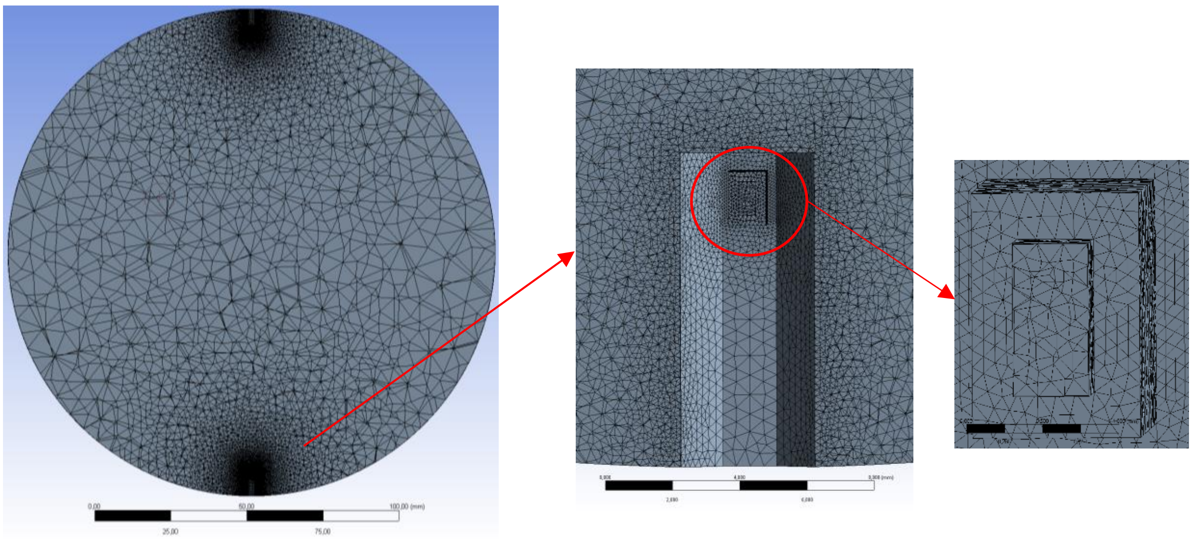

Figure 7: Global mesh topology (left); Mesh detail in the vicinity of and in the through-hole of the EFV-sensor (right)

Two turbulence models were considered, namely the Realizable k-ε model combined with the Enhanced Wall Treatment function in order to consider the high velocity gradient in the near-wall region and the k-ω model with shear stress transport (k-ω SST). In all simulated cases, steady-state conditions were assumed. The pressure-velocity correlation coupled between velocity and pressure using SIMPLE. Green-Gauss Node Based and second-order accurate scheme of pressure and energy were used to perform spatial discretization. The third-order accurate Monotonic Upwind Scheme for Conservative scheme of Laws (MUSCL) was used in order to limit the discontinuity, oscillation and spurious in the prediction of momentum, turbulent kinetic energy and turbulent dissipation rate in the region with a high gradient [4]. The under relaxation number for momentum and turbulent equations were 0.7 and 0.8 respectively. Solutions were considered converged when the normalized sum of the absolute dimensionless residuals of the discretized equations was less than or equal to 10^{-3} in the case of using the k-ω SST model and less than or equal to 10^{-4} when using the Realizable k-ε model.

5. Results and Discussion

Laboratory studies

Figure 8 presents the EFV response while measuring air velocities, up to 0.2 m/s, in a pipe with a diameter of 1.14 mm, which interfaced directly the through-hole of the sensor. The studies at Princeton University showed that the sensor could measure air velocities down to 0.05 m/s (Figure 8), with an uncertainty of ± 0.025 m/s. Note that the high accuracy of the sensor has been achieved through the integrated temperature compensation of the measured outputs.

