Simulating the effect of forced pit ventilation on ammonia emission from a naturally ventilated cow house with CFD

A.A. Sapounas[1], J.B. Campen[1], M.C.J. Smits[2] and H.J.C. van Dooren[2]

[1] Wageningen UR, Plant Science Group, P.O. Box 644, 6700 AP Wageningen,
The Netherlands
[2] Wageningen UR, Animal Science Group, P.O. Box 65, 8200 AB, Lelystad,
The Netherlands
athanasios.sapounas@wur.nl

Abstract

Atmospheric NH_3, mainly originates from agricultural sources, can cause serious environmental problems related to eutrophication and soil acidification. Emissions from dairy houses are 15% of total agricultural NH_3 emissions. Due to open buildings, existing abatement options are limited. Pit air separation was identified as a potentially efficacious option. In this study a model simulation of a commercial dairy cow building with slatted floor is presented. The model was solved for 12 cases, differing wind speed, direction and both air and manure temperature. For each case three solutions were obtained, which correspond a) to a building where a forced pit ventilation system is applied at capacity of 250 and 500 m^{-3} h^{-1} cow^{-1} and b) to a building without forced pit ventilation system. The results show that due to forced pit ventilation system, at 250 and 500 m^{-3} h^{-1} cow^{-1}, the ventilation rate was increased 3.1% and 6.2% respectively. The contribution of the pit ventilation system to the total ammonia released from the pit during winter, ranged from 31-35%, 16-19% and 11-8%, for wind speed of 1.0, 4.0 and 8.0 m s^{-1} respectively. Correspondingly, during summer, the contribution of the system ranged from 44-48%, 20-21% and 12-9%. Although obvious benefits arise from a forced pit ventilation system, the main mass flow of ammonia from the pit still emitted through the building ventilation openings, especially at high wind speeds.

Keywords: air pollutants, tracer gas, ventilation rate, numerical simulation

Introduction

Nowadays environmental problem such as eutrophication and the effects of greenhouses gases have increased the demand for knowledge of emissions of aerial pollutants from the livestock production sector. Animal producers are facing increasing pressure from the society to comply with environmental legislation, i.e. to produce in an environmentally friendly and sustainable way (Pedersen, 2004). Atmospheric NH_3, mainly originates from agricultural sources. It can cause serious environmental problems related to soil acidification and eutrophication. Approximately 75% of the NH_3 emissions in Europe originate from livestock production (Ye, 2008) and a significant part of them refer to emissions from dairy houses and slurry storages (approximately 15% in Netherlands). Ammonia emissions become more and more a critical design parameter especially for large scale dairy farms (Van Dooren and Galama, 2007).

In livestock buildings, estimates of emission rates generally require the measurement of ventilation rates and pollutant concentrations. Spatial and temporal distributions of ammonia concentrations and emissions depends on the ventilation rate itself, the airflow patterns inside the building, floor construction, waste storage system, animal activity level and type of feed. The airflow pattern is an important factor inside the building; it is influenced by building geometry and construction, size and distribution of ventilation inlets and outlets, heat production, and particularly for the naturally ventilated buildings the local wind environment.

At given ventilation rate the pollutant point or area source location such as feeders and floor, also affect the aerial distribution of the ammonia gases (Demmers, 2000).

In recent years, several research projects have been carried out to quantify the levels of ammonia emissions under different conditions. Nevertheless, the relation between climatic conditions and the behaviour of ammonia gases in animal buildings and ambient environment still remains an important issue. According to experiments carried out in a wind tunnel, in order to investigate the ammonia emission from five naturally ventilated dairy buildings, the overall measured emission rates were in range of 10-56 g day^{-1} cow^{-1}, (Wang et al., 2005). Rumburg et al. (2008) used differential optical absorption spectroscopy (DOAS) method to estimate the ammonia concentration of a dairy cow free stall with concrete floors. In this study the SF_6 as tracer gas and a line source technique were used to estimate the ammonia flux from the stall. It was ranged from 29 ± 19 g NH_3 cow^{-1} h^{-1} at an average temperature of 18°C. The annual emission was calculated to 40 kg cow^{-1} year^{-1}.

