Environmental Engineering and Management Journal
September 2014, Vol.13, No. 9, 2193-2200
http://omicron.ch.tuiasi.ro/EEMJ/

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SPATIAL DISTRIBUTION OF AIR FLOW AND CO_2 CONCENTRATION IN A NATURALLY VENTILATED DAIRY BUILDING

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Abstract

Air flow measurements as well as concentration measurements within a naturally ventilated dairy barn (NVD) were carried out during one summer season of 2012. Air flow measurements were performed using ultrasonic anemometers (UA), either as short duration (20 min duration) measurements with a higher spatial distribution (using up to 9 UAs at the same time) or as long period (roughly 2 weeks) measurements with a lower spatial resolution (3 to 5 UAs). Measurements were conducted at two heights, at 1.5 m within the animal occupied zone (AOZ) and at 2.6 m height above the AOZ for understanding the distribution of airflow within the building. The three wind components (u, v and w) were measured either as lateral profile or evenly distributed at the ground area of the building. The results showed that wind speeds measured at the height 2.6 m were generally smaller than wind speeds measured at the height 1.5 m. The analysis of the lateral profile showed that only the first third of the wind facing side seem to benefit from the approaching wind. The long term measurements (duration 2 weeks) showed a high variability in the data and a correlation analysis showed lower CO_2 concentrations for higher wind speeds. However, the linear correlation was weak (p= -0.7), which implies that the relationship cannot be described simply by a linear correlation.

Key words: air flow, CO_2 concentration, natural ventilation, spatial distribution

Received: March, 2014; Revised final: August, 2014; Accepted: September, 2014

1. Introduction

Emissions of aerial pollutions from livestock buildings are a major subject of the environmental policy. Especially for natural ventilated buildings it is difficult to quantify the emission rates for regulatory purposes or the establishment of national inventories. The emission rates depend on varying factors such as the air exchange rate due to ventilating air which transports the pollutants (Saha et al., 2010) and the distribution of pollutant concentrations within the building. However, the air flow pattern is the most important factor for determining the ventilation rate and the distribution of pollutants within the building (Morsing et al., 2008; Ngwabie et al., 2009).

The air flow pattern within naturally ventilated buildings is strongly influenced by the outside wind and weather conditions, the size and distribution of in- and outlets, the building geometry and its surrounding buildings as well as inside constructions and the heat production by the animals. It is difficult to determine the ventilation rate and

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indirect methods are usually applied, such as the use of tracer gas (Samer et al., 2011) or the CO_2 balance method (Pedersen et al., 2008). The tracer gas method, whereby the decay curve of a tracer gas is determined, requires a perfect mixing of the air inside with the tracer, which is almost impossible to achieve (Chen, 2009).

For the CO_2 balance, the CO_2 concentrations must be recorded with a high resolution of time and space throughout the barn because the wind field causes significant variations in the measured CO_2 concentrations. Van Buggenhout (2009) found in their study that variations in the ventilation rate can rise to 86% depending on the chosen sampling points within the building. Saha et al. (2014) showed that the calculated air exchange rates vary strongly depending with the number and position of sampling points chosen. Thus, understanding the gas distribution and the corresponding flow field is essential.

In the literature only few field studies of the airflow patterns within livestock buildings with forced ventilation can be found (Hoff, 1995; van Wagenberg and de Leeuw, 2003). Several studies were conducted inside experimental buildings (Bjerg et al., 1999; Harral and Boon, 1997; Heber et al., 1996; Smith et al., 1999; Teodosiu et al., 2014). Most of the experimental buildings provide the advantage of defined outer boundary conditions because most were equipped with ventilation fans. These fans lead to some kind of forced ventilation of the outside conditions that may differ from the air conditions of a naturally ventilated livestock building. In wind tunnel studies (Ikeguchi and Okushima, 2001; Ikeguchi et al., 2003) the focus lay on the transport of gas from naturally ventilated buildings to their surroundings rather than on the airflow distribution inside the buildings. De Paepe et al. (2012) found in their wind tunnel study that the ventilation opening height affect the internal air velocities of simplified scale models. They found that lowering the inlet openings increased the internal air velocities in the simplified model. Numerical simulations allow more detailed information of air flow patterns in natural ventilated buildings.