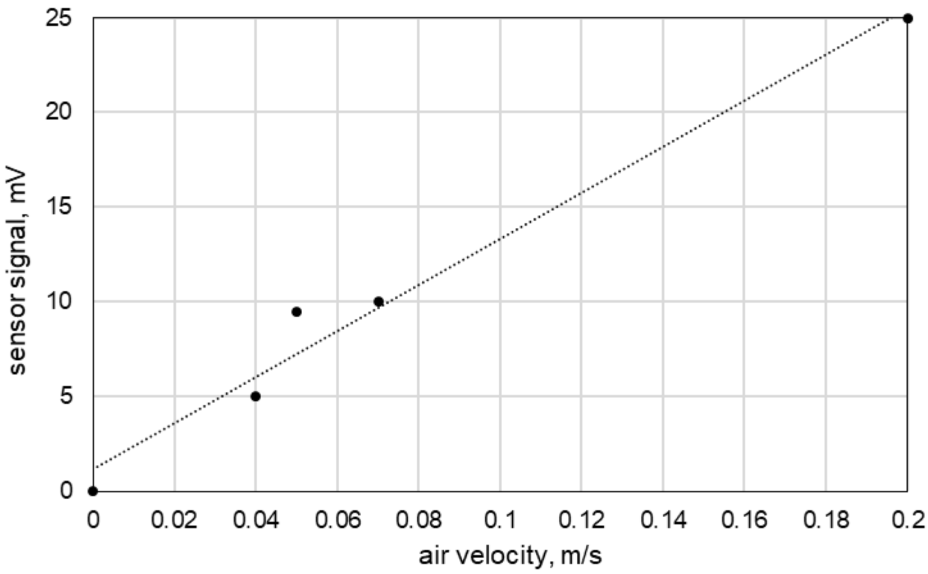

Figure 8: Output signal of the EFV-sensor as a function of the air velocity; airflow through a pipe of 1.14 mm diameter

During the laboratory studies at SBi, to investigate the capability of the EFV-sensor to measure air velocities in ventilation ducts as well as to examine the pressure drop due to different mounted measuring devices in the duct system, UltraLink FTCU was used to regulate the airflow rate. The uncertainty level of UltraLink FTCU at the considered conditions can be seen in Table 1. Furthermore, Table 1 presents the targeted average air velocities in duct system along with the actual regulated average air velocities.

Table 1: Uncertainty level of UltraLink FTCU for average air velocities from 0.2 m/s to 7.0 m/s

targeted average velocity, m/s	Regulated air velocity, m/s	Uncertainty level
0.2	0.20 ± 0.001	0.08 m/s (≈ 40.3 %)
0.3	0.30 ± 0.002	0.08 m/s (≈ 26.5 %)
0.4	0.41 ± 0.005	0.08 m/s (≈ 19.5 %)
0.5	0.50 ± 0.008	0.08 m/s (≈ 15.9 %)
0.6	0.62 ± 0.013	0.08 m/s (≈ 12.9 %)
0.8	0.80 ± 0.002	0.08 m/s (≈ 10 %)
1.0	1.00 ± 0.005	0.08 m/s (≈ 7.9 %)
2.0	1.98 ± 0.003	0.1 m/s (≈ 5 %)
3.0	2.98 ± 0.004	0.08 m/s (≈ 5 %)
4.0	3.97 ± 0.007	0.08 m/s (≈ 5 %)
5.0	4.99 ± 0.007	0.08 m/s (≈ 5 %)
6.0	5.98 ± 0.008	0.08 m/s (≈ 5 %)
7.0	6.98 ± 0.005	0.08 m/s (≈ 5 %)