As the most of the dairy houses are open naturally ventilated constructions, suitable abatement options are limited. Solid floors that diminish emissions from underfloor slurry pits conflict easily with animal welfare. To this direction, technical measures to reduce ammonia emission have been studied. Swierstra et al. (1995) studied the differences in ammonia emission of two compartments of cubicle house for cattle with slatted and solid floors. Emission from the compartment with a solid floor was about 50% of the emission of the compartment with a slatted floor. As the influence of the floor appears to be important, more research was carried out to this direction. Braam et al. (1997), investigate the influence of two methods to reduce the ammonia emission in a mechanically ventilated cow house. The first one consists of the construction of two extra urine gutters in the sloping floor parts, and the second one of spraying water at a rate of 6 l d^{-1} cow^{-1} with frequency of 12 times per day. Applying the first method, the ammonia emission was reduced by 50% on average and further reduction was measured when water was sprayed.

Ogink and Kroodsma (1996), Braam et al. (1997) and Monteny (2000) indicated that emissions from the slurry pit below a slatted floor in a cubicle house may contribute a varying proportion of the total ammonia emission of the building depending strongly on temperature differences between pit air and fresh incoming air and the resulting air flow through the pit. On average approximately 50-60% of the ammonia emissions from a Dutch dairy cow house building originates from the slurry pit.

Pit air separation and treatment was identified as a potentially efficacious reduction option too. By modelling the effects of air flow patterns and air velocities on ammonia emission at high spatial and temporal resolution, design parameters of a pit air removal and treatment system can be studied.

In the present study a simulation model of a commercial, naturally ventilated dairy cow building with slatted floor is presented. The main objectives were: i) to calculate the ammonia emissions from the pit under different climatic conditions and ii) to investigate the potential influence of a forced pit ventilation system, which is planned to be installed in the pits below the slatted floor. Because the focus was on the contribution of the pit as a source of ammonia emission, ammonia emissions from the floor were not modelled.

Materials and methods

Computational Fluid Dynamics (CFD), a numerical technique, has already been used to investigate the internal air flow in agricultural structures such as livestock buildings and greenhouses (Harral et al., 1997; Mistriotis et al., 1997). CFD model was used to investigate the performance of a forced ventilation system of a piglet house with perforated ceiling which is very popular in Korea (Lee et al., 2002). Sun et al. (2002) used 2D CFD analysis to describe the air flow patterns and ammonia distribution of a High-Rise^{TM} hog building. The computational results were similar to experimental data especially when the turbulence flow characteristics were taken into account. A 3D CFD model was used to simulate the airflow and ammonia distribution in a High-Rise^{TM} hog building (Huawei, 2004). The good agreement between simulation results and experimental data concerning 8 positions and two elevations indicated that the CFD model is an effective tool to evaluate air quality and ventilation of livestock buildings. The use of CFD for predicting the air flow makes it possible to include the effect of structure geometry in the design of ventilation system. In addition, turbulence modelling has a significant effect on the predicted concentration field of pollutants inside livestock buildings, (Quinn, 2001).

In this study the geometry of the dairy cattle livestock building and its surrounding environment was designed by the geometrical processor Gambit 1.1. The final 3D full scale model, which consists of 456411 cells, extended from 0-200 m both to x and z directions and from 0-40 m to y direction. The dairy cattle building was designed taken into account all the characteristics influencing the flow in the building. These concerned the side-wall and ridge ventilation openings (115.5 m^2 and 15.4 m^2 respectively), the slatted floor (462 m^2), the doors (40 m^2), the pits and the potential location of the forced pit ventilation system, Fig. 1. The ventilation openings area per cow was 1.1 m^2.

