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Techniques for airflow measurements to determine the real efficiency of heat recovery in ventilation systems

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Techniques for airflow measurements to determine the real efficiency of heat recovery in ventilation systems

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Abstract. Heat recovery in ventilation is essential to reduce energy use and thus mitigate greenhouse gas emissions from the building sector. Heat recovery efficiency of at least 80 % in new buildings is required according to Norwegian standards. However, measurements show that the real heat recovery efficiency during operation is commonly 10-20 % lower. Measuring heat recovery efficiency in buildings is challenging, mainly due to difficulties measuring airflow rates close to the air handling unit (AHU). This study assesses the following duct airflow measurement techniques and equipment: pressure differential, velocity traversal technique, ultrasound and tracer gas. The pressure differential method can provide accurate flow rates and thus it is used as the reference measurement. However, it is not suitable for duct flow measurements due to its high pressure penalty and long straight duct requirement. Velocity traverse and tracer gas methods introduce less disturbance to the flow. Nevertheless, both methods require intensive labour work and cannot track quick changes of the airflow with time. The application of ultrasound to measure airflow is relatively novel and it can automatically measure constant and fluctuating airflows with low pressure drop and acceptable accuracy when the proper installation and minimum straight duct are provided.

1. Introduction

Heating, ventilation and air-conditioning (HVAC) systems play a vital role in achieving the desired indoor environment. Energy use for HVAC in the building sector accounts for a large proportion of the total energy use in most countries around the world. Heat recovery is employed as an efficient manner to reduce energy use in ventilation systems and thus mitigate greenhouse gas emissions from the building sector. Heat recovery effectiveness higher than 80 % is needed to meet the requirements in Norwegian building regulations for new buildings [1]. To be precise, an efficiency ≥80 % is required using the "energy measure" calculation method in Ref [1], although there is no minimum demand in the "energy frame" calculation method, an efficiency ≥80 % is commonly used and probably required in practice [2]. However, field measurements have shown that the actual heat recovery efficiency during operation is commonly 10-30 % lower than the expected efficiency. For extreme cases with improper installation, an efficiency as low as 10 % has been measured [3].

The thermal efficiency for heat exchangers can be calculated from equation (1) [4],

$$\eta_{\mathrm{T}} = \frac{\dot{m}\,c_p}{(\dot{m}\,c_p)_{\min}}\frac{\theta_2 - \theta_1}{\theta_3 - \theta_1} \qquad\qquad 1)$$

Where ṁ is the mass flow rate, c_p is the specific heat capacity of air, the subscript min is the minimum value of the supply and exhaust side, θ1 is the air temperature before the heat exchanger on the supply side, θ2 is the air temperature after the heat exchanger on the supply side and θ3 is the air temperature before the heat exchanger on the extract side.

The thermal efficiency varies as a result of the quality of the installation, system control and operating conditions associated with balanced or unbalanced airflow rates, condensation and frost formation in the heat recovery. Energy calculations with constant and overestimated thermal efficiency may lead to an underestimation of building heating demands [5]. The indoor thermal comfort will additionally be degraded by the possible cold draught problem due to under dimensioned heating coil. The discrepancy between expected and real performance is worth further investigation through field measurements. Through field airflow measurements, one can additionally identify malfunctions and improvement potential for the heat recovery, as well as leakages and recirculation.

To determine the field efficiency of heat recovery in buildings, measurements of air temperatures, relative humidity and airflows in the ducts connected to the air handling unit (AHU) are needed. In addition, several measuring points at the same cross-section are required to account for non-homogenous distribution of air temperatures, humidity and velocities in the ducts [6]. However, measuring heat recovery efficiency in buildings is challenging, mainly due to difficulties measuring accurate airflow rates close to the AHU. The equipment for measuring duct airflow rates normally requires minimum distances of straight duct up-and-downstream the measurement point to ensure fully developed velocity profiles. In most buildings, space around the AHU and ducts is insufficient to perform measurements in this manner. There is also a lack of standards for field measurements of heat recovery efficiency, as most measurement recommendations are defined for lab conditions. In practice, lab standards are difficult to follow as real systems have bends or devices disturbing the flow, making it difficult to find and access straight duct sections close to the AHU [6]. Consequently, measurement complexity increases in the field, and the accuracy is reduced due to more measuring points needed to account for the developing velocity profiles.