Several studies used the Reynolds Averaged Navier Stokes (RANS) CFD simulation (Harral and Boon, 1997; Wu and Gebremedhin, 2001; Bartzanas et al., 2007; Teitel et al., 2008; Norton et al., 2009) but in most studies the ventilation openings were much smaller than complete open side walls of dairy buildings which are common in Germany.

Also, the results of air flow patterns from numerical simulations strongly depend on the chosen turbulence closure model (Bartzanas et al., 2007) and therefore need to be validated. Thus, field data preferably with a high spatial distribution is needed to serve as validation. In this study, spatial distributed velocity measurements as well as CO_2 concentration measurements in a naturally ventilated dairy barn were conducted. The air flow measurements were obtained next to a horizontal distribution in two heights and are therefore an extension to a study presented by Fiedler et al. (2013) at the same location.

2. Materials and methods

2.1. Building and site description

The experimental site is located in northeast Germany (at 54°1′0′′N, 12°13′60′′E, altitude 43 m). The dairy building is 96.15 m long and 34.2 m wide (Fig. 1). The height of the sheet metal roof varies from 4.2 m at the sides to 10.73 m at the gable top. The room volume of the building is 25,499 m^3 (70 m^3 per animal). During the presented measurements periods around 375 cows were accommodated in loose housing with freestalls in the NVD building. The building has a concrete solid floor and the manure handling takes place with a winch-drawn dung channel scraper.

The dairy building is naturally ventilated by the complete open long sidewalls (protected by nets) with adjustable curtains (polyethylene film, 1 mm), which were open fully during the field campaigns. The building roof is equipped with solar panels, which resulted in a nearly closed open ridge slot. The gable walls were a wooden space board (11.5 cm width and 2.2 cm thickness and spaced by 2.5 cm) at the western side of the building and a sheet metal wall at the eastern side. Each gable wall was equipped with one gate (size 4m × 4.4m) and 4 doors with adjustable curtains (where two doors are 3.2 m × 3 m, and two doors are 3.2 m × 4 m). The gates and the doors were open during field campaign. Three additional ceiling fans (Powerfoil® X2.0, Big Ass Fans HQ, Lexington, KY, USA) were mounted on the ceiling along the building centreline.

Normally, the fans are used to enhance the uniformity of air distribution inside the building during the summer season, but they were turned off during the experiments. The aim was to study the indoor spatial distribution of wind and CO_2 in relation to the outside wind conditions. The surrounding of the investigated NVD building is complex. On the Northern side a milking parlour, another dairy building, and a forage storage building are located. On the Eastern side manure storage tanks and on the north-eastern side a young stock house and workshop are located. The southern and western sides are surrounded by open fields (Fig. 2).

The layout of the field site shows that the approach flow conditions for the investigated barn differ depending on the outside wind direction. Hence the wind field inside is expected to be influenced differently for varying outside boundary conditions.

2.2. Experimental set-up

Measurements of the airflow as well as concentration measurements were conducted in two campaigns in August and September 2012.

Fig. 1. Outside view of the investigated barn

Airflow measurements were carried out with ultrasonic anemometers (UA, Windmaster Pro ultrasonic anemometer, Gill Instruments Limited, Lymington, Hampshire, UK). The three wind components (u, v and w) were measured as time series with a temporal resolution of 1 Hz.

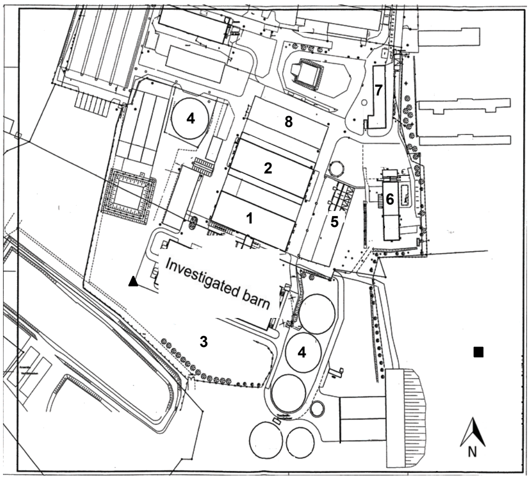


Fig. 2. Overview of the investigated field site with (1) another dairy barn, (2) a milking parlour, (3) an open field, (4) a manure storage area, (5) a young-stock house, (6) a workshop, (7) an administration building and (8) forage storage buildings. Triangle (▲) indicates position where outside wind was measured as local reference point, and square (■) denotes the location of the weather station