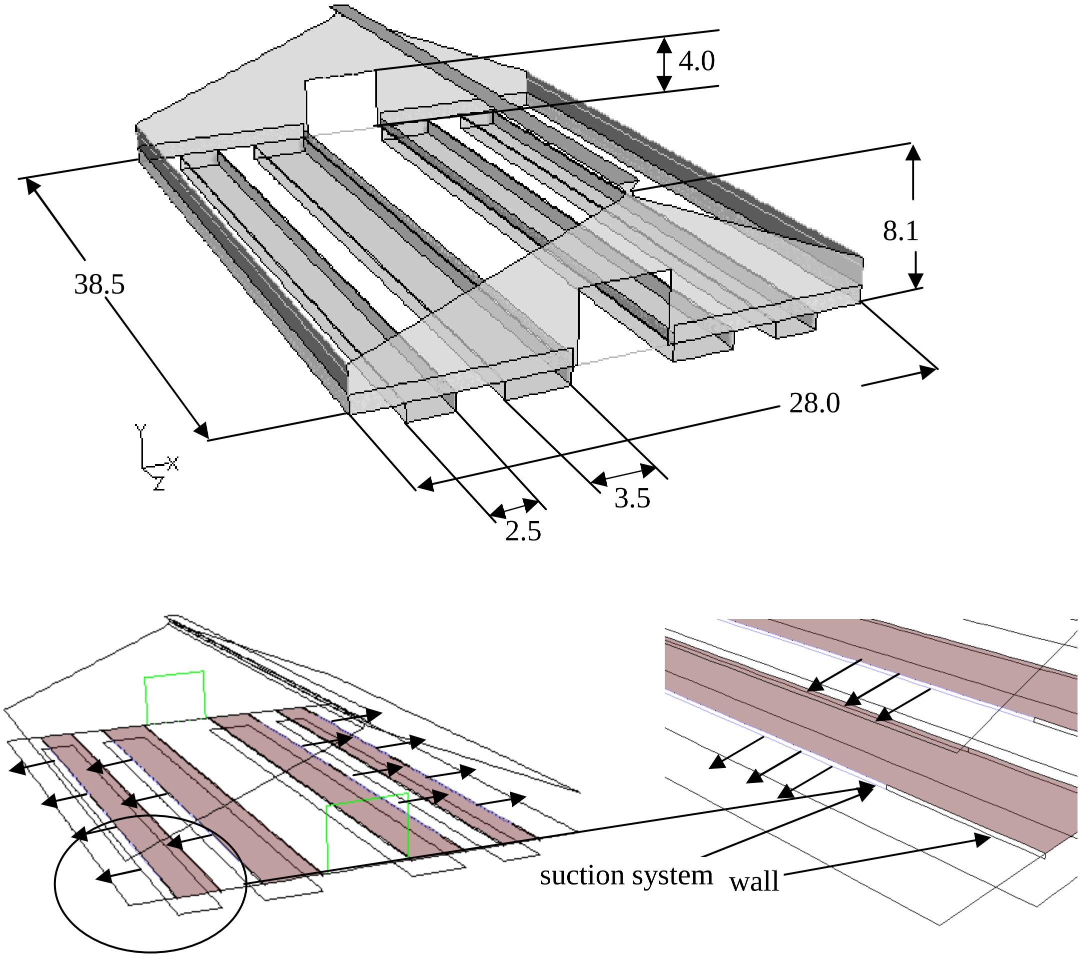

Fig.1. Geometrical design of the dairy cow building with the forced pit ventilation system and dimensions (m) of the main structural components

Various techniques have been used to measure and predict ventilation rate such as tracer gas techniques, energy balance and measurements of pressure differences between inside and outside (Baptista et al., 1999, Demmers et al., 2000, Monteny and Erisman, 1998, Van Duinkerken et al., 2005, Smits and Huis in ‘t Veld, 2007). Decay tracer gas method was used to determine the ventilation rate of four naturally ventilated dairy houses in northwest Germany (Snell et al., 2003). The ventilation rate was ranged from 4.3 to 14.5 air changes per hour when only the ridge ventilator was opened. Brehme and Krause (2002) indicated that not only the wind velocities but also the locations of the measuring points have a big influence on the decay behaviour of a tracer gas. Assessments of two methods to measure the ventilation and gaseous pollutant emission rates of naturally ventilated buildings indicated that the constant release tracer gas method performed better than the method based on measured pressure coefficients (Demmers et al., 2001). In this study the ventilation rate of the dairy cow building was calculated by simulating the method of constant injection of a tracer gas. In the simulation model the tracer gas is a virtual gas called air-tracer which has the same physical properties as normal air. The ventilation rate in $m^3\ s^{-1}$ is given by equation 1.

$$\phi_{v,kelder} = \frac{\phi_{m,tracer}}{c_{tracer}} \tag{1}$$

Where $\phi_{m,tracer}$ is the constant mass flux of the tracer gas (air-tracer) in kg s-1 and c_{tracer} is the concentration of the tracer gas in the building in kg m^{-3}.

The simulation model was solved for 12 cases concerning the wind speed, the wind direction and both air and manure temperature (Table 1). The heat production of cows were specified only as sensible heat to 700 W cow^{-1} when the external air temperature was 20°C and 1200 W cow^{-1} when the external air temperature was 0°C. For every case three simulations were performed in order to calculate the ventilation rate and the mass flux of ammonia through each of the ventilation openings. Firstly a convergence solution without forced pit ventilation system was obtained. Secondly, a forced ventilation system was applied with velocity magnitude at the suction points of 0.741 m s^{-1} (corresponds to sucked air flow of 250 $m^3\ h^{-1}\ cow^{-1}$). Finally, a forced pit ventilation system was applied with velocity magnitude of 1.481 m s^{-1} (corresponds to sucked air flow of 500 $m^3\ h^{-1}\ cow^{-1}$). The three solutions for every case are referred as A, B_250 and B_500 respectively.

