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Flow fields within a dairy barn – Measurements, physical modeling and numerical simulation

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Abstract

The present study investigates airflow characteristics of a naturally ventilated dairy barn with three methods: Field measurements, boundary layer wind tunnel measurements and numerical simulations (CFD). The field data are used to implement and validate the wind tunnel study and the numerical simulations.
The field measurements of the flow field inside the building showed a significant decrease from the luv-side-wall to the centre of thee bulding. Dimensionless wind speed data was used for better comparison of the wind tunnel measurements data and the numerical simulation data with the field data. In the wind tunnel, a model of the investigated barn was built at a scale of 1:100. Experiments presented here were performed with the barn only and neglected the wind protecting net. Flow field measurements within the scaled model were carried out with a 2D-Laser-Doppler-Anemometer (LDA; Dantec©). For all experiments the same measurement locations as in the real situation were chosen. The normalised profiles from the wind tunnel show the same shape as the measured normalized profile in the field.
The numerical simulations were realized with the open source C++ toolbox OpenFOAM. The real setup was implemented into 2D numerical domain (mesh). Different methods were used as well as different initial conditions for the wind profile. The analysis gives detailed information on the air flow characteristics and on the air flow dynamic inside the naturally ventilated building.
The aim of the study is to bring all results of the used methods together to enhance the dataset from the field and to gain more information of the airflow and ventilation of dairy cow barns.

Keywords: flow-field, CFD, wind-tunnel, natural ventilation

1 Introduction

Dairy cow housing in temperate zones are designed often as open-fronted buildings with natural ventilation and wind netting as the only protection on the long sides, which means indoor climate is directly influenced by the outdoor weather conditions (temperature, relative humidity and wind). The wind is hereby a significant factor, that influences the distribution of heat, air moisture, gases and other substances within the barn and also determines the ventilation rate of the building that removes the mentioned components from the barn. Thus, understanding of indoor airflow characteristics is essential to understand and validate the airflow dynamics and ventilation rate in a naturally ventilated barn (NVD). Additionally, the ventilation rate determines the pollutant emission rates (e.g. Saha et al., 2010) which serve as the source for dispersion and the immission processes and is the basic research for important topics in agricultural research.

However, determining the air exchange within a naturally ventilated dairy cow barn is a difficult task because the approach flow is highly variable due to the local turbulent wind field around the building. Accordingly, the conditions continuously change the airflows at their inlet and outlet points. In order to identify the air exchange processes directly, wind velocity and direction must be measured as comprehensively as possible over the respective cross sectional areas of all the openings of the building (Kiwan et al., 2012). In practice this is only possible with disproportionately high measurement instrumentation and costs. Because of this, more indirect methods such as the use of tracer gas (e.g. Samer et al., 2011) or CO_2 balancing (Pedersen et al., 2008) are usually applied for determining air exchange. The tracer gas method, whereby the decay curve of a tracer gas is determined, requires a perfect mixing of building interior air with the tracer gas, which is almost impossible to achieve (Chen, 2009). For the CO_2 balance, the CO_2 concentration must be accurately recorded throughout the barn because the wind field causes significant variations in CO_2 concentrations (Ngwabie et al., 2009). Determined ventilation rates vary strongly depending on the chosen number and location of different sampling locations (Van Buggenhout, 2009 and Saha, 2013). Further, measurements have to take place over long periods of time in order to obtain statistically representative data. This is not only complicated but also associated with very high costs and almost impossible to carry out in practice.

It is therefore effective to complement data recorded in practice with recordings made in a boundary layer wind tunnel and results from numerical simulation, which supply information about the flow field inside and outside natural ventilated buildings. Physical modelling provides statistical sound representative data under controlled laboratory conditions with a 3D resolution of turbulent flow. Numerical simulations allows a better understanding on air flow conditions which can only be investigated partly in the field or in the wind tunnel, but need to be validated because they use parameterisations by the solution of turbulent flow describing equations.

In this study, exemplarily air velocity measurements recorded at one line in streamwise direction within the barn from a wind tunnel study and numerical simulation are presented here in order to examine how they can enhance the database of the airflow and ventilation of dairy barns.