The measurements were performed either as short duration (20 min duration) with a higher spatial resolution (using up to 9 UAs at the same time) or as long period (roughly 2 weeks) measurements with a lower distribution (5 UAs). Air flow measurements were conducted within the animal occupied zone (AOZ) at 1.5 m (only short term measurements) and 2.6 m height for understanding horizontal distribution of airflow inside the NVD barn.

Short term measurements were measured either as a lateral profile in 2.6 m height (triangles in Fig. 3) or evenly distributed within the animal zone (squares in Fig 3) at 1.5 m height. All short term measurements were carried out at four zones in the barn (colored areas in Fig. 3) that correspond to four different groups of animals. Data were collected separately from each zone but simultaneously within each zone during milking (when the animals leave the building in four different groups). This procedure ensured that the animals could not harm the instruments but limited the measurement time and record length for the building section from which the cows (group 1 to group 4, see Fig. 3) were milked. This led to the limited significance of the short term samples (a higher number of samples would be needed to increase the significance of the data). Therefore, long term measurements were added. However, the long term measurements could be carried out only above the AOZ in 2.6 m height and their locations are also shown in Fig. 3 as gradients.

Concentration measurements of gases (i.e. carbon dioxide (CO_2)) were measured continuously at eight measuring points at six locations within the barn and four locations outside. At two of the six locations within the barn, the CO_2 concentrations were measured at two heights 0.2 m and 2.6 m above ground and at the other four locations at 2.6 m height. Gas concentrations were measured using an infrared photo-acoustic analyzer (INNOVA 1312, Innova AirTech Instruments, Ballerup, Denmark) with 12 sampling points. The concentration measurements took place in a continuous sequence.

Outside weather and wind conditions were recorded by a weather station (DALOS 515c-M, F&C Forschungstechnik & Computersysteme GmbH, Gülzow, Germany) located near the NVD building (i.e. 150 m east of the building). Additionally, to obtain more local reference for the air flow measurements, velocity was measured near the barn (triangle in Fig. 2) with an ultrasonic anemometer (UA) (Model 81000, R.M. Young Company, Traverse City, Michigan, USA) with the same time resolution as the inside measurements.

2.3 Data analysis

For all air flow measurements a time series of raw data for the single wind vector components u, v and w (on the x-, y- and z- axes) was recorded. The internal coordinate system of the anemometer does not agree with the meteorological conventions that are defined as follows: positive u for wind components directed from west to east, positive v for wind components directed from south to north and positive w for upward wind motion.