There are very few studies on the real efficiency of heat recovery through field measurements. Heide [7] collected examples with deviations up to 37 % compared to the rated efficiency for Norwegian residential buildings. Lassen et al. [8] refer to several studies in Norway, Switzerland and Sweden with 10-20 % lower efficiency. A study with field tests of 20 centralized and 60 decentralized ventilation systems found significantly lower heat recovery efficiencies for all units, with 65 % ±24 % for centralized systems and 70 % ±17 % for decentralized systems [9]. For this study, tracer gas was used in addition to thermal wires to determine the air temperature. Only one of the studies measured an efficiency higher than specified, with 77 % when 75 % was specified [10]. The study also pointed out challenges of performing in situ measurements in occupied buildings, such as uncontrollable boundary conditions and placing the sensors where they do not disturb the occupants. A common finding from the reviewed literature is the difficulty of measuring airflow rates with acceptable uncertainty. The provided measurement uncertainties of the temperature efficiency ranged from ±8 to ±24 %, which are higher than the typical uncertainties (±5 %) for laboratory testing [6]. Methods and protocols for rating and testing the real performance of the heat recovery for existing buildings are needed. The most significant barrier is the ability to measure duct airflow rates close enough to the AHU with an acceptable accuracy, which is assessed in this paper.

2. Methods

The focus of this study is to assess various measurement techniques and available measuring equipment to measure duct airflow rates with acceptable accuracy. During the project, researchers, equipment suppliers and contractors in this field were contacted asking for advice regarding measurement protocols. A selection of currently available methods and devices are tested through laboratory experiments at the Department of Energy and Process Engineering at NTNU in Trondheim. Field duct airflow measurements in real buildings are also performed. To compare the different equipment, they are tested in the same setup in the lab. The lab setup represents similar conditions as can be found for

AHU in buildings, but in order to have the same boundary conditions, the tests are done in the lab and not in the field. The velocity traversal method was tested in the field, but unfortunately, it was not possible to validate the results. Further details about the techniques, measuring equipment, relevant standards for measurements and the performed experiments can be found in [11].

3. Measurement techniques
Four different measurement techniques are presented and compared.

3.1. Pressure differential through an orifice plate
The pressure differential method with an orifice plate is widely used in laboratories to determine and monitor airflows. When a fluid passes through a reduction of the open area in a pipeline, it causes a static pressure drop. Based on Bernoulli's equation, the flow rate can be calculated using the measured static pressure difference before and after the orifice plate. Flow conditions should be constant or only varying slightly and slowly with time. The orifice plate must be mounted according to specified minimum straight duct lengths without disturbances or branch connections both upstream and downstream. Although highly accurate, this method introduces an additional pressure loss and has low sensitivity at very low airflow rates [12]. This method is mostly used in laboratories, due to the extra pressure loss and large intervention to ventilation systems in buildings. The airflow rate and corresponding uncertainties are calculated according to NS-EN ISO 5167-1 and NS-EN ISO 5167-2.

3.2. Velocity traversal method
By measuring the velocity at multiple designated positions over the cross-section of a duct, one can obtain the area-averaged velocity. The number of measuring points and accuracy is decided based on the flow regime, the duct diameter and velocity profile in the duct. Turbulence caused by bends, fans, branching and limited straight ductwork increases the inaccuracy and thus it may require more measuring points. Minimum straight duct length, the number of measurement points and other criteria for using velocity traversal method is specified in NS-EN 16211:2015. One significant weakness of the method is that it cannot capture the quick airflow variations with one set of measurements. The measured airflows are assumed constant within the measurement time. The sensor probe will also interfere with the velocity profile, further decreasing the measurement accuracy. The method is intuitive, but traversing the sensor needs to be conducted manually, thus requiring time-consuming labour. The measurement uncertainty is high for very low velocities and developing flows.

