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Effect of sampling density on the reliability of airflow rate measurements in a naturally ventilated animal mock-up building

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ABSTRACT

Measuring natural ventilation rates in buildings with large vents with high accuracy and precision is not straight forward due to high spatial and temporal variabilities in the velocity distribution. Simplification of airflow rate measurements are mostly effectuated by lowering sampling density. Different sampling densities were investigated for both direct and tracer gas methods and compared with a detailed direct measurement method were in a naturally ventilated animal mock-up building. The results obtained by the reference method indicated that using only sampling locations in the middle of the side openings overestimated the airflow rate. In view of wind variations, better accuracy, precision and lower coefficients of variation were obtained with a higher number of sampling locations. The coefficients of variation varied between 5% for the reference and 29% using only one sampling location in the side outlet. In the ridge opening, only one middle sampling location was sufficient for an accuracy of 2% and a precision of 3%. The indirect tracer gas method gave varying concentrations with high confidence intervals resulting in non-significantly different measurement results between the different sampling strategies. The pattern of sampling locations was found to be very important resulting in different accuracies for a given sampling density.

1. Introduction

Ventilation in buildings is used for controlling indoor air parameters as temperature, relative humidity, velocity and chemical species concentrations [1]. Measurement of the ventilation rate for naturally ventilated buildings is not always straightforward because naturally ventilated buildings have large spatial and temporal variabilities in velocity in the vents and in the building [2–4], especially for (very) large vents as for e.g. dairy stables [5,6]. Models are available to support measurements for airflow rates through naturally ventilated buildings, but only a few are applicable to buildings with large vents as they are often excluded when high accuracy is needed [7]. Etheridge [7] suggested models for naturally ventilated buildings, using a discharge coefficient for the openings. However, because the velocity distributions in large vents are not strictly uni-directional (all velocities go in or out the opening simultaneously), the method using a discharge coefficient is not appropriate. For the same reason of potentially changing directions in the opening, the pressure difference method is not reliable for large vents either [3]. To measure natural airflow rates in livestock buildings, VERA [8] suggests the tracer gas method. However, according to this protocol, the proposed measurement technique cannot be applied when vents of the building are too open to allow proper mixing of the tracer (the assumption of homogeneity cannot be fulfilled and therefore high measuring uncertainty exists [4,9,10]). In the last version of the VERA-test protocol (2011, currently under revision) is written that no adequate method exists to measure the airflow rate when sufficient amount of air mixing. In practice, most experiments to assess natural ventilation in buildings with large openings use direct methods or tracer gas methods. A lot of these airflow measurements are conducted in the vents of a building. Especially when airflow rate measurements are combined with pollutant concentration measurements. The outlet is normally considered the most representative sampling location for emission measurements [3]. To measure the airflow rate, direct measurements combine velocity measurements in the vents with the surface area of the openings. Tracer gas measurements are based on conservation of mass of the tracer, while the tracer can be artificial [11,12] or natural [13–16]. However, for both direct and tracer techniques, air is locally sampled. Dense sampling of the full opening is recommended because of wind variations, but this approach is not realistic for large vents. So currently, the conven-

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tional way is to treat the velocity distribution of a vent as a mainly uniform profile using a limited sampling density [17], however, few or no calibration is conducted to compare this simplification to the true mean velocity over a surface. Choosing sampling locations that are representative of the full building or vent is crucial to obtain accurate measurements. The accuracy of a method is related to the number of measurement points used [18]. However, not only the number of sampling locations, but also the positions of the sampling points have an impact on the accuracy. Kiwan et al. [19] measured the velocity in the vent at three different heights and found that the velocity varied over the whole area of the opening and found the highest air velocities at the centre of the opening [20]. Not only air velocities, but also point concentrations of the tracer method are influenced by wind speed and wind direction [5]. The choice of sampling locations could result in errors up to 86% for measurements inside a mechanically ventilated building [21], so errors for naturally ventilated buildings could be expected to be higher due to effects of changing wind conditions.

Currently, for economical or practical reasons, measurement simplifications, mostly carried out by sampling along a horizontal line in the side vents [18,22–24], are applied without a prior study of accuracy against the actual airflow rate. Moreover, the airflow rates obtained by simplified methods, are being used as reference to test or calibrate proposed models. However, the main problem to determine uncertainties due to measurement reduction is the lack of a reference [21,25], especially when investigating the effect of using a limited number of sampling points on the uncertainties under changing wind conditions [23]. Ogink et al. [3] stated that few scientific reports on field measurements can be found concerning the effect of high variation of the wind velocity in the openings and the fact that measurements are sampled only locally. Because no reference technique is available in buildings with very large openings, the accuracy of airflow rate measurements cannot be determined, only the precision of the measurements. Nevertheless, measurement conditions (e.g. wind unsteadiness) are of great impact on measurement results of airflow rates and results of uncertainty analyses should therefore always be noted [4].