Figure 9 indicates the mean values of EFV-sensor response while measuring air velocities in a ventilation duct of 160 mm diameter, while Table 2 shows the mean values for each case along with the Type A standard uncertainties of repeated measurements. During these measurements, the center of the sensor through-hole was approximately at 70 mm from the duct wall. The amplifier gain of the first sensor version was 64 dB. Figure 9 shows that the measuring range of the sensor was up to an average air velocity in the duct of 3.0 m/s. The measuring range was limited by the electrical amplification, and thus it was decided to decrease the gain to 58 dB. Figure 10 shows that when the gain decreased, the EFV-sensor gave signal for average air velocities in the duct up to 7.0 m/s. It should be pointed out that the maximum velocity is not limited by the sensing element, but only on the settings of the electronics. The duct measurements and the CFD simulations clearly show that the size of the through-hole affects the capabilities of the EFV-sensor to measure air velocities in ventilation ducts lower than 0.4 m/s. Later in this report, the results from CFD simulations along with suggestions that could improve the performance of the sensor are presented.

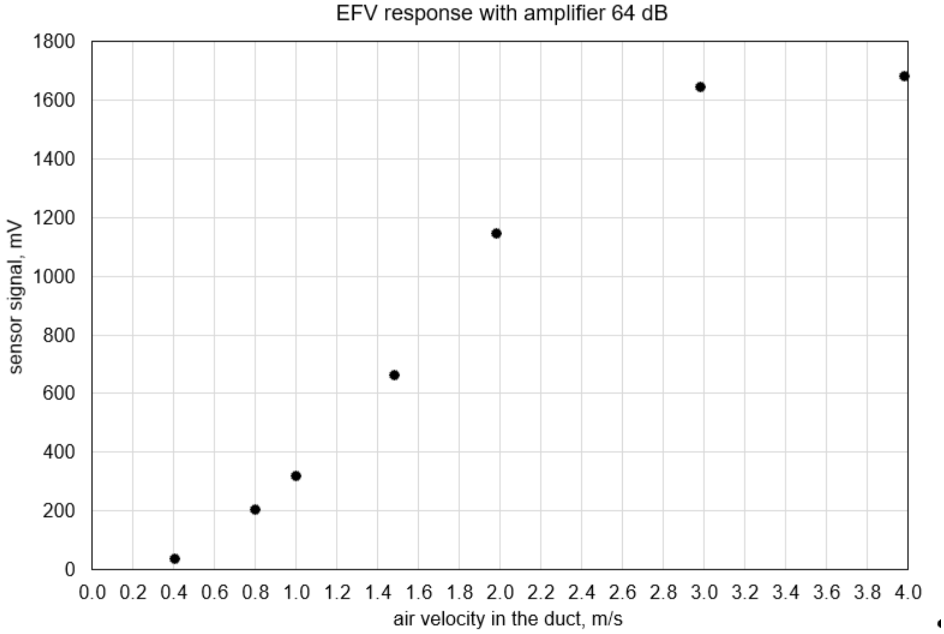

Figure 9: Output signal of the EFV-sensor as a function of the air velocity; airflow through a duct of 160 mm, amplifier 64 dB

Table 2: Mean values of EFV response and Type A standard uncertainties of repeated measurements; amplifier 64 dB

Average air velocity, m/s	EFV response, mV
0.4	32.6 ± 1.9
0.8	199.3 ± 9.4
1.0	316.5 ± 12.4
1.5	660.6 ± 19.4
2.0	1141.8 ± 21.3
3.0	1641.0 ± 15.3
4.0	1678.1 ± 0.3