For this project, two different types of TSI anemometers were used, VelociCalc 8388 and VelociCalc 9565-P. These are hot-film anemometers with extendable measurement probes. VelociCalc 9565-P measures air velocity, temperature and relative humidity simultaneously. A drawback of this device is that the placement of the sensors requires that at least 75 mm of the probe is in the flow [13].

3.3. Ultrasonic measurements
Ultrasonic devices are based on the Doppler effect [14]. Through ultrasonic measurements, one can monitor both constant and time-dependent airflows at a wide range of air velocities as it responses linearly to flow velocity change. This is especially beneficial at low air velocities, and so the technique is emerging for use in VAV dampers in new buildings aiming for low energy use for fans [15, 16]. Another major benefit is that there is no additional pressure loss.

Lindab UltraLink FTMU is tested to measure airflow and temperature. Measurements are logged automatically and exported to a computer using Modbus. UltraLink also has requirements regarding minimum straight duct lengths. Its uncertainty also depends on the orientation of the device relative to disturbances as referred in the datasheet [17]. Another drawback is that the product is currently only available for relatively small duct sizes (Ø100-Ø315).

3.4. Tracer gas method

Tracer gas dilution techniques are well-known for assessing airflow rates and air distributions within buildings and ventilation systems. With the tracer gas method, the air is "marked" with one or more tracer gases, and then the concentrations are measured at various positions. By interpreting the evolution of tracer concentrations, it is possible to calculate airflow rates, ventilation efficiency, the age of air and leakage flow rates [18]. However, tracer gas measurements are difficult to perform in the field, as it requires specific knowledge for setting up the measurements and analysing the concentrations. The key factor for successful tracer gas method is the good mixing of the tracer and the air, which tends to be difficult to achieve in the ductwork where there is very limited space.

For this project, carbon dioxide (CO_2) and nitrous oxide (N_2O) are used as tracer gases, and Lumasense photoacoustic gas monitor is used for analysis of the tracer concentrations, the same device as used by [9]. Due to its background concentration, CO_2 is not ideal for analysis but was chosen for its low global warming potential and low price relative to other gases.

3.5. Comparison of measurement techniques and equipment

The selected measurement techniques and equipment used in the project are compared in table 1. The VelociCalc is the only one able to measure velocity, temperature and relative humidity, while tracer gas can determine parasitic airflows (like for example leakages in rotary heat exchangers). However, for determining the annual heat recovery efficiency, the UltraLink has a significant advantage due to its automatic logging. For the other methods, intensive manual labour is required for the measurement if the annual performance of the system is monitored. In addition, demand-controlled ventilation is becoming increasingly popular, and fluctuating airflows can be tracked by the ultrasonic measurement.

Table 1 Comparison of the selected measurement techniques and equipment used in the project.

Airflow measurement method		Velocity traverse	Ultrasound	Pressure differential	Tracer gas
Selected measuring equipment in this project		VelociCalc 9565-P [13]	Lindab UltraLink [17]	Orifice plate, TT series manometer	CO_2 and N_2O tracer gases, Lumasense photoacoustic gas monitor
Velocity	Range	0-50 m/s	0.2-15 m/s	Reynolds number ≤5000	NA
	Uncertainty	±3 % of reading or ±0.015 m/s, whichever is greater	±5 % of reading or ±X[a] l/s, whichever is greater	Depends on the flow rate, orifice plate, etc.	Uncertainty mainly depends on the mixing level
	Resolution	0.01 m/s	NA	NA	NA
Temperature	Range	-10 to 60 °C	-10 to 50 °C	NA	NA
	Uncertainty	±0.3 °C	±1.0 °C	NA	NA
	Resolution	0.1 °C	NA	NA	NA
Relative humidity	Range	5 to 95 % RH	NA	NA	NA
	Uncertainty	± 3 % RH			
	Resolution	0.1 % RH			
Automatic logging		Yes (in 1 point)	Yes	Depends on the micromanometer and the logger	For tracer concentration, yes
Duct size		Ø25 to Ø12700	Ø100-Ø315	Ø50-Ø1000 [19]	Any size
Strengths		Easy to implement and understand	Accurate, intuitive, low uncertainty for low air velocity, no flow interference	Accurate	Able to determine the main and parasitic airflows at the same time, relatively accurate
Drawbacks		High measurement uncertainty for varying flow conditions, requires manual labour	Could be difficult to install in existing ducts, not available for large duct sizes	Creates extra pressure loss, not suitable for field tests	Need good mixing, which is almost impossible in AHU, and specialized knowledge to calculate the airflows
Costs		Low equipment cost and medium/high labour work depending on measurement points	Low equipment cost and low labour work	Low equipment cost and low labour work	Very high equipment cost and high labour work

