International Conference of Agricultural Engineering
AgEng 2014 Zurich 6–10 July

Ref: C0246

Assessing effects of different opening combinations on airflow pattern and air exchange rate of a naturally ventilated dairy building –A CFD approach

Chayan Kumer Saha, Leibniz Institute for Agricultural Engineering Potsdam-Bornim (ATB), Department of Engineering for Livestock Management, Max-Eyth-Allee 100, 14469 Potsdam, Germany and Department of Farm Power and Machinery, Bangladesh Agricultural University, Mymensingh-2202, Bangladesh

Merike Fiedler, Leibniz Institute for Agricultural Engineering Potsdam-Bornim (ATB), Department of Engineering for Livestock Management, Max-Eyth-Allee 100, 14469 Potsdam, Germany

Thomas Amon, Livestock-Environment-Interactions at the Institute of Animal Hygiene and Environmental Health in the Department of Veterinary Medicine, Free University of Berlin and Leibniz Institute for Agricultural Engineering Potsdam-Bornim (ATB), Department of Engineering for Livestock Management, Max-Eyth-Allee 100, 14469 Potsdam, Germany

Werner Berg and Barbara Amon, Leibniz Institute for Agricultural Engineering Potsdam-Bornim (ATB), Department of Technology Assessment and Substance Cycles, Max-Eyth-Allee 100, 14469 Potsdam, Germany

Reiner Brunsch, *Leibniz Institute for Agricultural Engineering Potsdam-Bornim (ATB), Max-Eyth-Allee 100, 14469 Potsdam, Germany*

Abstract

Ventilation airflow in buildings is paramount important for creating comfortable environment with acceptable indoor air quality by regulating indoor air parameters, such as air temperature, relative humidity, air speed, and concentrations of chemical species in the air. Airflow inside naturally ventilated dairy (NVD) building is highly variable because of the direct effect of outside weather and large openings. It is difficult to understand airflow characteristics and estimate air exchange rate (AER) precisely with the existing methods. Computational fluid dynamics (CFD) based numerical simulation would be alternative to full scale and scale model experiments for understanding airflow characteristics of an NVD building. The aim of the study was to investigate the effect of different seasonal opening combinations of an NVD building on airflow patterns and AER in and outside of the NVD building using CFD. Typical NVD building located in Northeast Germany was selected for model development and simulation which was designed to accommodate 364 dairy cows. ANSYS 14.5 was used for creating model geometry, meshing and simulation. The standard kinetic energy (k)-dissipation (ε) turbulence model was used for all simulations. In order to improve the quality of CFD calculations, i.e. to make calculations with sufficient accuracy, several important issues (e.g. grid independency and convergence criteria etc) were considered carefully for both the governing equations and the computation. Common seasonal practices in the NVD building were considered as opening combinations for simulation. The opening combinations were namely middle of both sidewalls open (SW), middle and bottom parts of both sidewalls open (SWB), middle and top parts of both sidewalls open (SWT), both sidewalls completely open (SWC), middle and bottom parts of sidewalls and all doors open (SWBD), middle and top parts of sidewalls and all doors open

(SWTD), both sidewalls complete and all doors open (SWCD), both sidewalls complete and only feeding alley doors open (SWFD). The roof opening was kept open in all cases. The model was validated using the data measured in a boundary layer wind tunnel using 1:100 scale model of NVD building inside under strictly controlled laboratory conditions taking into account full scale measurement scenarios. The air exchange rate of the NVD building was increased with the increase of external air velocity. Different airflow patterns and AERs were observed for different opening scenarios at the same external wind speed and direction, which may affect the cow comfort and gas emissions. As for example, the airflow intensity in the animal occupied zone was higher and re-circulation of air was opposite in SWB compared to SWT. AER as compared to SW opening combination was 1.94, 1.75, 2.65, 2.19, 2.09, 3.03 and 2.78 times higher in SWT, SWB, SWC, SWTD, SWBD, SWCD and SWFD opening combinations, respectively. Further investigations are required to understand the airflow pattern and estimate air exchange rates in unsteady conditions considering different wind speeds and changing directions. The effect of wind direction and obstacles on air exchange rates in NVD building will also be investigated in the proposed research.