Table 1. Boundary conditions for the simulation models

simulation case	wind speed (m s^{-1})	wind direction (° north)	air temperature (°C)	manure temperature (°C)	sensible heat per cow (W)	sucked air per cow ($m^3\ h^{-1}$)
01	1.0	0	0.0	10.0	1200	250 / 500
02	1.0	0	20.0	15.0	700	250 / 500
03	1.0	45	0.0	10.0	1200	250 / 500
04	1.0	45	20.0	15.0	700	250 / 500
05	4.0	0	0.0	10.0	1200	250 / 500
06	4.0	0	20.0	15.0	700	250 / 500
07	4.0	45	0.0	10.0	1200	250 / 500
08	4.0	45	20.0	15.0	700	250 / 500
09	8.0	0	0.0	10.0	1200	250 / 500
10	8.0	0	20.0	15.0	700	250 / 500
11	8.0	45	0.0	10.0	1200	250 / 500
12	8.0	45	20.0	15.0	700	250 / 500

Simplified simulations of ammonia volatilization from the top layer of the slurry in the pit were performed. In each run, a fixed mass fraction NH_3/air of 10^{-6} in the air layer just above the slurry was assumed. The concentration of NH_3 in reality is depended on several variables, e.g. the temperature of the top layer of the slurry, the ammonia concentration difference between slurry liquid in the top layer and the boundary layer of air just above it, pH, etc (Monteny et al., 2000). The mass transfer is directly related to the heat transfer. The total heat and mass transfer depends on the air velocity at the surface and the temperature and concentration difference at the surface and the passing flow. In this model approach, the calculated distribution of ammonia in the building is proportional to the initially assumed ammonia concentration at the surface of the pit's bottom.

The model calculates the air flow pattern within the building especially the air exchange between the slurry pit and the above floor compartment and the air exchange through the ventilation openings in the side walls and in the roof ridge. The results with and without the forced pit ventilation can be compared at different wind speeds (1 versus 4 versus 8 m/s), different wind directions (0, 45 and 90^o) and at a typical winter temperature (0 ^oC) versus a typical summer temperature (20 ^oC).

Results

The calculated ventilation rate of the building is dominated by the wind characteristics and buoyancy effect (temperature differences). Higher ventilation rates for a given wind speed were calculated when the direction of the air flow is perpendicular to the ridge of the building and during winter months. The influence of the wind direction decreases while the wind speed increases from 1 to 4 m s^{-1}. At high wind speeds (8 m s^{-1}) the air flow around and inside the building is hardly influenced by the wind direction and temperature differences, due to the high turbulence and recirculation flow. Temperature differences dominate the air flow obviously at low wind speeds and mainly during winter months. As the wind speed increases the temperature differences become less important. Concerning the wind speed there is a limit that above which, the wind direction and buoyancy effect has almost not influence to the ventilation rate. This limit is a function of geometrical design of the building and its surrounding region. In this study, since the simulation model was solved for only three wind speeds (1, 4, and 8 m s^{-1}) this limit can not be determined.

Applying a forced pit ventilation system below the slatted floor results in an increase of the ventilation rate of the building which ranged from 0.2 to 5.9% with flow capacity of 250 m^3 h^{-1} cow^{-1} (cases 01 and 06 respectively) and 0.3 to 13.2% with flow capacity of 500 m^3 h^{-1} cow^{-1} (cases 02 and 08 respectively). The suction system below the slatted floor in general increases the total mass flow of ammonia removed from the building. However, the influence of the suction system varies with different climatic conditions.

At wind speed of 1 m s^{-1} (cases 1-4), the potential increase of the total mass flow of ammonia due to forced pit ventilation system is higher during summer months (low temperature differences, outside air temperature equals to 20°C and manure temperature equals to 15°C) for both wind directions (0° and 45° respectively). No conclusions could be obtained for the relation between the total mass flow of ammonia resulting by the forced pit ventilation system and wind direction. At high temperature differences (winter months, outside air temperature equals to 0°C and manure temperature equals to 10°C), the mass flow of ammonia is higher when the wind direction is perpendicular to the ridge, although during summer months is higher when the wind direction is 45° to the ridge. The total increase mass flow of ammonia is ranged from 0.1% (case 3B_250) to 96.9% (case 4B_500). Doubling the flow capacity of the forced pit ventilation system (from 250 to 500 m^3 h^{-1} cow^{-1}) result a higher (more than double) increase of the mass flow of ammonia from the building (from 4.1 to 20.4%, from 11.3 to 60.7%, from 0.1 to 11.9% and from 29.9 to 96.9% for the cases 1-4 respectively).