[a] X equals the distance in dm, for instance Ø100 => 1 l/s and Ø200 => 2 l/s.

4. Lab experiments

Measurements have been performed with the above techniques and the main results are briefly presented here. More detailed information can be found in the project report [11].

4.1. Comparison between velocity traversal, ultrasonic measurements and pressure differential

For this experiment, the orifice plate is mounted according to straight duct requirements and used as a reference for testing Lindab UltraLink FTMU and VelociCalc 8388. The test rig is shown in figure 1 and measurements are performed on the same straight duct section (Ø200) but at different distances from the bend. Measurements are performed with four different setups with varying distances to the bend, and with five different airflow rates for each setup. Note that the tested setups are mostly outside producers and standards recommendations for distances relative to disturbances, as we want to evaluate the UltraLink and VelociCalc in conditions similar as to what can be found in the field. This paper only presents the setup with the shortest distance from the bend to the devices: 0.05 m to VelociCalc, 0.12 m to UltraLink and 4.00 m to orifice plate (see image to the right in figure 1). For the UltraLink, the measurement uncertainty is affected by the orientation of the flow sensors relative to disturbances. Consequently, the UltraLink is tested at different orientations. For the velocity traverse method, five measuring points are used, positioned according to NS-EN 16211:2015.

Figure 1 Left: Picture of the lab setup for testing Lindab UltraLink and VelociCalc 8388 and compare with calculated airflow rates found with the orifice plate. Right: setup used for the presented measurement results.

The results from the measurements are presented in table 2. The terms used for UltraLink orientation; *side, inner radius* and *outer radius*, refer to the placement of the first flow sensor on the device relative to the bend. Due to the very short distance from the bend, the airflow is highly turbulent and unevenly distributed over the cross-section of the duct, making it very difficult to achieve accurate measurements. An average deviation of 6.6 % when the UltraLink is oriented towards the side is observed. The deviations for the other orientations are significantly higher, with -22.8 % and -16.5 % for the inner and outer radius respectively. The results with the VelociCalc have an agreement with reference values from the orifice plate, with mean deviations between 3.8 % and 6.3 %.

Table 2 Measurement results with calculated flow rate over orifice plate, measured values for UltraLink and VelociCalc and deviations compared to the calculated value over the orifice plate.