Keywords: Ventilation, CFD, model, cow building

1. Introduction

Ventilation in buildings is very important for creating comfortable environment with acceptable indoor air quality. Ventilation air is also medium of transporting pollutants (i.e. gas, odor and dust) from livestock buildings (Saha et al., 2010) which adversely effects on animals, workers, neighbors, and environment (Bull and Sutton, 1998). In order to regulate the indoor air parameters and controlling emission, it is essential to have suitable tools to understand airflow characteristics and predict ventilation performance in buildings.

The natural ventilation system in dairy cow barns with large side openings and a roof opening are commonly used in mild climate regions (Samer et al., 2011). Hence, the emission from naturally ventilated dairy (NVD) barn directly depends on atmospheric influences under continuously changing conditions (Ikeguchi et al., 2003), such as outdoor wind speed and direction, as well as its turbulence nature. Moreover, dairy cows need a constant source of fresh, clean air to maximize their production potential. Stale air badly affects milk production and milk quality. The ability to maintain desired environmental conditions in intensive production systems depend on the design and performance of the ventilation system. Convective heat and mass transfers dominate the exchange processes in naturally ventilated structures, which due to pressure differences created by either temperature differences (thermal buoyancy), wind on the building or combination of these two. As a consequence, the indoor environmental parameters such as temperature, gases and humidity are governed by airflow patterns. Airflow patterns including air velocities and turbulences form the essential link between the outdoor environment and the buildings microclimate; thus an understanding of the principles of air motion is necessary in order to provide the correct quantities of air and the proper distribution patterns to meet the needs of the application.

The major problem of natural ventilation is the lack of accurate, continuous and online measuring and controlling techniques for air exchange rates (AERs) (Van Buggenhout et al., 2009). Different measuring techniques have been applied for measuring the AERs and to calculate the emissions streams from naturally ventilated buildings. Depending on the methods, these techniques have measurement errors of 5 to 100% due to imperfect mixing of tracer gases and lack of representative sampling errors (Van Buggenhout et al., 2009). These experimental methods are expensive, labour intensive, and technically difficult. Thus, a model with the function to predict the AERs and airflow characteristics by using easily measured or obtained parameters from the available literature or outside weather data would be very helpful. Computational fluid dynamics (CFD) based numerical simulation would be alternative to full scale and scale model experiments for understanding airflow characteristics of an NVD building. However, this CFD have not been fully exploited in NVD barn in comparison to naturally ventilated greenhouse crop production systems (Norton et al., 2007).

Gebremedhin and Wu (2005) solved the flow around cows to investigate, with an external program, the heat and mass transfer phenomena in a forced ventilated enclosure of simple geometry. They found that the total heat loss from an animal is highly dependent on both the animals' position and orientation to the flow field. Furthermore, a wall inlet producing a ceiling air jet seemed to create the most uniform environmental conditions in the building and minimized the large differences in animal heat loss (Gebremedhin and Wu, 2005). Even though Gebremedhin and Wu (2005) calculated heat and mass transfer from the simulated cows, only isothermal conditions were simulated in the CFD model. Norton et al. (2009) investigated ventilation effectiveness of naturally ventilated livestock buildings under wind dominated conditions using CFD and a ½ scale experimental duopitch building. The maximum ventilation homogeneity is experienced when the wind is blowing normal to the building. In other studies, Norton et al. (2010) used CFD to optimize the ventilation configuration of naturally ventilated livestock buildings for improved indoor environmental homogeneity and calf comfort. CFD technique was also applied in NVD building for checking suitability of response surface methodology for ventilation rate calculation (Shen et al., 2012a). However, airflow pattern inside barn and emission behavior vary depending on geometric structure and orientation of the buildings (De Paepe et al., 2012). Typical NVD building located in Germany has large side wall opening. There is no such study where CFD based numerical simulation has been applied for the typical NVD barn investigating airflow characteristics and AERs for different opening combinations practiced in different seasons. But, this is very important to understand detail of spatial and temporal characteristics of airflow inside barn and to predict AERs for proper ventilation control, emission reduction and animal comfort. Therefore, the aim of the study is to investigate the effect of different seasonal opening combinations of an NVD building on airflow patterns and AER in and outside of the NVD building using CFD.