To overcome measurement uncertainties due to spatial and temporal variability in the opening, Van Overbeke et al. [26–29] developed a detailed direct measurement method to determine natural ventilation rates in a test facility. The detailed data generated by the experiments using this method, can be used to test accuracy and precision when reducing the number of measuring locations [26].

The objective of the current research is to determine the effects of sampling density on the uncertainty of airflow rate measurements in a naturally ventilated test facility. Both a direct measurement method using anemometers and a tracer gas method were compared against the reference method of Van Overbeke et al. [26–29].

2. Materials and methods

2.1. Test facility and experimental setup

All airflow rate measurements were conducted at a test facility in Merelbeke near Ghent, *Belgium (+50° 58′ 38.56″ N, +3° 46′ 45.68″ E)*. The building, a section of a typical pig stable in Flanders, was placed in the open field with the nearest building at 50 m distance. The dimensions and internal volume of the barn were ($12.0 \times 5.3 \times 4.9$) m (length x width x ridge height) and 251 m^3, respectively. The ridge opening had dimensions of (0.35×4.0) m, the two side openings measured *0.5 m × 3.0 m with a depth of 0.2 m*. The side openings were placed in opposite concrete walls, that faced SW and NE. The test facility was accompanied by a telescopic mast of 10 m height with a 2D ultrasonic anemometer (referred to further as meteomast) to know the wind conditions at all times. The test facility and its surroundings are described in detail in Van Overbeke et al. [29] and De Vogeleer et al. [30].

2.2. Airflow rate methods

2.2.1. Direct airflow rate measurements

Reference airflow rate measurements were obtained applying the technique developed by Van Overbeke et al. and also applied by De Vogeleer et al. [30] using a high sampling density of direct wind velocity measurements [26–29]. The velocities in the opening were densely measured using ultrasonic anemometers in the vent openings and the airflow rate was calculated as a result of the multiplication of the measured air velocities and the surface areas representing the respective air velocities.

$$\boldsymbol{Q} = \sum_{1}^{\boldsymbol{n}} \left(|\bar{\boldsymbol{Y}}| \times \boldsymbol{A_n} \times 3600 \right) \quad (1)$$

Where:

Q = airflow rate (m^3/h)

$|\bar{Y}|$ = average normal (to the surface area) velocity component (m/s)

A_n = surface area of sampling location, related to N (m^2)

n = total number of surface areas (−)

The ridge opening was equipped with 8 fixed *2D* ultrasonic anemometers (Thies®, Göttingen, Germany) equally spread over the length of the opening and mounted as much as possible close to the axial symmetry of the ridge.

Each side opening was equipped with a single *3D* ultrasonic anemometer (Thies®, Göttingen, Germany) fitted in an automated linear guiding system to allow measurements at 48 predefined locations in the opening (4 rows and 12 columns). For this study solely the velocity components normal to the opening were analysed.

The sensor had a measuring speed of 250 Hz and every 1 s these measurements were averaged and logged. Each sampling locations was sampled during 10 s before moving to the next one. One measurement round was obtained after measuring all 48 locations within the duration of approximately 1h 36 min. In total ten such measurement rounds were conducted sequentially. The velocities per sampling location were averaged over 10 measurement rounds.

Using this method, an accuracy of (−8 ± 5)% was obtained for in- and outgoing airflow rates through the building [29].

Measurements were executed continuously day and night over a period starting from December 2014 through March 2015.

2.2.2. Indirect airflow rate measurements

The constant injection method was used to determine the airflow rate using tracer gas measurements. The method is based on mass conservation of the tracer. The tracer is injected into the building with a constant volume rate. The dilution of the tracer in the air is a measure for the airflow rate [2]. The tracer, carbon dioxide CO_2, also used in the method suggested by VERA, was selected because it is one of the least polluting tracers and because it is nontoxic to humans in the concentrations used. The volume rate of the tracer was chosen so the concentration of the mixed air was easily detectable and at a level of normal CO_2 concentrations in a (dairy) barn.

The tracer was released not in the supposed inlet, but in the middle of the building with a 6 point source at ground level (Fig. 1). After charging the test facility with tracer, to ensure a mixture as homogeneous as possible, measurements were started 10 min after the start of the gas release. The injection rate was set to a constant value during the complete experiment. The CO_2/air mixture was sampled