UltraLink orientation	Measurement #	1	2	3	4	5	Avg. error compared to orifice plate	Standard deviation
	Calc. flow rate from orifice plate [m³/h]	59.9	132.1	204.8	277.9	351.4	-	
Side	UltraLink [m³/h]	62	141	222	298	376	-	
	VelociCalc 8388 [m³/h]	64.3	143.4	218.6	293.5	363.3	-	
	Deviation UltraLink	3.5%	6.7%	8.4%	7.2%	7.0%	6.6%	1.8%
	Deviation VelociCalc 8388	7.4%	8.6%	6.7%	5.6%	3.4%	6.3%	2.0%
	Calc. flow rate from orifice plate [m³/h]	59.9	132.1	204.8	277.9	351.4	-	
Inner radius	UltraLink [m³/h]	48	98	156	215	275	-	
	VelociCalc 8388 [m³/h]	64.1	144.3	215.5	285.0	361.3	-	
	Deviation UltraLink	-19.9%	-25.8%	-23.8%	-22.6%	-21.7%	-22.8%	2.2%
	Deviation VelociCalc 8388	7.0%	9.3%	5.2%	2.6%	2.8%	5.4%	2.8%
	Calc. flow rate from orifice plate [m³/h]	59.9	132.1	204.8	277.9	350.9	-	
Outer radius	UltraLink [m³/h]	50	109	171	233	295	-	
	VelociCalc 8388 [m³/h]	62.5	143.0	212.0	279.3	358.6	-	
	Deviation UltraLink	-16.5%	-17.5%	-16.5%	-16.2%	-15.9%	-16.5%	0.6%
	Deviation VelociCalc 8388	4.4%	8.3%	3.5%	0.5%	2.2%	3.8%	2.9%

Based on our measurements, including those not presented here, the UltraLink achieves the best accuracy when oriented towards the side when the distance from a bend is shorter than recommended. In general, measurements with the VelociCalc are more accurate than with the UltraLink, especially when the UltraLink is oriented towards the inner or outer radius relative to the bend. Aside from the setup in table 2, the orientation towards the inner radius was more accurate than towards the outer radius. Note that results may differ for other disturbances. The deviations for the VelociCalc are highest for low airflow rates, albeit still acceptable, and in the same range as the deviations found with the UltraLink oriented towards the side. However, for higher airflow rates, the VelociCalc is more accurate, and so the optimal choice of measurement equipment is also dependent on the range and frequency of variation of the airflow rate to be measured. However, the measurement accuracy of the ultrasonic device oriented towards the side is acceptable without additional pressure loss and interference on the velocity profile. Considering automatic logging, the ultrasonic airflow measurement technique is thus considered a superior alternative to both the velocity traversal and pressure differential techniques for field measurements, if it is properly installed.

4.2. Tracer gas measurements

The aim of this experiment is to investigate the feasibility and complexity of using the tracer gas technique to determine the main and parasitic airflow (leakage) rates in an AHU. Figure 2 shows a principle sketch of the system including tracer gas dosing and sampling spots. The test rig has the same AHU illustrated in figure 1. A LabView program is used to control the supply and extract airflows and rotary speed of the heat wheel, which are kept constant during each test scenario. The ductwork connected to the heat wheel has a dimension of Ø500, and balance between supply and exhaust airflows are verified using Testo 420 flow hood. Multiple tests are performed, including tests with two tracer gases (CO_2 and N_2O) to determine the airflows in different ducts at the same time. However, as these two gases have some overlapping wavelength adsorption intervals, the tracer concentration results obtained from the experiments are unreasonable due to the lack of cross-compensation for wave adsorption. Besides the test with two tracer gases, the airflow measurement with the single tracer gas test (CO_2) is also conducted. The single tracer gas must be applied sequentially for different ducts, with

sufficient time in between to eliminate the influence from the last test. For this case, the time interval is 24 hours and the injection rate of CO_2 is constant at 4 l/min. To achieve sufficient mixing, the gas is injected through multiple holes in two tubes positioned perpendicular to the cross-section of the duct. Leakages through the ducts between the dosage point and the AHU, as well as external leakage through the AHU box, are considered negligible compared to the recirculation flow rates.
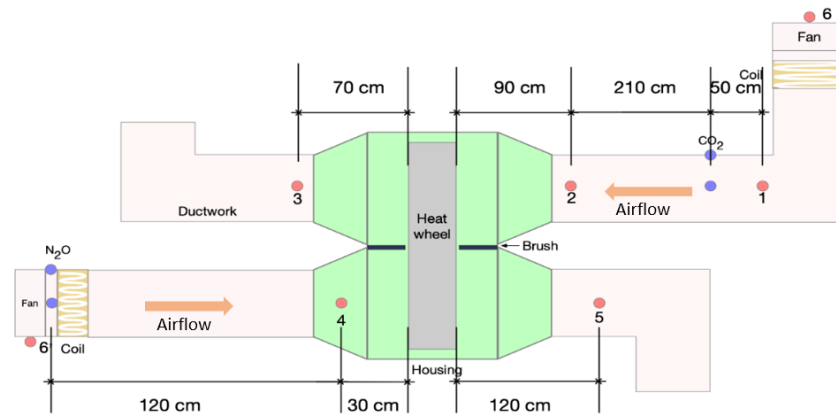
Figure 2 Principle sketch of the lab setup for tracer gas tests, with ducts, injection points in blue and measuring points in red.