2. Materials and methods

2.1 CFD modeling

2.1.1 Geometry

The size of the geometry was based on the wind tunnel experiment as described in section 2.2.1 (Fig.1). Geometry was simplified for the convenience of the simulation. Previous research has shown that high level of detail in the CFD model would not influence the overall airflow inside the room but significantly increase grid and computational cost (Hajdukiewicz et al., 2013). In the scale model, there were no interior partitions except elevated cow resting areas and feeding alley. The airflow pattern in the tunnel is governed by the conservation laws of mass, momentum and energy. Building geometry and meshing were done by ANSYS ICEM CFD (ANSYS Inc). The result of CFD calculation is the solution of conservative transport equations for mass, momentum and energy. Commercial code ANSYS CFX 14.5 (ANSYS Inc), used in this work, is based on the finite volume approach.

2.1.2 Model set up and boundary conditions in CFD

The steady state conditions were used in the CFD analysis of the single phase airflow in the domain. Accurate use of CFD techniques involves defining boundary conditions that match the case being modelled closely enough. Computational domain had the dimension of L×W×H = 5.06m × 6.06m × 2.03m, the distance from the inlet of scale model was almost $19H_1$ (H_1 = 0.107 m, height of the building) from the inlet. The distance from the scale model NVD building to the outlet was $24H_1$, and from the building to the side walls (i.e. parallel to airflow) was almost $23H_1$. The height of the domain from the building to the top was nearly $17H_1$. The boundaries of the computational domain should be far enough away from the region of interest to not contaminate the solution there with the approximate boundary conditions. The distance from the building to the sides, to the inlet and to the top of the domain at least five times the height of the building and the distance from the building to the outlet at least fifteen times the height were recommended (Franke et al., 2007). In our study, distances from each side from the region of interest were far bigger than recommended. These distances from the regions of interest were chosen intentionally for studying wind direction effects on airflow characteristics using same geometry for later use though it would cost more meshes and calculation time.

Three different types of boundary conditions were adopted in the present computations: velocity inlet, pressure outlet, and walls. The principles to define these boundary conditions can be found in the literature (Saha et al., 2011). The inlet air velocity profile was calculated by eq. (1) using same reference value u_{ref} and z_{ref} as the wind tunnel experiment. Then this velocity profile and constant turbulence intensity of 5% was set at the inlet. For the ground surface in the direct vicinity around the modeled building, the sand grain roughness height 0.0003m was chosen, which was equivalent to the surface roughness of the wind tunnel without any spike. The top of the computational domain is modeled as a free slip wall (zero normal velocity and zero normal gradients of all variables) and zero static pressure is imposed at the outlet. The other boundaries were set as no-slip smooth wall. The standard k-ε turbulence model was chosen for good results accuracy with the robustness of the solution (Hajdukiewicz et al., 2013, Shen et al., 2012b). Only isothermal simulations are performed in this study in line with BLWT measurement. High resolution option was used both for advection scheme and turbulence numeric. The solution was considered to be converged when there was no obvious change of the average velocity at the specific point inside the building. The eight opening combinations (Fig. 1) were simulated using the same boundary settings.

