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Calculation of the ammonia emission reduction potential in a naturally ventilated cattle stable using a numerical model

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Cattle farming in naturally ventilated stables is a major source of ammonia emissions. Numerical models of livestock buildings make it possible to virtually simulate the flow, the concentration distribution of harmful gases and the emission behaviour of a real barn under any relevant operating condition on the computer. Thus, ventilation strategies for naturally ventilated dairy cattle stable can be developed, which reduce emissions and increase animal welfare at the same time.

In the present work the numerical model of a real existing dairy cattle barn was extended by a partial underfloor suction with subsequent exhaust air treatment and the emission behaviour at different inflow conditions and operating states was calculated. The simulations showed a clear potential for a reduction of ammonia emissions and possibilities for optimizing the ventilation of an open barn system.

In comparable studies, numerical simulations have also shown a positive effect of partial underfloor suction with regard to ammonia emissions in naturally ventilated cattle barns. In this context, a fundamentally improved ventilation of cattle barns by partial underfloor suction was also found.

Keywords
Computational fluid dynamics, cattle stable, partial underfloor suction, emissions

Soil acidification and nitrogen accumulation in soil and water bodies are ecosystem pressures that can be attributed to the emission of ammonia (NH_3). The NERC Directive 2016/2284 (2016) requires Germany to reduce these emissions by 5 % each year between 2020 and 2029 and by 29 % from 2030 onwards, measured against 2005 levels. Around 95 % of the ammonia emitted comes from agriculture. Of this, 52 % alone comes from cattle farming (UBA 2014). Of these, 32.4 % come from livestock housing, 9.0 % from manure storage, 56.2 % from spreading manure and 2.4 % from grazing (Haenel et al. 2020).

In Germany, according to the Federal Statistical Office, in November 2019 approximately 12 million cattle were kept on over 135,000 farms (Statistisches Bundesamt 2020). Only 26 % of these farms have herds of more than 100 animals. However, these few farms hold most of all cattle (76 %). This shows that there is a general trend towards increasing the size of livestock buildings (Tergast et al. 2020). Technical measures to reduce emissions, such as an exhaust air washer, work more effectively above a certain plant size and work better with the associated standardised management. It should be examined whether technical measures such as intelligent ventilation and subsequent treatment of the exhaust air in open housing systems for cattle can also reduce ammonia emissions.

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There is also a great desire among the population for more sustainability, especially in livestock farming. The priority themes here are animal welfare and environmental protection. Livestock farms, for example, should release only low emissions into the environment, e.g. by closing material cycles such as nitrogen. In addition, they should also consider the needs of the animals and provide, for example, sufficient space, light, and fresh air. This often leads to a conflict of objectives which must be resolved in order to make animal husbandry more acceptable from the consumer's point of view.

The promising possibility of reducing emissions from cattle stables by means of partial underfloor suction with subsequent exhaust air treatment is to be examined in the present study. The system has already been successfully tested in practice on a force-ventilated pig fattening unit (Musslick et al. 2015). The basic principle is to divide the air space into an above-floor area (the area above the slatted floor where the animals are located) and an underfloor area (slurry cellar). The high ammonia concentrations near the floor are extracted in the slurry cellar under the slatted floor and fed to an exhaust air washer. In this way, the air pollutants do not reach the breathing area of the animals and wind-induced natural ventilation with fresh air continues to take place in the above-floor area. The challenge with this method is to extract only the lowest possible air volume flow under the floor in order not to release additional air pollutants from the liquid manure. This can best be implemented with an intelligent ventilation concept that has been optimised in advance by simulations on a numerical model.

The aim of the study was to provide a numerical model of a real, naturally ventilated dairy cattle stable with partial underfloor suction and to optimise the ventilation concept with the aid of numerical simulation. This is intended to evaluate the potential of the process to reduce emissions and increase animal welfare.

The real stable

The basis for the numerical simulation was a real box barn (Figure 1) measuring 12 × 43 × 78 m (H × W × D) and with a capacity for 255 dairy cows. The animals are supplied by two feeding tables located on the long sides. Between the feeding tables there are opposite cubicles in three rows spread across the width of the barn. This barn concept is particularly suitable for an extension with a partial underfloor suction system, as the walkways here are designed with slatted floors according to DIN EN 12737:2008-02 (2008). Through them, the faeces of the animals are discharged and stored in two independent slurry cellars. Scrapers are used to clean the slatted floors. Ventilation is regulated by blinds on the eave’s sides, which can be seen fully opened in Figure 1. Inside the barn, four milking robots with waiting yards and one sick and one regeneration compartment each are accommodated.