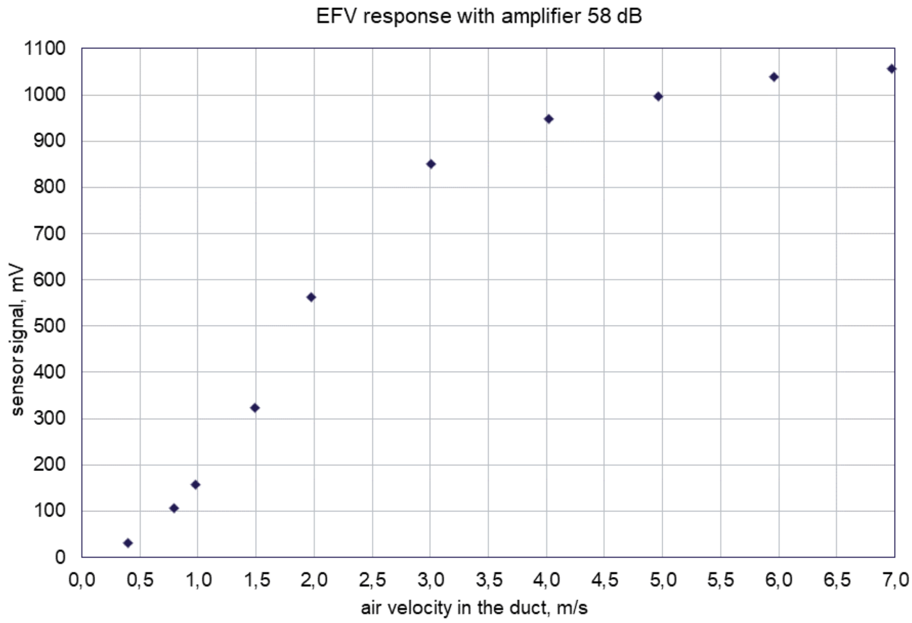

Figure 10: Output of the sensor vs. air velocity; airflow through duct Ø160 mm, amplifier 58 dB

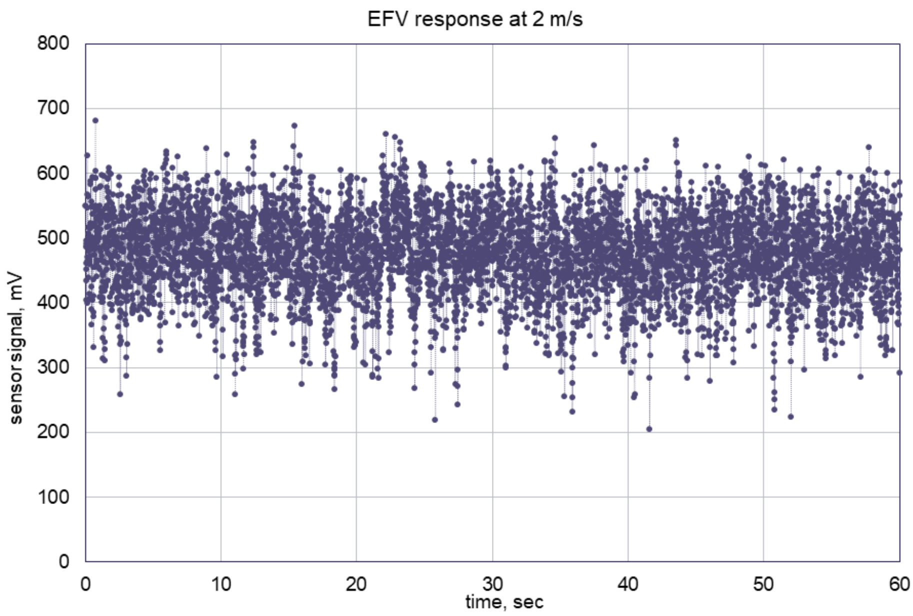

Figure 11: 1-min output of the sensor; avg. air velocity in the duct of 2.0 m/s, amplifier 58 dB

Figure 11 presents the 1-min measured outputs of the EFV-sensor for an average air velocity in the duct of 2.0 m/s (amplifier gain of 58 dB). The EFV-sensor reacts quickly to fluctuations in the flow velocities making it a promising alternative for turbulence measurements. The turbulence intensity was calculated to 13.3 %.

Figure 12 presents the mean values of pressure drop in the duct system due to the EFV-sensor and measuring crosses Type A and Type B under the considered average air velocities. Furthermore, the pressure drop without any sensor mounted is presented. Table 3 indicates the mean values of pressure drop for each case along with the Type A standard uncertainties of repeated measurements. Figure 12 shows that replacing a measuring cross with an EFV-sensor could result in energy savings, as an EFV-sensor creates a lower pressure drop.