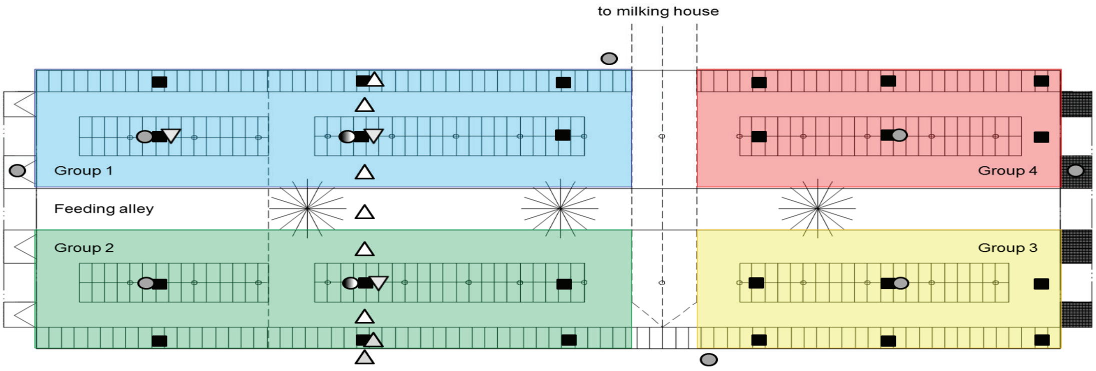


Fig. 3. Layout of the experimental set-up.
Black squares indicates air flow measuring point at 1.5 m height, white triangles indicates air flow measurements at 2.6 m height, gradients indicates long term air flow measurements at 2.6 m height, circles indicates concentration measuring points, where black and white filling indicates concentration measuring points at two heights (1.2 and 2.6 m height). Coloured areas indicate occupied zones with the four groups of animals

Therefore, the raw data were rotated to correspond with the meteorological conventions and the rotated data are used for the further analysis Averages of the data were calculated as followed:

Mean of the wind components (Eq. 1):

$$\overline{u} = \frac{\sum u_i}{N} \quad \overline{v} = \frac{\sum v_i}{N} \quad \overline{w} = \frac{\sum w_i}{N} \tag{1}$$

The horizontal wind speed (Eq. 2):

$$V_{hor} = \sqrt{\overline{u}^2 + \overline{v}^2} \tag{2}$$

Total mean wind speed (Eq. 3):

$$V_{3D} = \sqrt{\overline{u}^2 + \overline{v}^2 + \overline{w}^2} \tag{3}$$

The wind direction (calculated from the u and v components with trigonometric functions using the meteorological conventions where the angle gives the direction from which the wind is blowing – for example a northern wind at 360° is blowing from the north) (Eq. 4):

$$WD = 360 - \left(\tan^{-1}\left(\frac{\overline{v}}{\overline{u}}\right)\frac{180}{\pi} - \left(\frac{abs(\overline{u})}{\overline{u}} - 1\right) \times 90 + 90 \right) \tag{4}$$

3. Results and discussion

3.1. Climate conditions

Table 1 gives an overview of the outside climatic conditions obtained by the weather station during the short term experiments. The temperature and humidity differences within the barn and between inside and outside of the barn were < 2°C and < 15%, respectively.

3.2. Spatial distribution of short term measurements

The short term data showed a high variability, therefore in a first step the data were sorted by wind direction from the outside local reference measurements. The data were sorted in eight different wind sectors of 45° as shown in Fig. 4. The sectors were not chosen according to the geographical orientation of the building, but according to the approach flow direction to the building.

Table 1. External climatic conditions obtained by the weather station during the short term measurements
Short term measurements points were evenly distributed according to squares in Fig. 3 except of 18.9.2012 where the lateral profile (triangles in Fig. 3) was measured

Campaign	*Date*	*Measurement locations in*	*T [°C]*	*RH [%]*	*Wind direction*	*V_{hor} [m s^{-1}]*
1	07.08.12	Group 1	16	96	Not available	Not available
		Group 2	18	95		
	08.08.12	Group1	17	86	Not available	Not available
		Group 2	17	83		
		Group 3	18	86		
		Group 4	19	80		
2	18.09.12	Group 1	21	54	SW	2.2
		Group 2	21	55	SW	1.5
	19.09.12	Group 1	15	55	W	2.8
		Group 2	14	58	N	2.4
	20.09.12	Group 3	8	100	SSW	1.4
		Group 4	11	90	SSW	1.7