Figure 1: View into a box pen on a feeding table. The blinds on the eaves side are fully open (©Thünen-Institut)

The partial underfloor suction

The concept of partial underfloor suction was developed at the Thünen Institute for Agricultural Technology. The procedure and the device for aeration and ventilation of a stable building, which has an above-floor area and an underfloor area, are described in Krause (2012). Krause et al. (2010) describe an example of how intelligent ventilation technology and subsequent exhaust air treatment can reduce emissions. In this case, the area under the slatted floor in a forced-ventilated fattening pig house is partially sucked and this air, which contains a high concentration of ammonia, is fed to an exhaust air washer.

In the technical execution of the numerical model examined in this thesis and shown in Figure 2, an exhaust air duct is modelled in the area under the perforated floor to gain access to the underfloor air of the stable. In order to be able to achieve a uniform suction over the entire depth of the barn, the duct is divided into several segments of equal length in terms of construction and thus also in terms of ventilation. The air above the slurry is extracted through a line sink, which is designed as a multitude of suction slots.

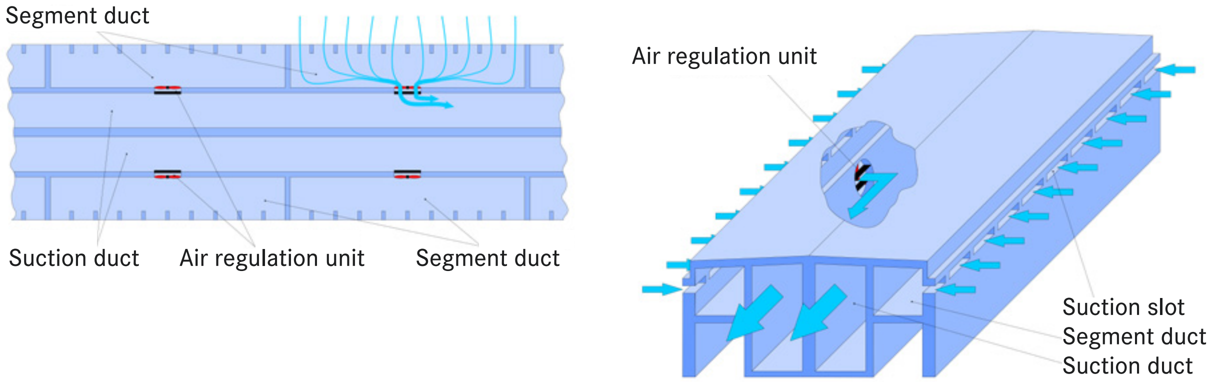


Figure 2: Technical implementation of partial underfloor suction in the pit house

Important for the proper functioning of partial underfloor suction is a negative pressure gradient between the above-floor area, i.e. the area where the animals stay, and the underfloor area where the liquid manure is stored. This can be guaranteed by several sensory differential pressure measurements between the above- and underfloor areas if a central barn computer calculates the measured data. The pressure gradient can thus be controlled via the suction volume flow. This means that, depending on the external climatic conditions, a minimum suction volume flow (setpoint) must be set to keep the pressure gradient below zero.

Each segment has an air regulation unit. It consists of control valves and a measuring fan. The actual value of the sucked air volume flow of each individual segment is recorded by the respective measuring fan and transmitted to the climate computer. By comparing the setpoint values, the corresponding control valves can be assigned a position that keeps the air volume delivered in all individual segments identical. In the numerical model, the behaviour and effectiveness of partial underfloor suction for fixed suction volume flows are investigated as a function of external climatic parameters such as wind speed. Without the additional segment channels, each air regulation unit would form a point sink which sucks in air with a high impulse and consequently high turbulence, thereby further increasing the release of ammonia from the slurry. Only the combination of air control unit and segment channel with the upstream line sink enables a low-pulse and uniform air suction over the entire depth of the barn. In the suction duct, the exhaust air from the individual segments is bundled and fed to an exhaust air washer.

At present, a large number of single- or multi-stage exhaust air purification systems are used, especially in pig farming. These are either biological or chemical systems, which differ in their basic mode of operation. In addition to ammonia, they can also bind other pollutants in the stable air. The separation efficiency for ammonia in current systems is 70 - 90 % (Hahne et al. 2016). In an evaluation of electronic operating logs of single-stage biological exhaust air purification systems in pig fattening, this value was even 93 % on average. The cleaning performance of the washer depends, among other things, on the pH value of the washing water, the blowdown rate, and the ammonia concentration in the supply air (Hahne 2019). The provision of the necessary negative pressure for the partial underfloor suction or the volume flow through the washer is carried out by a central suction system located on the front side of the barn. Here the air is blown out into the environment after treatment. An arrangement in the main airflow direction should be avoided in order not to impair the natural wind flow through the stable.

There is currently no certified system for cleaning the exhaust air from the barn for dairy cattle either in Germany (DLG 2020) or in Europe (VERA 2020). The combination of partial underfloor suction and downstream exhaust air treatment represents a possibility for new barn buildings or extensions to reduce ammonia emissions.