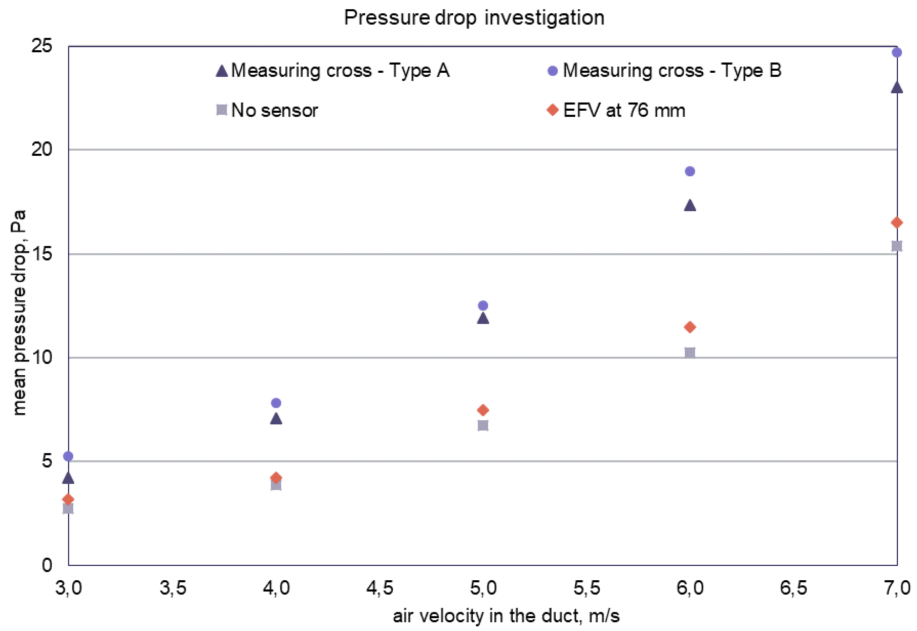

Figure 12: Pressure drop investigation for average air velocities in the duct ranging from 3.0 m/s to 7.0 m/s; Mean values of repeated measurements of 5-min

Table 3: Mean values of pressure drop and standard uncertainties of repeated measurements

Cases		**No sensor**	**Measuring cross Type A**	**Measuring cross Type B**	**EFV**
Air velocity, m/s	Airflow rate, L/s		Pressure drop, Pa		
3.0	60.3	2.7 ± 0.1	4.2 ± 0.3	5.2 ± 0.2	3.2 ± 0.2
4.0	80.4	3.9 ± 0.3	7.1 ± 0.2	7.8 ± 0.2	4.2 ± 0.3
5.0	100.5	6.8 ± 0.3	11.9 ± 0.3	12.5 ± 0.3	7.5 ± 0.3
6.0	120.6	10.3 ± 0.1	17.4 ± 0.3	19.0 ± 0.4	11.5 ± 0.3
7.0	140.7	15.4 ± 0.1	23.0 ± 0.2	24.7 ± 0.7	16.5 ± 0.3

Note that during these measurements, the EFV-sensor extended to the middle of the duct in order to examine the pressure drop. One objective of this project is to leverage the fact that the EFV-sensor measures flow velocity in a point to establish correction factors for the EFV measured outputs, such that it will be possible to mount the sensor no more than 0.3 D from the duct wall. In this way, the mean pressure drop can be decreased even more.

CFD simulations

To predict the effect of the support body of the EFV-sensor on airflow conditions, CFD simulations were conducted for several inlet air speeds (Table 4).

In all simulated cases, the temperature of air was 20ºC. The other air properties considered were:

air density (ρ) 1.204 kg/m^3,
specific heat capacity (c_p) 1007 J/kgK and
dynamic viscosity (μ) 1.825 x 10^{-5} kg/ms.