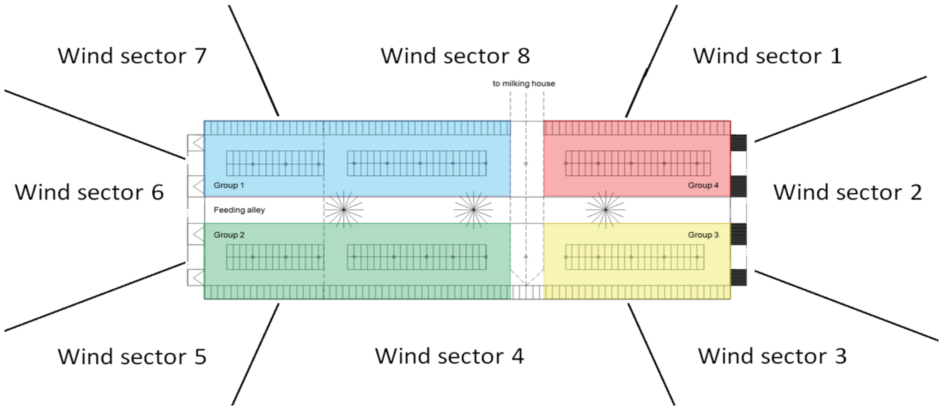


Fig. 4. Sketch of wind sectors of approach flow

In a second step the horizontal wind speed (Eq. 2) was calculated and normalized with the horizontal wind speed of the outside local reference (location marked with triangle in Fig. 2).

In this way the variability of the data could be decreased by reducing the influencing factor "outside wind speed". The ratios $V_{hor,\ in}/V_{hor,\ out}$ are shown in Fig. 5 for four different approaching flow sectors (sector 3 to 6) of the defined wind sectors. These sectors represent the main sectors of the measured approaching flow. Approaching flows from the other sectors occurred at roughly 15% from the total data set.

3.2.1. Vertical spatial distribution

A statistical summary of the obtained data at the four selected wind sectors for the two heights 1.5 m and 2.6 m is given in Table 2. Included in this table are all short time measurements, which were conducted in the AOZ when the animals went to milking. The mean wind components recorded at two heights are in the same order of magnitude, except of the v component. The median of the v component obtained at the height 2.6 m was much smaller than that obtained at 1.5 m. The flow at height 2.6 m should be less disturbed by inside constructions, which may cause these differences. However the variability of the wind speed components, expressed by the standard deviations, were not lower at 2.6 m height. The vertical wind component was close to zero for both heights, because of the absence of the animals. Therefore no significant difference between the horizontal wind speed and the total wind speed was observed. The medians of the V_{3D}/V_{out} ratio was roughly ¼.

Fig. 5 gives a more detailed view of the data. In general, the ratios $V_{hor,\ in}/V_{hor,\ out}$ obtained at the height 2.6 m were lower than the ratios obtained within the AOZ at the leeward side of the building. To explain this effect by a certain flow pattern a more detailed study of the air flow pattern within the barn would have to be investigated either by more measurement points in the field or wind tunnel studies as well as numerical studies. It is difficult to compare the findings of existing numerical simulation studies (Norton et al., 2009; Bartzanas et al., 2004) with the results found in this study. In both studies, zones in a naturally ventilated building exist where the wind speed at higher levels was lower than in lower levels.