2 Materials and methods

2.1 Field measurements

The investigated NVD is located in the North East of Germany and the layout of the field site is given in Fig. 1. The NVD building is 96 m long, 34 m wide and the height (H) varies from the side wall H = 4.2 m to the gable top of H~10 m. The indoor volume amounts to 25500 m³ (70 m³/animal). The dairy building was naturally ventilated by air introduced into the building through adjustable curtains in the sidewalls (which were protected by nets), space boards of one gable wall at the western side, and open doors in both gable walls. An open ridge was

closed by newly mounted solar panels. The barn is oriented such, that the long side wall is facing the prevailing wind direction.
Field measurememts of flow properties of the NVD are investigated in cooperation with the Institute for Animal Production of the State Research Institute for Agriculture and Fisheries, Mecklenburg-Vorpommern.

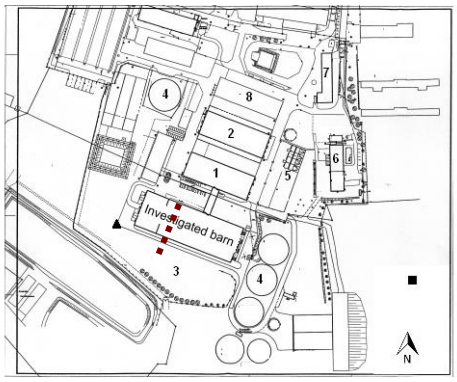


Figure 1: Overview of the investigated field site with (1) another dairy barn, (2) a milking parlour, (3) an open field, (4) a manure storage area, (5) a young-stock house, (6) a workshop, (7) an administration building and (8) forage storage buildings. Triangle (▲) indicates position where outside wind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

2.1.1 Experimental Set-up

The air flow measurements presented for this study were conducted with ultra sonic anemometers (UA) at 2.6 m height as a lateral profile (red dotted line at the investigated barn) at sampling points 0.5 m in front of the wind protecting net on the prevailing wind facing side and within the building at 0.5, 3, 6.5, 10.5, 16.5 and 25.5 m distance from the wind protecting net within the building (compare Fig. 2). The single wind vector components u, v, and w (on the x-, y- and z- axes) were recorded as raw data time series of 20 min duration. The sampling frequency for all air flow measurements was 1 Hz.
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. Therefore, the raw data were rotated to correspond with the meteorological conventions and the rotated data are used for the further analysis. The procedure is similar to that described in Fiedler et al. (2013) and the measurements presented here are an extension of the mentioned study.

2.2 Wind tunnel study

Experiments are carried out at the Boundary Layer Wind Tunnel (BLWT), Leibniz Institute for Agricultural Engineering Potsdam-Bornim (ATB). The BLWT is 20 m long, 3 m wide and has an height of 2m. It is equipped with an adjustable double ceiling up to 0.25 m to ensure a constant pressure gradient (according to the VDI-guidelines, 2000). The inlet of BLWT is fitted with honeycombs inlet nozzle and the contraction ratio between inlet nozzle and testsection is 1:4. An axial fan of diameter of 2.8 m is sucking the air through the test section, by which inlet wind speed can be reached up to 20 m s^{-1}.
A detailed scaled model of the investigated field barn was built in the scale 1:100, because of the structure of agricultural buildings (long, but flat buildings) to get a better overview of flow fields within the model. The model was built with a transparent acryllic glas which allowed flow measurements within the building with a Laser-Doppler-Anemometer (LDA). The model was placed 13.3 m behind the inlet to ensure a fully developed approaching flow in front of the model. The blockage of the model to the wind tunnel cross-section was 1.7% which is below the limit of 5% for closed test-sections (VDI, 2000). Larger models would lead to a

tunnel effect between the model and the wind tunnel wall (e.g. De Paepe et al., 2012) and influence the wind entering and exiting the house through the ventilation openings.
All experiments presented here were performed with the single barn (without surrounding buildings) and without the wind protecting (model) net.