Monitoring of the tracer gas concentrations is performed by infrared spectroscopy with the Lumasense photoacoustic gas monitor. The air is pumped into the tracer gas measurement chamber from the sampling points. The main and parasitic airflow rates can be determined with measured CO_2 concentrations and the injection tracer rate using tracer mass conservation. For a rotational speed of 10 rpm, the supply and extract recirculation rates for the tested AHU with rotary heat wheel are 15.2 % and 9.3 % respectively. At 20 rpm, the corresponding values are 14.3 % and 17.0 %. The extract air recirculation increases at the higher rotational speed (20 rpm), and thus more polluted air is introduced into the supply air. This may degrade the performance of the heat recovery and reduce indoor air quality. Another interesting finding is that a test with a long straight duct attached in the supply side (i.e. unbalanced static pressures between supply and extract), led to a large fraction of supply air penetrating to the exhaust side. This caused malfunction of the heat wheel and indicates that balanced duct resistance and balanced static pressure in the extract and supply sides should be pursued in practice to avoid large leakages in rotary heat recovery units.

To conclude, the single tracer gas method is able to present the main and parasitic airflows in the AHU. Good mixing between the tracer and airflow is, however, a big challenge, even when multiple injections are used. In addition to the challenges of achieving sufficient mixing of the tracer with the airflow in AHU in practical systems, the tracer gas technique is in general more difficult to perform than the other techniques. When using multiple tracer gases, the cross-compensation function of adsorption spectrums for different tracers should be activated in the gas analyser to reduce the interference between various tracer gases.

5. Conclusion

In order to reveal the field heat recovery efficiency, accurate measurements on duct airflow close to the AHU is needed. The available measuring techniques presented in this paper can be categorized as the pressure differential, velocity traversal, ultrasonic and tracer gas methods according to the measurement principle. All the equipment presented in this study requires minimum straight duct lengths to perform good measurements. On the other hand, the requirement for the available ductwork to place the sensor and provide sufficient straight length is rarely met in real buildings.

The orifice plate with pressure differential method could provide accurate airflow measurements, however, it causes high extra pressure loss and requires long straight duct. The orifice plate is not considered suitable for field duct airflow measurement and long-term monitoring due to its difficulty of

connection with existing ductwork and high pressure penalty. The velocity traverse and tracer gas methods have less interference with the airflows. The velocity traverse method is intuitive and easy to be performed. The tracer gas method is of specialization to be implemented and the analysis of the tracer gas result is relatively complicated. Both methods require intensive labour. The ultrasound method, as an emerging technique for airflow measurement, is able to measure the flow rates with low cost, no disturbance to the airflow and acceptable accuracy when the proper installation is provided. The measurements with UltraLink is slightly worse than the velocity traverse method with VelociCalc 8388 in terms of measurement accuracy. However, UltraLink is more automatic and need almost no extra labour once it is installed in the ductwork. The ultrasonic method is recommended as the most promising solution for duct airflow measurement if more options on device dimension are available with its development in the market. Additionally, the clamp-on ultrasonic equipment, which is typically used for liquid flow, would be recommended to be further developed and transferred to airflow application. The clamp-on solution will avoid the duct connection and could be applied to both existing and new systems without any disturbance for the airflow. A measuring uncertainty within ±3 % for airflow rate in the duct close to the heat recovery is pursued in order to obtain accurate heat recovery efficiency.

Acknowledgements

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