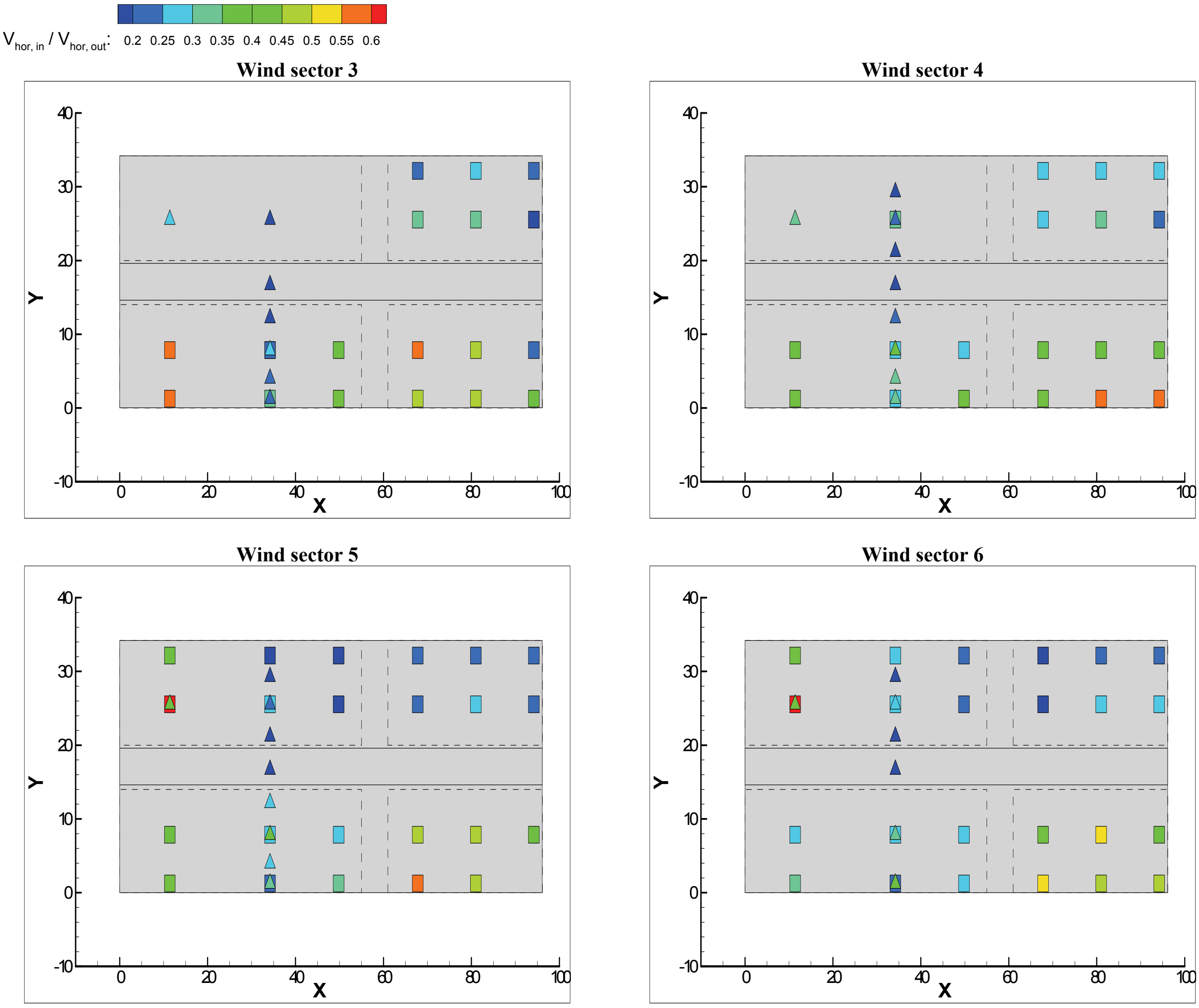
However, the investigated buildings in both studies had much smaller inlet openings and therefore are not suitable to draw conclusions on the findings presented in this study. It is recommended to do further research to get more knowledge on the processes, for example in wind tunnel studies which supply highly resolved data.

3.2.2. Horizontal spatial distribution

Fig. 5 shows generally lower wind speeds on the leeward side of the barn. Especially in group 4, low horizontal wind speeds were measured. These findings are in line with a former study by Fiedler et al. (2013). In this study the dependency of the wind patterns on the wind direction are not very pronounced.

Table 2. Statistical summary of the obtained data at the four selected wind sectors at two heights for the short term measurements (average values)

Height [m]		*u* *[m s^{-1}]*	*v* *[m s^{-1}]*	*w* *[m s^{-1}]*	σ_u *[m s^{-1}]*	σ_v *[m s^{-1}]*	σ_w *[m s^{-1}]*	V_{3D} *[m s^{-1}]*	V_{3D}/V_{out} *[-]*
1.5	95% Quantile	0.61	0.38	0.19	0.88	0.62	0.24	0.62	0.44
	Median	0.42	0.11	0.07	0.52	0.41	0.17	0.45	0.24
	5% Quantile	0.10	-0.45	0.03	0.30	0.30	0.13	0.25	0.12
2.6	95% Quantile	0.90	0.53	0.08	0.90	0.62	0.33	0.90	0.34
	Median	0.45	0.01	0.02	0.58	0.48	0.25	0.52	0.25
	5% Quantile	-0.04	-0.26	0.00	0.37	0.28	0.16	0.32	0.15



Wind sector 3

Wind sector 4

Wind sector 5

Wind sector 6

Fig. 5. Spatial distribution of the normalized horizontal wind $V_{hor,in}/V_{hor,out}$ for the four different wind sectors 3, 4, 5, and 6 as shown in Fig. 4. Grey area indicates the barn area. X- and Y- axis the distance in [m].