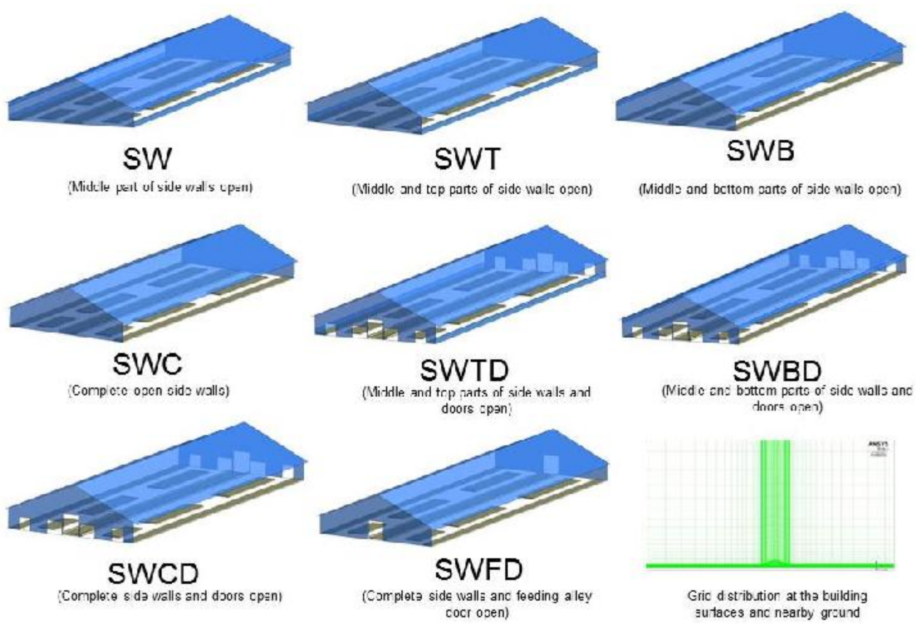


Figure 1: Geometrical opening scenarios of an NVD barn without cows for steady state CFD simulation. The roof opening was kept open in all cases. Grid distribution at the building surfaces and nearby ground.

The air velocity effect on AER was also investigated using inlet velocities 1 to 10 m s^{-1} and turbulence intensity 5% for the SW opening combination. Other boundaries were kept same as described before.

2.1.3 Grid independency and model validation

The computational domain was discretized by structural hexahedral cells. The grid distribution of computational domain with 1:100 scale model of NVD building using rectangular grids can be shown in Fig. 1. Grid independence was analyzed by using three different density grids and the total nodes were 867082, 2345564, and 4885144 which named as low, medium, high density, respectively. A grid independency analysis was conducted to ensure that the resolution of the mesh was not influencing the results. The optimum grid distribution was achieved by completing a grid-independence control, during which a number of different simulations were run with different mesh, until the velocity distribution was constant for the specific point. The computational model was validated using the BLWT experimental data. The wind speed ratio (non-dimensional wind speed) u/u_{ref} was calculated with CFD and both ratios were compared.

2.2 Wind tunnel experiment setup

2.2.1 Building model

Model validation with the experimental results using physical model with the same dimension and same boundary setting as the simulation (Franke et al., 2007) is important to ensure adequate results and is necessary before analyzing the airflow pattern.

The data used for CFD model validation was generated from the experiment at the Boundary Layer Wind Tunnel (BLWT), Leibniz Institute for Agricultural Engineering Potsdam-Bornim (ATB). The BLWT is 20 m long, 3m wide and 2m height with adjustable ceiling up to 0.25m. The inlet of BLWT is fitted with honey combs inlet nozzle and the outlet of BLWT is fitted with axial fan of diameter of 2.8 m, by which inlet wind speed can be reached up to 20 m s^{-1}.

A 1:100 scale model of NVD building was built for the BLWT experiment considering typical NVD building located in north-east Germany where long-term field measurements were carried out as described in (Saha et al., 2014) study. The 1:100 scale building is 0.962 m long and 0.342 m wide. The height of the sheet metal roof is varies from 0.042 m at the sides to 0.107 m at the gable peak. This resulted in a wind tunnel blockage ratio of 1.72%. A large scale model would have given to a tunnel effect between the model and the wind tunnel wall (De Paepe et al., 2012), likely influence the wind entering and exiting the house through the ventilation openings. In the scale model, there were no interior partitions except elevated cow resting areas and feeding alley. The main scale model was constructed using a welded brass frame. Two mm thick transparent acrylic glass were served as walls and roofs and were fixed onto the frame with smooth adhesive. The scale model of NVD building was placed 13.3 m away from the inlet of BLWT.

2.2.2 Experimental setup

Only one case of the simulations, i. e. side wall open completely (SWC), was consider for BLWT experiment and model validation. The scale model was placed in the wind tunnel work section at x = 13.3 m. At the upstream end of the test section, the velocity profile within BLWT was