2.2.1 Experimental Set-up

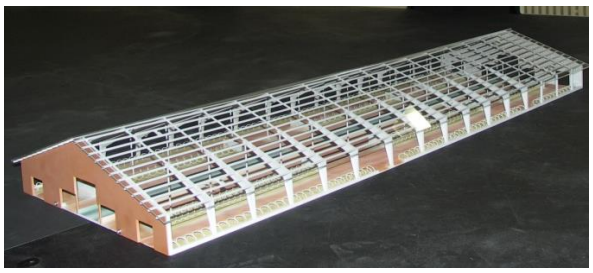
Flow measurements within and around the model were carried out with a 2D- LDA (Dantec©). The approach flow conditions are documented in detail as described below. First, the vertical profile of the time-averaged velocity u_z was described with the following exponential function

$$u_z = u_{ref}\left(\frac{z-d_0}{z_{ref}-d_0}\right)^{\alpha} \qquad \text{(eq. 1)}$$

Where z_{ref} is the reference height in m, u_{ref} is the average wind velocity at height z_{ref}, d_0 the zero plane displacement height in m and α the profile exponent. Also the logarithmic law was used for the near wall flow

$$\frac{u_z}{u_*} = \frac{1}{\kappa}\ln\left(\frac{z-d_0}{z_0}\right) \qquad \text{(eq. 2)}$$

Where u_* is the friction velocity, κ is the Karmann constant (~ 0.4) and z_0 the roughness length in m.
The parameters α, z_0 and d_0 related these flow properties to a terrain type in the field. Next to the presented parameters also the vertical turbulence intensity profiles, vertical turbulent flux profiles, the spectral density distributions of the kinetic energy of turbulence as well as the integral length scales were documented.
The approach flow condition correspond to a rural boundary layer (as it is defined by the VDI guideline, 2000) and was created by using spires in the inlet and roughness elements in the flow establishment section of the tunnel. By this way it was possible to create a rural boundary layer that was estimated by the integral lengthscale L_{ux} and the turbulence intensity profiles to a scale of 1:300. The mean wind profile was estimated with a profile exponent α = 0.19 and a roughness length z_0 = 0.15 m, which can be classified to the roughness class rough to moderately rough. The profiles of the turbulence intensity that could also be classified to the roughness class rough to moderately rough. However, the integral length scale showed slightly smaller values than provided by the overview of Counihan (1975). Altogether this boundary layer showed good agreement to the boundary conditions in the field, but does not match to the model scale which is 1:100. Therefore these flow measurements are not directly transferable to the field results. However, the boundary layer can be used for general systematic investigations and also for validation of numerical models.
For all experiments presented here, a lateral profile located on the same position in the model as the presented measurements in the field was measured. The single locations are shown in Figure 2.



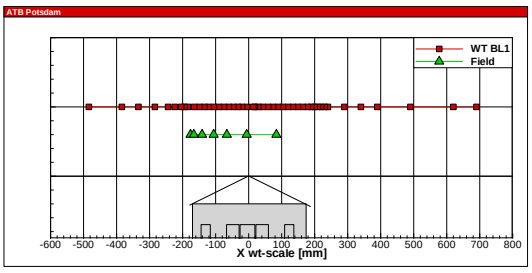


Figure 2: Left: model of the dairy barn. Right: Resolution and positions of the measurement locations of the lateral profile (compare red dotted line in Fig. 1). Green triangles: locations in the field, red squares: measurement locations in the wind tunnel model.