At wind speed of 4 m s^{-1} (cases 5-8), the potential increase of the total mass flow of ammonia due to forced pit ventilation system is lower than the one predicted when the wind speed equals to 1 m s^{-1}. The total mass flow of ammonia is higher during summer months for both wind directions (0° and 45°) but in this case the differences with the values corresponding to winter months are smaller. This was also found in experiments. The total increase mass flow of ammonia is ranged from -1.9% (case 5B_250) to 16.7% (case 8B_500). Doubling the flow capacity of the forced pit ventilation system (from 250 to 500 $m^3 h^{-1} cow^{-1}$) result a higher (almost double) increase of the mass flow of ammonia from the building (from -1.9 to -0.1%, from 5.0 to 11.1%, from 5.1 to 10.7% and from 6.2 to 16.7% for the cases 5-8 respectively, Fig. 2).

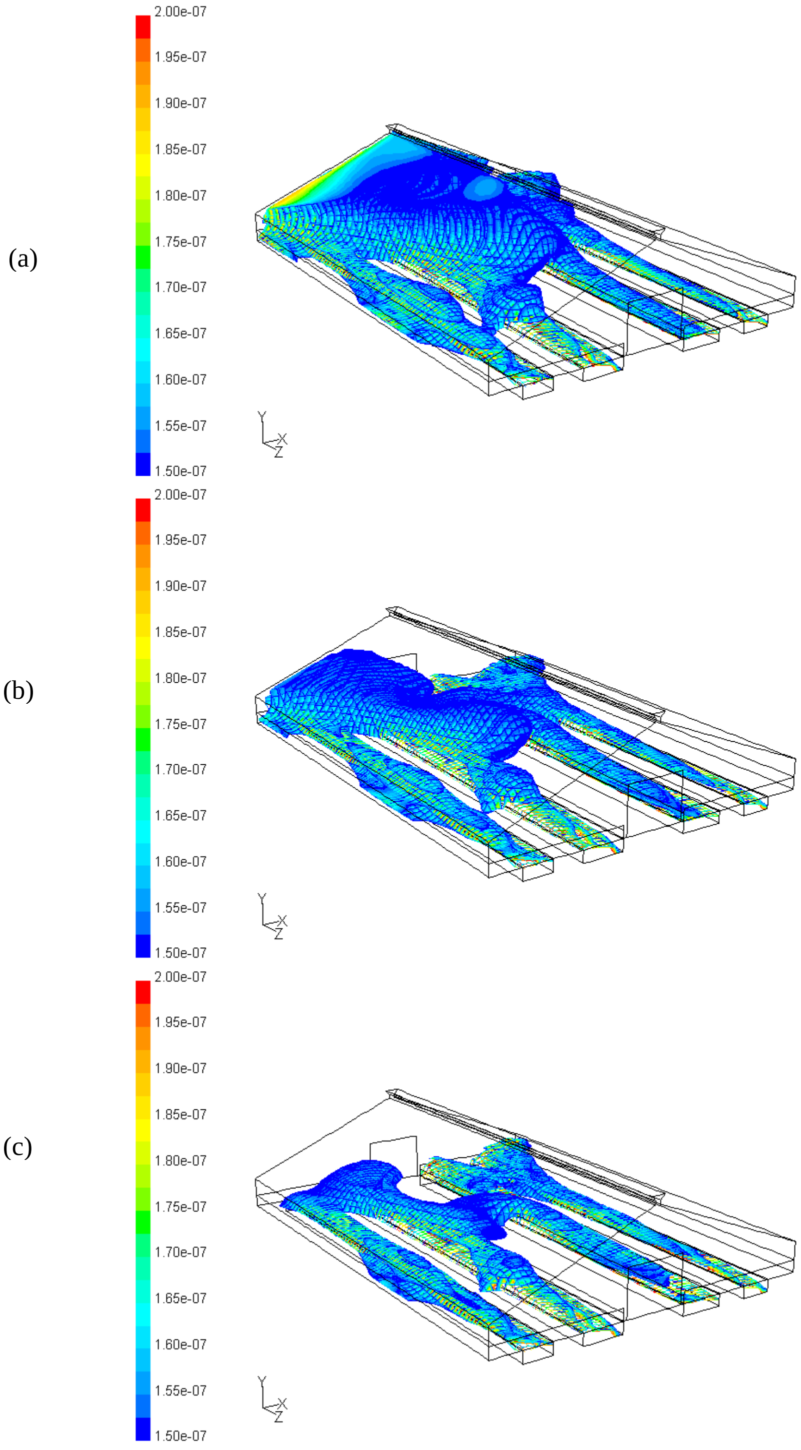

Fig. 2. Concentration of ammonia vapor (kg m^{-3}) in the dairy cow building: a) case 08_A (without forced pit ventilation), b) case 08_B_250 (forced pit ventilation of 250 $m^3 h^{-1} cow^{-1}$), c) case 08_B_500 (forced pit ventilation of 500 $m^3 h^{-1} cow^{-1}$)