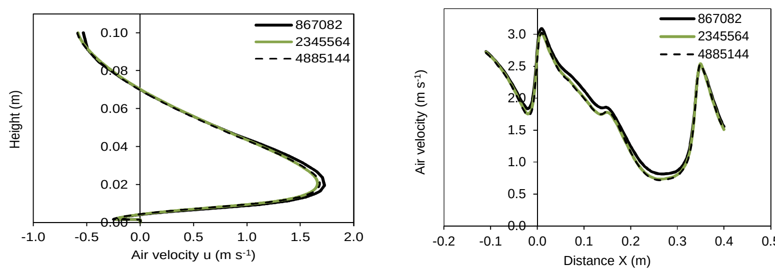
$$u_z = u_{ref}\left(\frac{z}{z_{ref}}\right)^{\alpha} \qquad (1)$$

Where u_z is the wind speed at the height z; u_{ref} is the reference wind speed at the standard height $z_{ref,}$ u_{ref} =8.17 m s^{-1} as for the horizontal velocity measurement. z_{ref} is the referred standard height and z_{ref} = 0.09 m was used in the experiment. The exponent α = 0.1 was the power law exponent of the turbulent boundary layer. In the experiment, the turbulence intensity was 5 % at the reference height z_{ref}. Measurement of the vertical velocity components took place at the middle of the building and 1m away (upstream side) from the NVD building. Horizontal velocity profile (at the height of z = 0.02 m) was measured at the middle from the upstream side of the building to the downstream side. A 2D laser Doppler Anemometer (LDA) (Dantec, Denmark) was used for the measurement. At every measurement point, time series of the wind velocity component U (in X direction) and the wind velocity component V (in Y direction) were recorded. The duration of the time series varied, with recording continue until the standard deviation of average value showed less than 2 % fluctuations. The temperature was measured at the inlet of the BLWT during the profile measurement.

3. Results and discussion

3.1 Grid dependency

The results of the grid independence for this study are displayed in Fig. 2. Fig. 2a shows vertical profile of air velocity u at the middle (x=0.165m, y =0.478m) of the NVD barn and Fig 2b. shows horizontal profile at the 0.02m height from 0.015 m from the windward side sidewall of NVD building and ended after 0.05m of the leeward side. No significant differences between the solutions on the last two meshes can be observed. There is slight difference between medium and low density. Therefore, in this study, the medium grid density (nodes 2345564) was used in this study for further simulation.

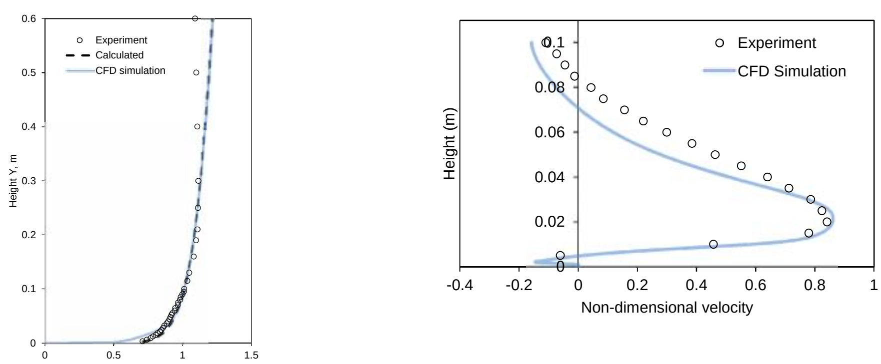


(a) (b)

Figure 2: Grid independency study at the inlet boundary velocity of 4 m/s (a) vertical profile, and (b) horizontal profile inside middle of NVD barn at SW opening conditions.

3.2 CFD model validation

The comparisons between the experimental and the numerical data of velocity profiles confirm the validity of the numerical model used in the CFD simulation (Fig. 3a and Fig. 3b). Fig 3a is the boundary layer profile entered to the NVD building. The CFD simulated velocity profile was similar to the wind tunnel experimental profile and calculated by Eq. (1). The characteristics of measured velocity were reasonably revealed by the numerical simulation with the standard *k-ε* model (Fig. 3b). However, there are discrepancies at close to the roof area between simulated and measured velocity. One explanation could be possible uncertainty might exist for laser-doppler anemometer precisely located at the specific measurement positions, although the much attention was paid to it. In spite of the uncertainties in the experiment and simulation, the preliminary results illustrate that numerical model is feasible for modelling characteristics of airflow in naturally ventilation situation.