At the duct inlet, a uniform turbulence intensity (TI) of 5 % was defined, while at the duct outlet, a zero average pressure condition was specified. A no-slip boundary condition was applied at both the duct wall and the walls of the EFV-sensors.

Table 4: Simulated conditions

Inlet air velocity [m/s]	Reynolds number
0.2	2111
0.3	3167
0.4	4223
0.5	5278
0.6	6334
6.0	63340
7.0	73897

Independently of the turbulence model considered, the CFD results showed that the EFV-sensor with the current design (through-hole size of 0.5 mm^2) could be used to measure air velocities in ventilation ducts down to 0.35 m/s (Figure 13). For example, Figure 14 and Figure 15 illustrate that almost no air passed the through-hole when the air velocity was ≈ 0.3 m/s. Similar trend was observed during the laboratory studies, supporting the validity of these CFD results. Therefore, it can be concluded that, apart from the capabilities of the sensing elements, the body of EFV as a whole could play a role in terms of the accuracy of the air velocity measurements.

Additional CFD simulations were performed to suggest a new geometry for the EFV-sensor in order to improve the possibilities of measuring accurately low air velocities (< 0.35 m/s) in ventilation ducts. Several simulations were performed considering different sizes and shapes for the sensor through-hole, as well as different geometries for the EFV-sensor as a whole. Finally, it was found out that increasing the size of the hole from 0.5 mm^2 to 6.375 mm^2 improved the possibilities of the sensor to measure air velocities down to 0.1 m/s. In Figure 16 it can be seen the suggested size and shape for the through-hole, while presents the results of the simulations.

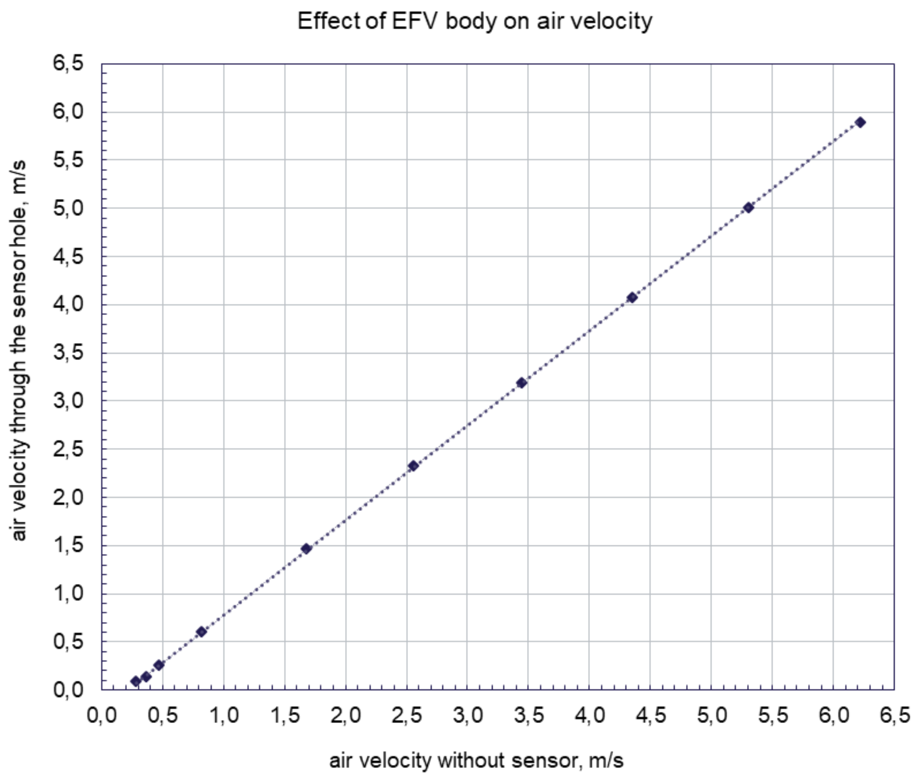

Figure 13: Effect of the support body of the EFV-sensor on air velocity; air velocity without sensor vs. air velocity through the sensor hole