It is remarkable that under specific conditions (winter months, wind speed 4 m s^{-1}, wind direction perpendicular to the ridge) applying forced pit ventilation below the slatted floor of the building result almost zero increase of the total mass flow of ammonia from the building, which means that the reduction of the mass flow of ammonia occurred in the ventilators equals to the mass flow of ammonia from the forced pit ventilation system.
At wind speed of 8 m s^{-1} (cases 9-12), the potential increase of the total mass flow of ammonia due to suction system is lower than the previous cases and the differences concerning the climatic conditions are not so important. The total increase mass flow of ammonia is ranged from 4.1% (case 12B_250) to 6.4% (case 10B_500). Doubling the flow capacity of the forced pit ventilation system (from 250 to 500 m^3 h^{-1} cow^{-1}) result a very small increase of the mass flow of ammonia from the stable (from 4.2 to 5.8%, from 4.5 to 6.4%, from 4.6 to 5.4% and from 4.1 to 6.3% for the cases 9-12 respectively). It is obvious that at high wind speeds the increase of the capacity of the suction system has almost no influence to the total mass flow of ammonia. The contribution of both forced pit ventilation system and building ventilators to the total ammonia emission from the cow house is depicted in Fig 3.

Conclusions

Application of a forced pit ventilation system below the slatted floor strongly influences the mass flow of ammonia from the building openings which means that part of the ammonia emitted from the building due to natural ventilation is removed by the system. For all the simulation cases the average reduction of the mass flow due to the forced pit ventilation system is -24.4%, -41.1% and -33.9% for the side openings, the ridge ventilator and the doors respectively. For a wind speed equal to 1 m s^{-1}, the decrease is higher than at higher wind speeds. No conclusions could be obtained about the influence of the wind direction and the temperature differences. In general, for wind direction perpendicular to the ridge, the reduction of mass flow of ammonia is higher at summer months although for wind direction 45° to the ridge, the reduction is higher at winter months. This conclusion is valid concerning the side openings and wind speeds 1 and 4 m s^{-1}. At wind speed of 8 m s^{-1} the reduction of mass flow of ammonia is higher during summer months for both wind directions. Concerning the ridge ventilator the higher reduction appears when the wind direction is perpendicular to the ridge for all wind speeds. At wind speed of 1 m s^{-1}, the highest reduction can be found during summer months. Although at wind speeds of 4 and 8 m s^{-1} the reduction is not influenced by the temperature differences. The same conclusion is valid also for mass flow of ammonia from the doors. For all the cases doubling the capacity of the forced pit ventilation system results a decrease of the mass flow of ammonia from the openings according to the factors 2.15, 1.77 and 1.89 for the side ventilators, ridge ventilator and doors respectively. The efficiency of the forced pit ventilation system is better at low wind speeds even with the flow capacity of 250 m^{-3} h^{-1} cow^{-1}. The above conclusions should be reconsidered when experimental data concerning the application of a forced pit ventilation system will be available.