2.3 Numerical simulation

The numerical simulations are realized with the open source C++ library OpenFOAM, which is a very powerful alternative to commercial tools like ANSYS with a rapidly growing professional user community world wide. The real setup of the barn is implemented into a 2D numerical domain (mesh). An LES 1-equation model is used to describe energy transfer into the sub-grid scales. To solve the problem the incompressible Navier-Stokes equations with suitable initial and boundary conditions given by the real setup are solved.
As boundary condition at the inlet of the building the logarithmic wind profile for turbulent atmospheric boundary layers are implemented (eq. 2). And the friction velocity u_* is calculated as follows

$$U^* = \kappa \frac{U_{ref}}{\ln\left(\frac{z_{ref}+z_0}{z_0}\right)} \qquad \text{(eq.3)}$$

For U_{ref}=10 m/s at reference height z_{ref}=200m, κ=0.41 is the Karman's constant, z_0 = 0.01 ist the roughness of the surface.
The Reynolds number of the given setup is Re ~ 3.6e7. The Mesh has about 1.2e6 grid points. We use the solver pisofoam to solve the problem. For more informations of the numerical aspects of implementaton see the online user guide of OpenFOAM at www.openfoam.org.

3 Results and Discussion

3.1 Field measurements

The profile flow measurements for the mean and root-mean square value of the streamwise velocity component U within the barn are shown in Figure 3. All results were normalized by the measured out side wind speed at the reference point (Fig. 1). For the presented measurements the outside measured wind speed was 2 m/s blowing from 216°, which is roughly perpendicular to the barn.
The normalised profile U/Uref showed directly behind the inlet at the wind protecting net a maximum value of 0.2. Then the values decrease for the first 4 measurement positions within the barn and hold low values at the other measurement positions (left side, Fig. 3).

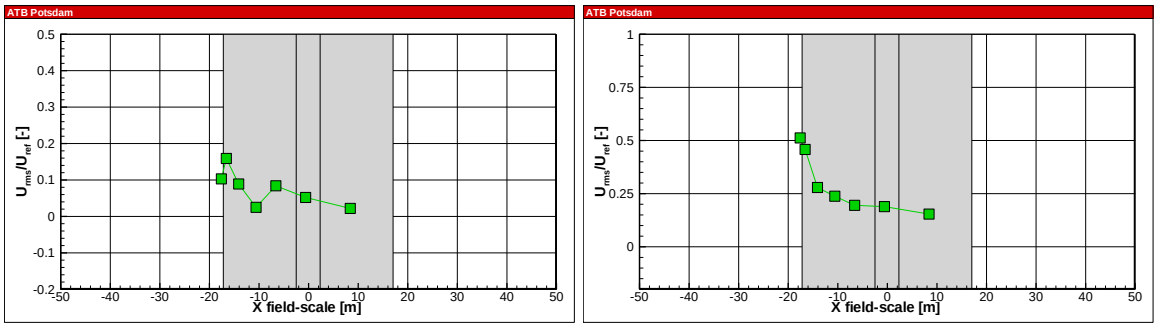


Figure 3: Profile measurements of the normalised streamwise mean velocity component U/Uref (left) and the root-mean-square value U_{rms}/U_{ref} (right). Grey shaded area indicates the area of the investigated barn, also shown the feeding alley in the center of the barn.

It seemed that the approaching wind influenced the flow within the barn only for a short distance from the net. This assumption was verified by additionally calculating the correlation coefficient of the horizontal wind speed U between the outside measurement and the inside

measurements. The correlation coefficient was approximately p = 0.5 for the first three measurement points (X = -176 in front of the wind protecting net to positions X = -16.6 and X = -14.1 within the barn) and decreased to p = 0.2 at position X = -6.6 and p = 0.03 at position X = -0.06 (roughly at the barn centerline). These results are in line with a former study from Fiedler et al. (2013).
The right side of Figure 3 showed the normalised U_{rms}/Uref profile, which is an example for a turbulent quantity. The strongest variations within the obtained time series occur directly in front and behind the wind protecting net and is decreasing strongly within in the barn. This shows, the net has a strong impact on the flow and its effects should be studied further.

A short analysis of long-term field measurements showed, that the wind protecting net reduces the wind speed up to 75% depending on the approaching wind direction. This should be considered in the wind tunnel scaled model as well as in numerical simulations.