(a) (b)

Figure 3: (a) Boundary layer profile 1m before the NVD barn, and (b) vertical profile in the middle of the barn where Y =0.478m where sidewall was complete open (SWC). The inlet profile velocity at 0.09m was 8.17 m s^{-1} and turbulence intensity was 5%.

3.3 Effect of opening combinations on airflow characteristics and AER

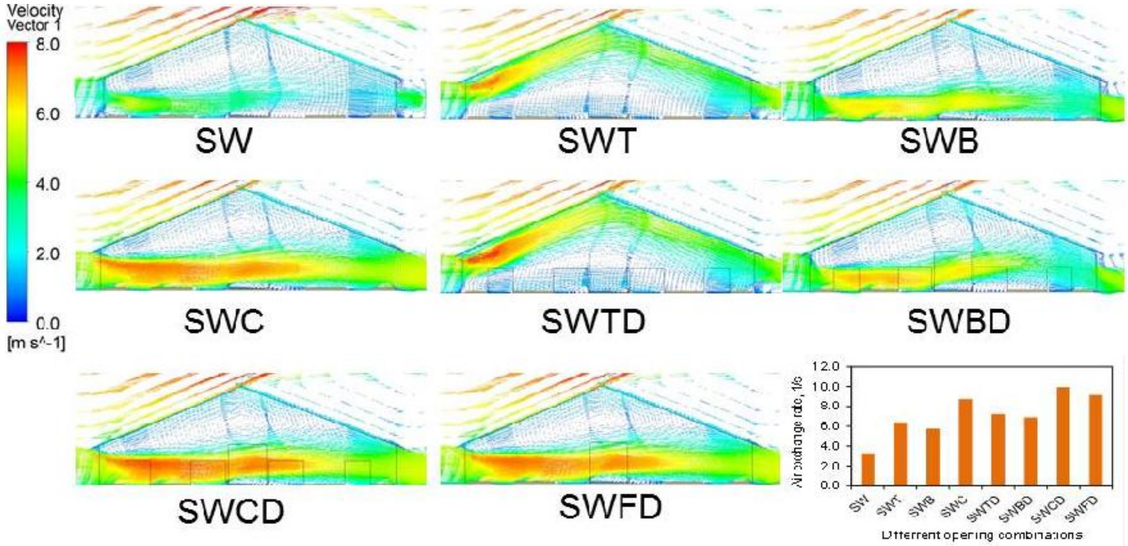


Figure 4: Steady state simulation results of vertical airflow pattern inside and outside of NVD barn for the inlet velocity profile set by Eq. (1) with the reference velocity of 8.17 m s^{-1} at the height of 0.09m and turbulence intensity of 5%, and air exchange rate (AER) in different opening combinations.

The results show the steady state simulation results of vertical airflow pattern inside and outside of NVD building for different opening combinations and their air exchange rate (Fig. 4). The air exchange rate was calculated using ventilation rate divided by volume of the building. The air exchange rate of the NVD building was increased with the increase of external air velocity. Different airflow patterns and AERs were observed for different opening scenarios at the same external wind speed profile, which may affect the cow comfort and gas emissions. As for example, the airflow intensity in the animal occupied zone was higher and re-circulation of air was opposite in SWB compared to SWT. AER as compared to SW opening combination was 1.94, 1.75, 2.65, 2.19, 2.09, 3.03 and 2.78 times higher in SWT, SWB, SWC, SWTD, SWBD, SWCD and SWFD opening combinations, respectively. The larger openings gave higher AER than smaller openings (Fig. 4). This study is in line with the study of De Paepe et. al. (2012). They found that larger openings mean higher airflow rates. Aforementioned results show that changing the opening combinations, AER of NVD building can be controlled and airflow pattern can be guided to the direction according to the need. Adding air guiding plate may help in changing airflow pattern and providing the cow best comfort. However, this study was based on isothermal case. Further study is needed to investigate non-isothermal case with cow inside.

4. Conclusions

Airflow pattern can be understood well and AER can be calculated easily using CFD modelling technique after validating by experimental measurement data. The CFD simulation revealed that higher the external wind speed, higher the AER is. Different opening combinations showed larger variations in AER of NVD building and airflow pattern were also different. Further studies are required to understand wind directions and surrounding effects on airflow pattern and AER of NVD building.