For approaching wind from sector 3 the highest values of the ratio $V_{hor,\,in}/V_{hor,\,out}$ were found on the wind-ward side and not as expected from the approach flow normal to the building (from sector 4).

The lowest values of the ratio $V_{hor,\,in}/V_{hor,\,out}$ for the wind-ward side were found in sector 6. Here, the space board has the most influence from the investigated approaching wind sectors. The differences in the ratio $V_{hor,\,in}/V_{hor,\,out}$ patterns were obtained by the same type of approaching flow (open field, compare to Fig. 1), where only the orientation of the building was different for the investigated wind sectors but it should be kept in mind that these results based on short term measurements.

Though, Fiedler et al. (2013) showed in their study that a complete different approach flow from North which is disturbed by the surrounding buildings led to a different flow field. Latter finding is also supported by literature (Ikeguchi et al., 2003; Norton et al., 2009).

Because of the obtained low wind speeds on the lee-ward side of the building, an estimate of the impact from the outside wind to the inside barn should be investigated. For this purpose, the time series measurement of the lateral profile was analyzed separately. The horizontal wind was calculated as the mean value over the whole measurement period of 20 min and the correlation between the outside measurement and the inside measurements were calculated. The outside approaching wind during these measurements was from sector 4, which meant the wind was blowing normal to the wind protecting net. This should be the most effective ventilation situation.

The results are shown in Fig. 6. The horizontal wind speed of the lateral profile in front of the wind protecting net was 0.83 m/s and decreased to 0.45, 0.45, 0.44, 0.3, 0.23 and 0.16 m/s at 0.5, 3, 6.5, 10.5, 16.5 and 25.5 m distance from the wind protecting net respectively within the building.

The Pearson correlation coefficient of the horizontal wind speed between the outside measurement directly in front of the wind protecting net and the inside measurements was approximately p

= 0.5 for the first two measurement points at 0.5 m and 3 m, decreased to p= 0.2 at 10.5 m and p=0.03 at 16.5 m (roughly at the barn centreline) distance from the wind protecting net within the building. This leads to the conclusion that the first third of the windward-side of the building benefits the most from the approaching wind.

3.3. Long term measurements

Short term measurements represent only a random sample therefore the results of long term measurements at two measurement locations along the lateral profile are presented. Fig. 7 shows box plots of long term measurements of wind speed and CO_2 concentrations. Generally the data show a high variability which complicates the interpretation. For this measurement period a Pearson correlation coefficient of about -0.7 between CO_2 concentration and wind speed was found. The higher wind speed led to lower CO_2 concentrations, which was also found by Saha et al. (2013). Fig. 7 shows CO_2 concentration measurements of two heights. It show a significantly higher CO_2 concentration measured near above ground (due to the presence of animals) in contrast to short term measurements without presence of animals (which showed nearly no difference between two heights). This phenomenon indicates that airflow was obstructed by the animal, hence increased concentration in AOZ.

4. Conclusions

An analysis of a lateral profile of measured wind speeds indicated that only the first third of the windward-side benefits from the approaching wind. This fact has strong implications on the barn climate and animal welfare in less ventilated spaces and needs further investigation.

A linear correlation (with a weak correlation coefficient of -0.7) showed lower CO_2-concentrations for higher wind speeds which implies either that the data amount is not sufficient or the relationship is nonlinear.