3.2 Wind tunnel measurements

The results from the flow measurements (figure 4) from the wind tunnel presented here are also normalised with the wind speed measured at the reference point outside the model. For the normalised streamwise mean component U/Uref an acceleration directly behind the inlet occur. Within the model the values of U/Uref decrease from 1.2 at the inlet to 0.5 behind the centerline of the barn and increases again to 0.7 at the outlet. These values are much higher then the values obtained in the field, but the overall shape is comparable. This shape of the profile within the model was also found in a study by De Paepe et al. (2012), they found for models with the same inlet and outlet size high values of the air velocity at the inlet low values in the center and again higher values at the outlet. The U_{rms}/Uref profile (right side, Fig. 4) is less pronounced than in the field. Reason is the absence of the wind protecting net and hence no wind breaking effect should act.

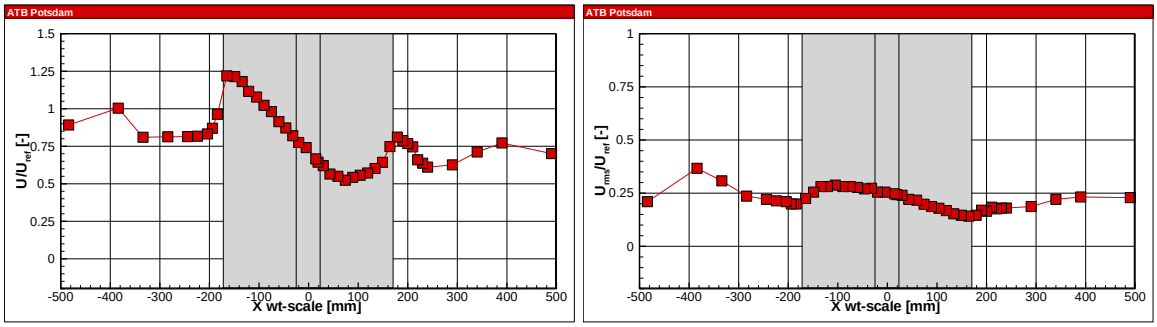


Figure 4: Wind tunnel measurements of the normalised streamwise mean velocity component U/Uref (left) and the root-mean-square value U_{rms}/U_{ref} (right) profile. Grey shaded area indicates the area of the investigated barn, also shown the feeding alley in the center of the barn.

However additional facts have to be considered, which can explain differences for measurements from the wind tunnel and the field: The approach flow conditions in the wind tunnel were identified to the scale 1:300 while the model has the scale 1:100. Which corresponds to smaller vortices than in the field and therefore are the results not directly transferable to the field measurements. Also it has to be considered, that the field values base on 20 min time-averages which may be not statistically representative.

3.3 Numerical simulation

The visualization of the results of the numerical simulation give first detailed information about the airflow characteristic and the airflow dynamic inside and around the building. Exemplarily U_{mean}, the mean velocity in streamwise direction (from left to right) is shown. The temporal averaging of this quanitiy is done over 1000s and shown in Figure 5. Here one observes an increase of U_{mean} at the barn luv side inlet (yellow) and a mean backflow (blue)

under the luv side roof. At barns lee side one finds that the mean velocities decrease (green) up to heights of about 10-15 m from the ground.

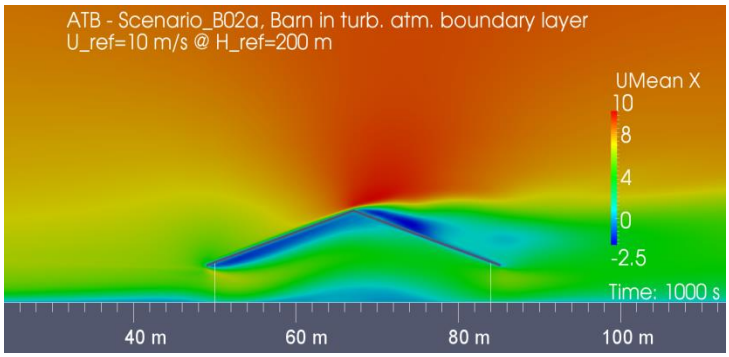


Figure 5: Numerical simulation of a natural ventilated dairy barn. Shown is the mean velocity in steamwise direction U_{mean} in (m/s). The amplitude is color coded linearely.