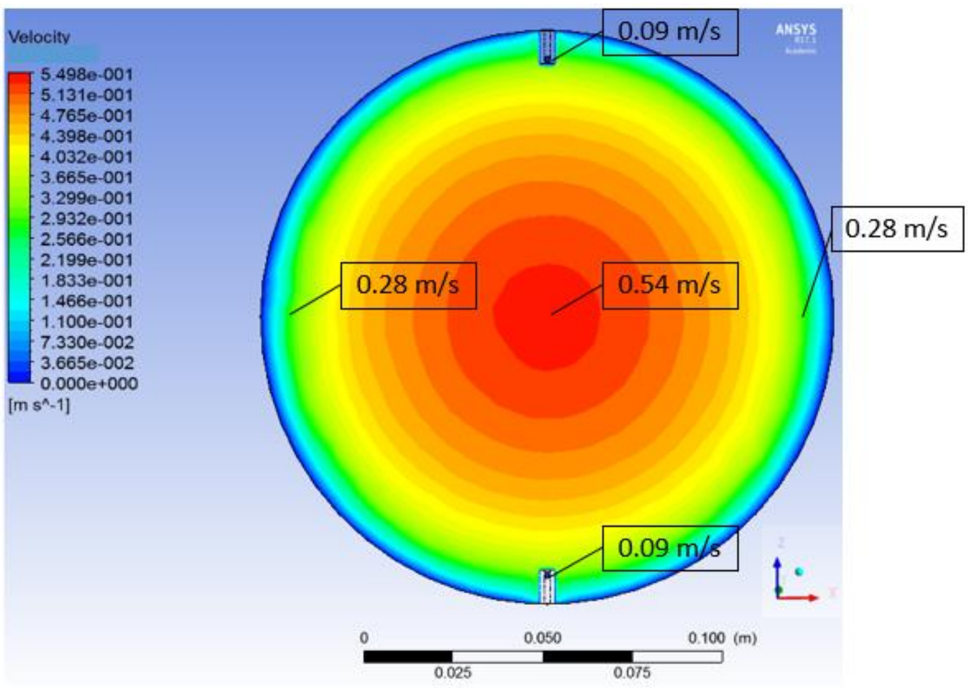

Figure 14: Contours of air speed at the plane where the two EFV-sensors were located