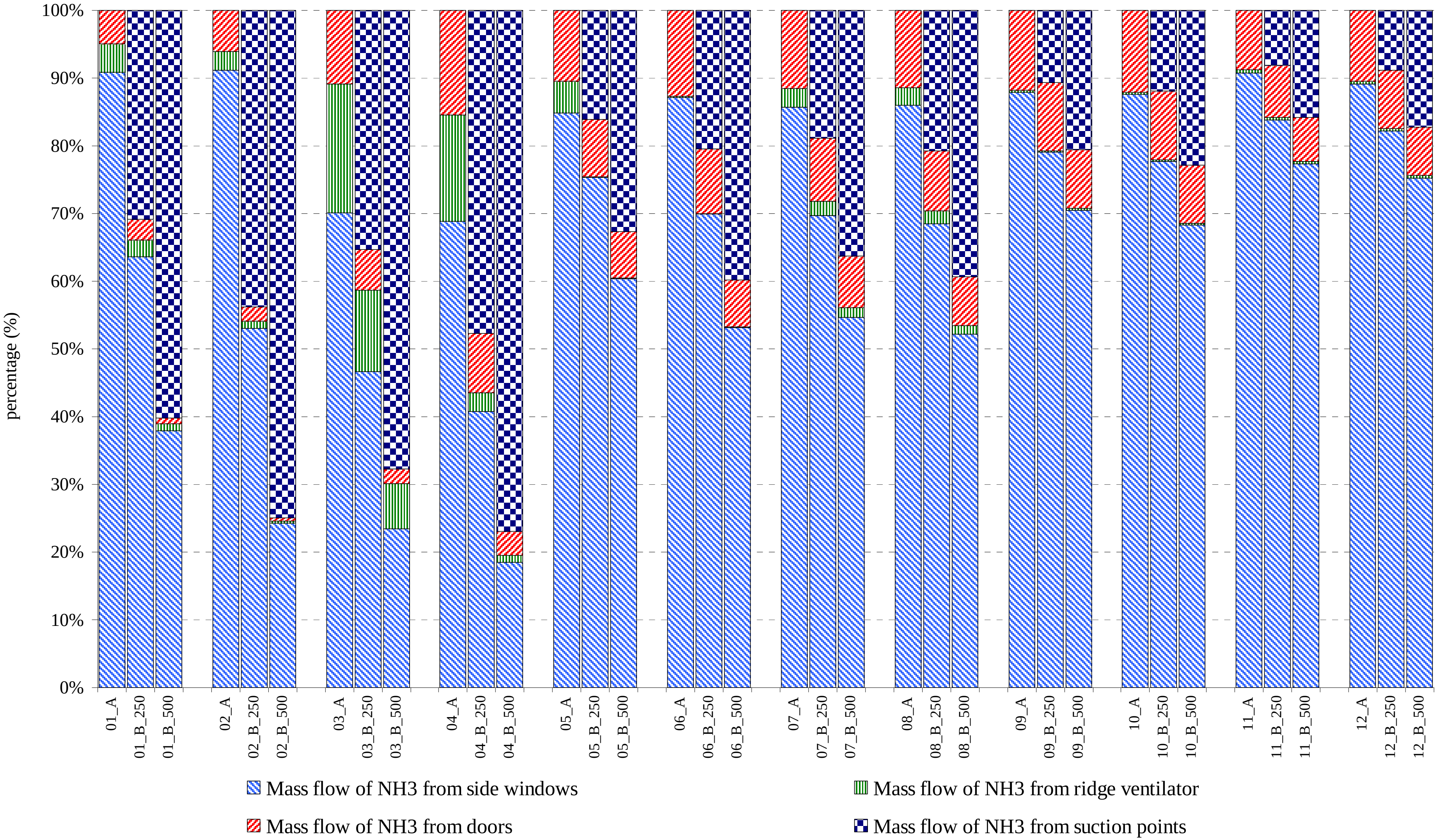

Fig. 3. Contribution of ventilators and forced pit ventilation system to the mass flow (kg h^{-1}) of NH_3 from the dairy cow building. A: without forced pit ventilation system, B_250: with forced pit ventilation of 250 m^{-3} h^{-1} cow^{-1} and B_500: with forced pit ventilation of 500 m^{-3} h^{-1} cow^{-1}

References

Baptista, F.J., Bailey, B.J., Randall, J.M., and Meneses, J.F., 1998. Greenhouse Ventilation Rate: Theory and Measurement with Tracer Gas Techniques. Journal of Agricultural Engineering Research 72, 363-374.

Braam, C.R., Smits, M.C.J., Gunnink, H. and Swierstra D. 1997(a). Ammonia Emission from a Double-Sloped Solid Floor in a Cubicle House for Dairy Cows. Journal of Agricultural Engineering Research 68, 375-386.

Braam, C.R., Ketelaars, J. and Smits, M.C.J., 1997(b). Effects of floor design and floor cleaning on ammonia emission from cubicle houses for dairy cows. Netherlands Journal of Agricultural Science 45: 49-64

Brehme, G. and Krause K.H. 2002. Compartmental Airflow Simulation in Stables with Natural Ventilation. Agricultural Engineering International: the CIGR Journal of Scientific Research and Development, IV.

Demmers, T.G.M., Burgess, L.R., Phillips, V.R., Clark, J.A. and Wathes, C.M., 2000. Assessment of techniques for measuring the ventilation rate, using an experimental building section. Journal of Agricultural Engineering Research 76, 71-81.

Demmers, T.G.M., Phillips, V.R., Short, L.S., Burgess, L.R., Hoxey, R.P. and Wathes, C.M. 2001. Validation of Ventilation Rate Measurement Methods and Ammonia Emission from Naturally Ventilated Dairy and Beef Buildings in the United Kingdom. Journal of Agricultural Engineering Research 79, 107-116.