To benchmark the results of the numerical simulation with the experiments in the wind tunnel the velocity data of the horizontal cross section through the barn at height z = 2.5 m are extracted. As reference velocity the data of streamwise velocity at probe point (49 m, 2.5 m) in the mesh was extracted. This point is 1m luv side the inlet of the barn. Its value is U_{ref} = 5.29 m/s. The cross section and the probe point are pictured schematically (magenta) in Fig 4. The increase of streamwise mean velocity at the barns inlet can be quantify by 1.2 * U_{ref} corresponds to the wind tunnel measurements. The mean profiles U_x/U_{ref} and $|U/U_{ref}|$ decrease to minimal values of 0.3 * U_{ref} resp. 0.45 * U_{ref} in the barns center at x = 18m. Than the values increase again. In the wind tunnel data one observes the decreasing too, but a lower increase at the barn outlet. The reason is that the simulated barn has still no interior. Further simulations will realize this. The wall normal component U_y/U_{ref} starts with negative values of -0.2 * U_{ref} at barns inlet (x = 0 m), passes a maximum of 0.22 * U_{ref} at x = 7 m and decreases more or less linearly to values of -0.2 * U_{ref} at the barns outlet. The results of the numerical simulation are qualitatively conform to the wind tunnel data, at barns inlet quantitatively too. We trace back the differences to the absence of interior in the numerical setup. In the frame of comparability our first numerical results are in accordance with Lee et al. (2007).

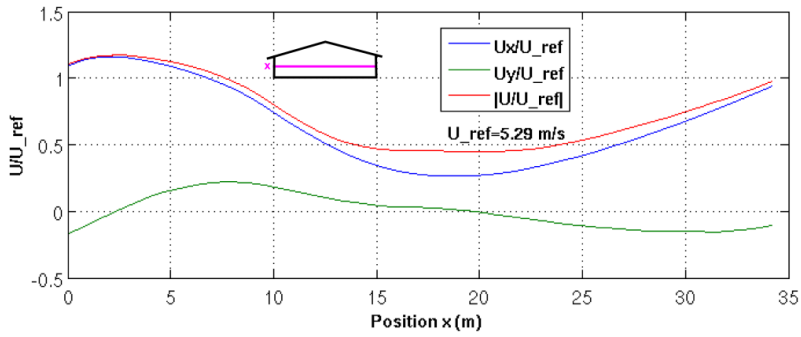


Figure 6: Numerical simulation of a natural ventilated dairy barn. Shown are the normalized mean velocity components streamwise U_x/U_{ref} (blue), wall normal U_y/U_{ref} (green) and the absolute value $|U/U_{ref}|$. The reference velocity U_{ref} of the turbulent atmospheric boundary layer at height z = 2.5 m is equal to U_{ref} = 5.29 m/s which corresponds to the roughness of the wind profile z_0 = 0.01.

4 Conclusions

The combination of the used three different methods – field measurements, wind tunnel measurements and numeric simulation – provide a better understanding and improved results of the flow properties within a NVD. Air velocity measurements done exemplarily at one line in streamwise direction within the barn show that the results of the wind tunnel and the numerical simulation are in promising agreement even though they were obtained under slightly different conditions (the numerical simulation was 2D and had no interior within the

model). At this stage the results from the model and the simulation are not directly transferable to the field data. However, the shape of the profiles from the wind tunnel and numerical simulation are comparable with the shape of the profile measured in the field, but the quantitative air velocities are different. The main reason for this is, that in the wind tunnel and in the numerical simulation the models are simplified by neglecting the wind protecting nets of the open sidewalls of the NVD. To implement the wind breaking effect correctly in the wind tunnel or numerical model more research to the net effects are needed. This aspect will be considered for the future work as well as more will be done to improve the transferability of the results to the real conditions. The field data set needed to be enhanced to provide statistically sound more representative data. In the wind tunnel the scale of the used boundary layer approach flow has to be adapted to the scale of the model. And the numerical simulation need to be upgraded in 3D as well as the interior has to be implemented.

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