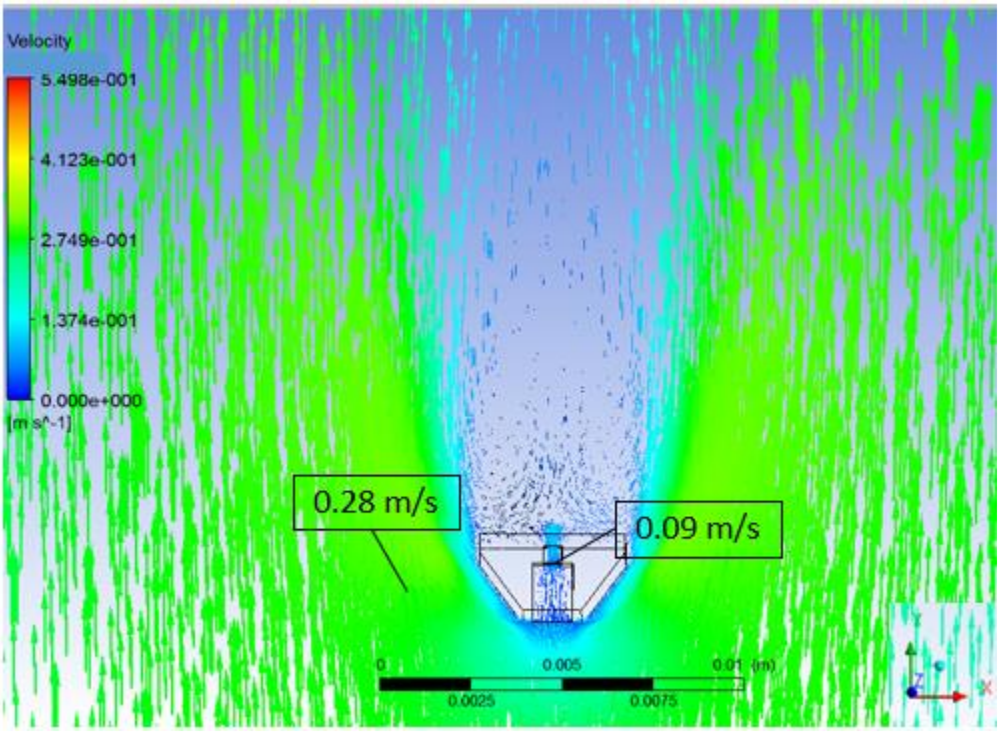

Figure 15: Vectors of air velocity in the vicinity of the EFV-sensor

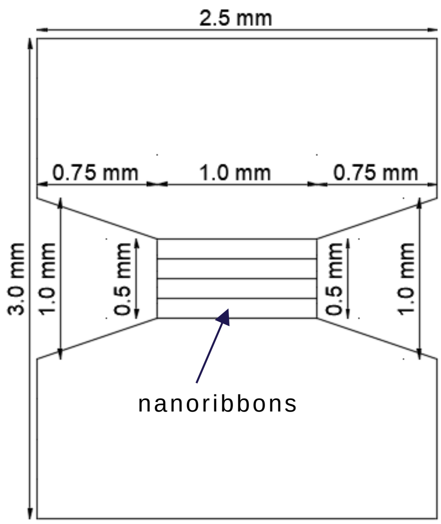

Figure 16: Suggested size and shape for the sensor through-hole

Table 5: CFD results with the new "suggested" shape and size of sensor through-hole

Model	air velocity through the sensor hole [m/s]	Air velocity without sensor [m/s]	Effect (Air velocity without sensor / air velocity through the sensor hole) [-]
Realizable k- ε	0.106	0.126	1.2
k – ω SST	0.083	0.119	1.4

6. Conclusion

The results show that the EFV-sensor is a promising alternative for measuring air velocities in ventilation ducts without imposing significant pressure drop in the distribution system. Specifically, it has been found that:

- The experimental studies in laboratory show that the EFV-sensor is capable of measuring air velocities lower than 0.1 m/s in a pipe with a diameter of 1.14 mm and from 0.4 m/s in a venti-lation duct with a diameter of 160 mm. The uncertainty of the measured data is ± 0.025 m/s
- The CFD simulations indicate that a larger through-hole in the sensor can improve the capa-bilities of the EFV-sensor to measure air velocities in the duct system below 0.4 m/s.
- The results show that the EFV-sensor creates a lower pressure drop compared to a measuring cross, indicating that replacing measuring crosses with EFV-sensors can lead to a reduction of the energy use for fan operation.
- The experimental studies show that the EFV-sensor is capable of measuring turbulence intensity, as the response frequency of the sensor can be 100 kHz.

Furthermore, the price for an EFV-sensor is expected to be at least 100-200 times lower than that of UltraLink.

The low price may lead to a significantly wider use of sensors, which can be used in machine learn algorithms for improvement of comfort and reduction of energy use in the next generation ventilation systems

7. Future work

The present pilot project has shown the potential of the EFV-sensor for measuring air velocities in ventilation ducts.

The pilot project forms basis for further studies of the sensor and a wider use of it as described in ELFORSK 2020 application *352-008 Phase 2: Miniature sensor for resistanceless measurement of air velocities in ventilation ducts* (ELFORSK 2020: 352-008 Fase 2: Miniatureføler til modstandsfri lufthastighedsmåling i ventilationskanaler)

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