5. Acknowledgements

The authors would like to thank Alexander-von-Humboldt Foundation (AvH) for granting fellowship for carrying out this research project. The authors also would like to acknowledge K. Schröter and A. Reinhardt, technicians at the Department of Engineering for Livestock

Management at the Leibniz Institute for Agricultural Engineering Potsdam-Bornim (ATB) for their technical and logistical support during the wind tunnel measurements.

6. References

Bull, K. R., and Sutton, M. A. (1998). Critical loads and the relevance of ammonia to an effects-based nitrogen Protocol. *Atmospheric Environment,* 32(3), 565-572.

De Paepe, M., Pieters, J. G., Cornelis, W. M., Gabriels, D., Merci, B., and Demeyer, P. (2012). Airflow measurements in and around scale model cattle barns in a wind tunnel: Effect of ventilation opening height. *Biosystems Engineering,* 113(1), 22-32.

Franke, J., Hellsten, A., Schünzen, H., and Carissimo, B. (2007). Best practice guideline for the CFD simulation of flows in the urban environment. *COST Action 732*,1-52.

Gebremedhin, K. G., and Wu, B. (2005). Simulation of flow field of a ventilated and occupied animal space with different inlet and outlet conditions. *Journal of Thermal Biology*, 30(5), 343-353.

Hajdukiewicz, M., Geron, M., and Keane, M. M. (2013). Formal calibration methodology for CFD models of naturally ventilated indoor environments. *Building and Environment,* 59, 290-302.

Ikeguchi, A., Zhang, G., Okushima, L., and Bennetsen, J. C. (2003). Windward windbreak effects on airflow in and around a scale model of a naturally ventilated pig barn. *Transactions of the ASAE,* 46(3), 789-795.

Norton, T., Grant, J., Fallon, R., and Sun, D. W. (2010). Optimising the ventilation configuration of naturally ventilated livestock buildings for improved indoor environmental homogeneity. *Building and Environment*, 45(4), 983-995.

Norton, T., Sun, D. W., Grant, J., Fallon, R., and Dodd, V. (2007). Applications of computational fluid dynamics (CFD) in the modelling and design of ventilation systems in the agricultural industry: A review. *Bioresource Technology,* 98(12), 2386-2414.

Saha, C. K., Ammon, C., Berg, W., Fiedler, M., Loebsin, C., Sanftleben, P., Brunsch, R., and Amon, T. (2014). Seasonal and diel variations of ammonia and methane emissions from a naturally ventilated dairy building and the associated factors influencing emissions. *Science of the Total Environment,* 468–469, 53-62.

Saha, C. K., Wu, W. T., Zhang, G. Q., and Bjerg, B. (2011). Assessing effect of wind tunnel sizes on air velocity and concentration boundary layers and on ammonia emission estimation using computational fluid dynamics (CFD). *Computers and Electronics in Agriculture,* 78(1), 49-60.

Saha, C. K., Zhang, G. Q., Kai, P., and Bjerg, B. (2010). Effects of a partial pit ventilation system on indoor air quality and ammonia emission from a fattening pig room. *Biosystems Engineering,* 105(3), 279-287.

Samer, M., Fiedler, M., Mueller, H., Glaeser, M., Ammon, C., Berg, W., Sanftleben, P., and Brunsch, R. (2011). Winter Measurements of Air Exchange Rates Using Tracer Gas Technique and Quantification of Gaseous Emissions from A Naturally Ventilated Dairy Barn. *Applied Engineering in Agriculture,* 27(6), 1015-1025.

Shen, X., Zhang, G. Q., and Bjerg, B. (2012a). Investigation of response surface methodology for modelling ventilation rate of a naturally ventilated building. *Building and Environment,* 54, 174-185.

Shen, X., Zhang, G., and Bjerg, B. (2012b). Comparison of different methods for estimating ventilation rates through wind driven ventilated buildings. *Energy and Buildings,* 54, 297-306.

Van Buggenhout, S., Van Brecht, A., Ozcan, S. E., Vranken, E., Van Malcot, W., and Berckmans, D. (2009). Influence of sampling positions on accuracy of tracer gas measurements in ventilated spaces. *Biosystems Engineering,* 104(2), 216-223.