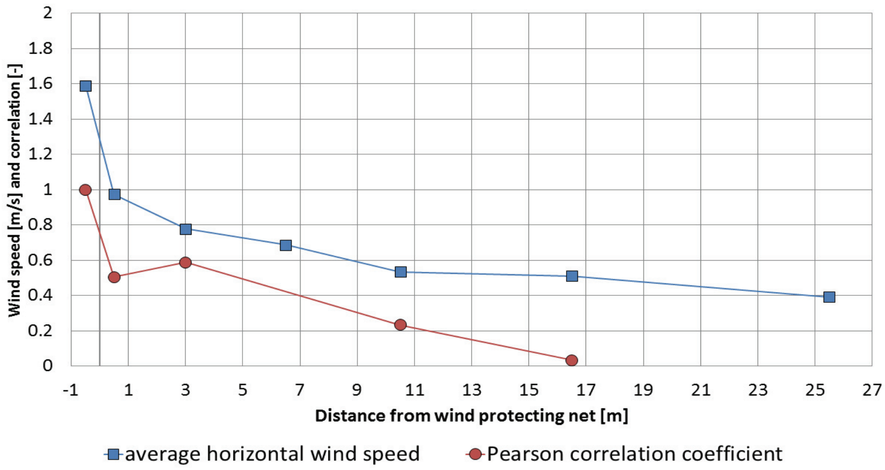
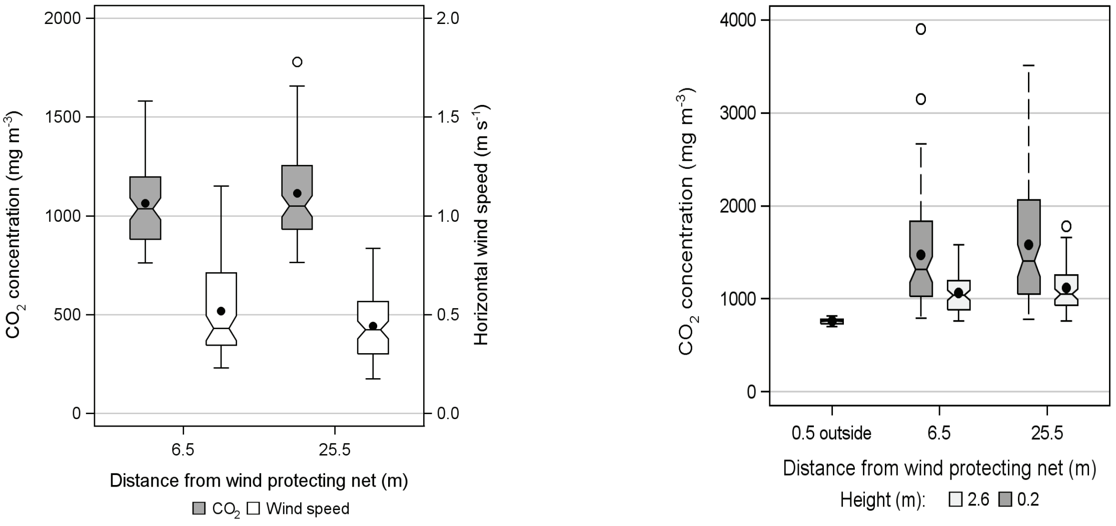


Fig. 6. Measurements of the horizontal wind speed for a lateral profile within the NVD. Squares indicates the correlation of the outside measuring point directly in front of the wind protecting net with the inside measurements



a **b**

Fig. 7. Box plot of long term measurements (roughly two weeks): a) CO_2 concentrations and wind speed at 2.6 m height for two measurement locations, b) CO_2 concentrations for two heights 0.2 and 2.6 m

Because of the variability of the outside boundary conditions further investigations in controlled laboratory conditions, such as a boundary layer wind tunnel, are required.

Acknowledgements

The authors would like to acknowledge U. Stollberg and K. Schröter, technicians at the Department of Engineering for Livestock Management at the Leibniz Institute for Agricultural Engineering Potsdam-Bornim (ATB) in Germany, for their technical and logistical support during the measurements. Furthermore, we gratefully acknowledge the contribution of O. Tober at the Institute for Animal Production, State Institute for Agriculture and Fishery MV, Dummerstorf, Germany, for his technical and logistical support during the measurements. Second author thankfully acknowledge Alexander-von-Humboldt foundation for a post-doctoral research fellowship.

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