Harral, B.B. and Boon C.R. 1997. Comparison of predicted and measured airflow patterns in a mechanically ventilated livestock without animals. Journal of Agricultural Engineering Research 66, 221-228.

Huawei, S., Keener, M.H., Deng, W., Frederick, C. and Michel, C.F. 2004. Development and Validation of 3-D CFD Models to Simulate Airflow and Ammonia Distribution in a High-RiseTM Hog Building during Summer and Winter Conditions. Agricultural Engineering International: the CIGR Journal of Scientific Research and Development, VI.

Lee, I., Park, B., Yu, B., Yun, J. Chun, J., Kim, K. and Cho, H. 2002. Optimum design of forced ventilation system of piglet house using computer simulation. In: Proceedings of 2002 ASAE Annual International Meeting, July 28-31, Illinois, USA.

Mistriotis, A., Bot , G.P.A., Picuno, P. and Scarascia-Mugnozza, G. 1997. Analysis of the effeciency of greenhouse ventilation using computational fluid dynamics. Agricultural and Forest Meteorolgy 88, 121-135.

Monteny, G.J., 2000. Modelling of ammonia emissions from dairy cow houses. Thesis Wageningen University, Wageningen, the Netherlands, 155 p.

Monteny, G.J. and J.W. Erisman. 1998. Ammonia emission from dairy cow buildings: a review of measurement techniques, influencing factors and possibilities for reduction. Neth. J. Agric. Sci. 46:225–247.

Ogink, N.W.M. and Kroodsma, W., 1996. Reduction of ammonia emission from a cow cubicle house by flushing with water or a formalin solution. Journal of Agricultural Engineering Research (63): 197–204

Pedersen, S., Monteny, G., Xin, H. and Takai, H. 2004. Progress in Research into Ammonia and Greenhouse Gas Emissions from Animal Production Facilities. Agricultural Engineering International: the CIGR Journal of Scientific Research and Development, VI.

Quinn, A.D., Wilson, M., Reynolds, A.M., Couling, S.B. and Hoxey, R.P., 2001. Modelling the dispersion of aerial pollutants from agricultural buildings – an evaluation of computational fluid dynamics (CFD). Computers and Electronics in Agriculture 30, 219-235.

Rumburg, B., Mount, H.G., Filipy, J., Lamb, B., Westberg, H., Yonge, D., Kincaid, R. and Johnson, K., 2008. Measurement and modelling of atmospheric flux of ammonia from dairy milking cow housing. Atmospheric Environment 42, 3364-3379.

Smits, M.C.J., Huis in 't Veld, J.W.H., 2007. Ammonia emission from cow houses within the Dutch 'Cows & Opportunities' project. In: Ammonia emissions in agriculture. Wageningen: Wageningen Academic Publishers, - p. 119 - 120

Snell, H.G.J., Seipelt, F. and Van den Weghe, H.F.A., 2003. Ventilation Rates and Gaseous Emissions from Naturally Ventilated Dairy Houses. Biosystems Engineering 86(1), 67-73.

Sun, H., Stowell, R., Keener, H.M. and Michel, F.C. 2002. Two-Dimensional Computational Fluid Dynamics (CFD) Modelling of Air Velocity and Ammonia Distribution in a High-RiseTM Hog Building. Transactions of the ASAE 45(5), 1559-1568.

Swierstra, D., Smits M.C.J. and Kroodsma, W. 1995. Ammonia Emission from Cubicle Houses for Cattle with Slatted and Solid Floors. Journal of Agricultural Engineering Research 62, 127-132.

Van Dooren, H.J.C. dnd Galama, P.J., 2007. In: Proceedings of Sixth International Dairy Housing Conference. June 16-18, 2007. Minneapolis, Minnesota, USA.

Ye, Z., Zhang, G., Li, B., Strøm, J.S. and Dahl, P.J., 2008. Ammonia Emissions Affected by Airflow in a Model Pig House: Effects of Ventilation Rate, Floor Slat Opening, and Headspace Height in a Manure Storage Pit. Transactions of the American Society of Agricultural and Biological Engineers 51(6), 2113-2122.

Wang, C., Zhang, G., Rom, H.B., Strøm, J.S. and Li, B. 2005. Comparing model estimation with measured ammonia emission data from naturally ventilated dairy cattle buildings with slatted floor. In: Proceedings of Seventh International Symposium Livestock Environment II, May 2005, Beijing, China.