The numerical model

The numerical simulations were carried out with the commercial software STAR-CCM+ from Siemens PLM in version 12.06.011 using the Reynolds-Averaged Navier-Stokes (RANS) method at various reference speeds. All geometries, with the exception of the wind protection nets and the fans in the underfloor area, were modelled in detail. The geometric model of the entire barn is shown in Figure 3.

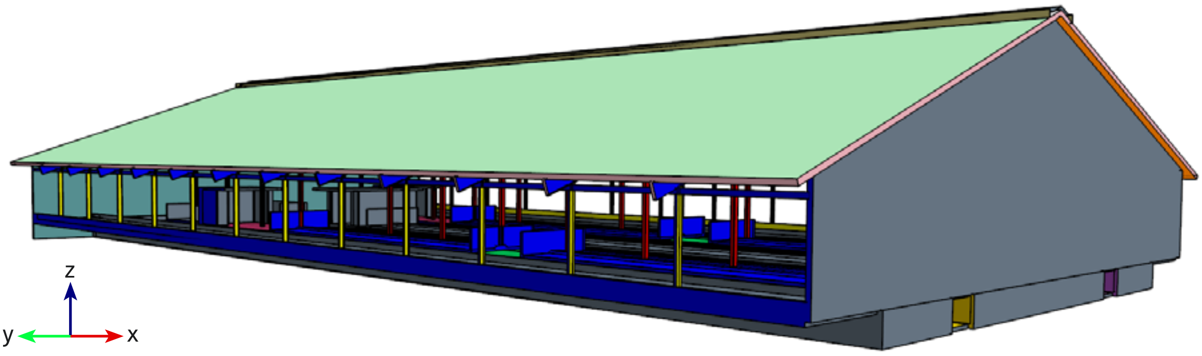


Figure 3: Representation of the stable geometry

The wind protection nets were presented as a porous-baffle-interface with different porosities and the fans first via a fan-interface and later as a mass flow-inlet with negative mass flow. The ammonia source was the surface of the slurry and the top and side surfaces of the slatted floors, each with a concentration of 20 ppm derived from our own practical measurements.

The inlets were given a velocity-inlet boundary condition on which the velocity profile $v_x(h)$ is imprinted as a parabolic shape (Equation 1). It is calculated as a function of the wind speed v_{10} at a height of 10 m:

$$v_x(h) = v_{10} \left(\frac{h}{10}\right)^{0,262} \qquad \text{(Equation 1)}$$

The outlets were modelled as pressure-outlets with a pressure of 0 Pa.

The spatial discretization of the model resulted in a number of elements of 7,120,559. The unstructured mesh is shown in Figure 4.

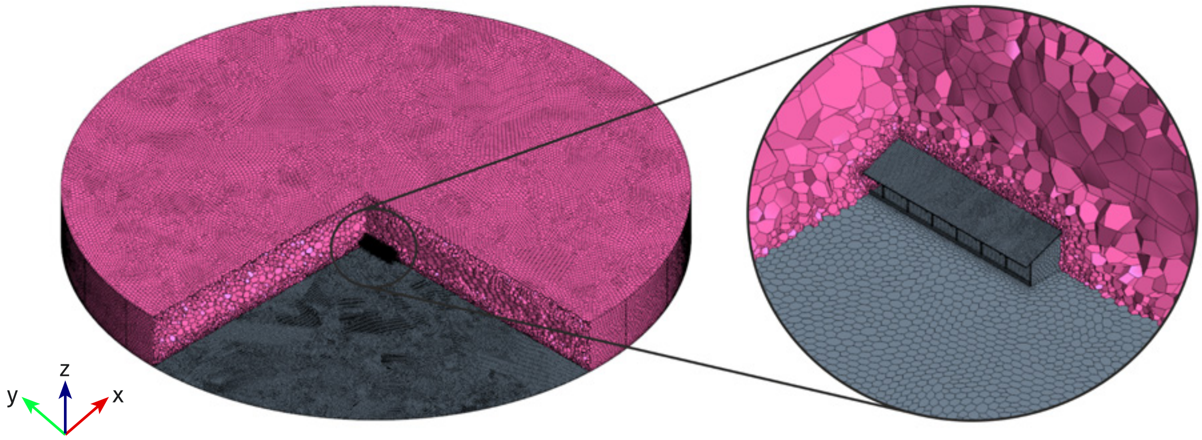


Figure 4: Representation of the volume mesh and the surface mesh of the barn geometry

The results of the emission reduction by the partial underfloor suction

Initially, a wind speed of v_{10} = 3 m/s was chosen at a height of 10 m according to Equation 1. The average speed of all measuring fans was set at 800 rpm. This corresponds to a volume flow of $\dot{V}$ = 172,000 m^3/h per suction duct.

The uniformity of the suction in the underfloor area was assessed by means of a schlieren pattern on which the speed distribution is shown as a scalar quantity (Figure 5).

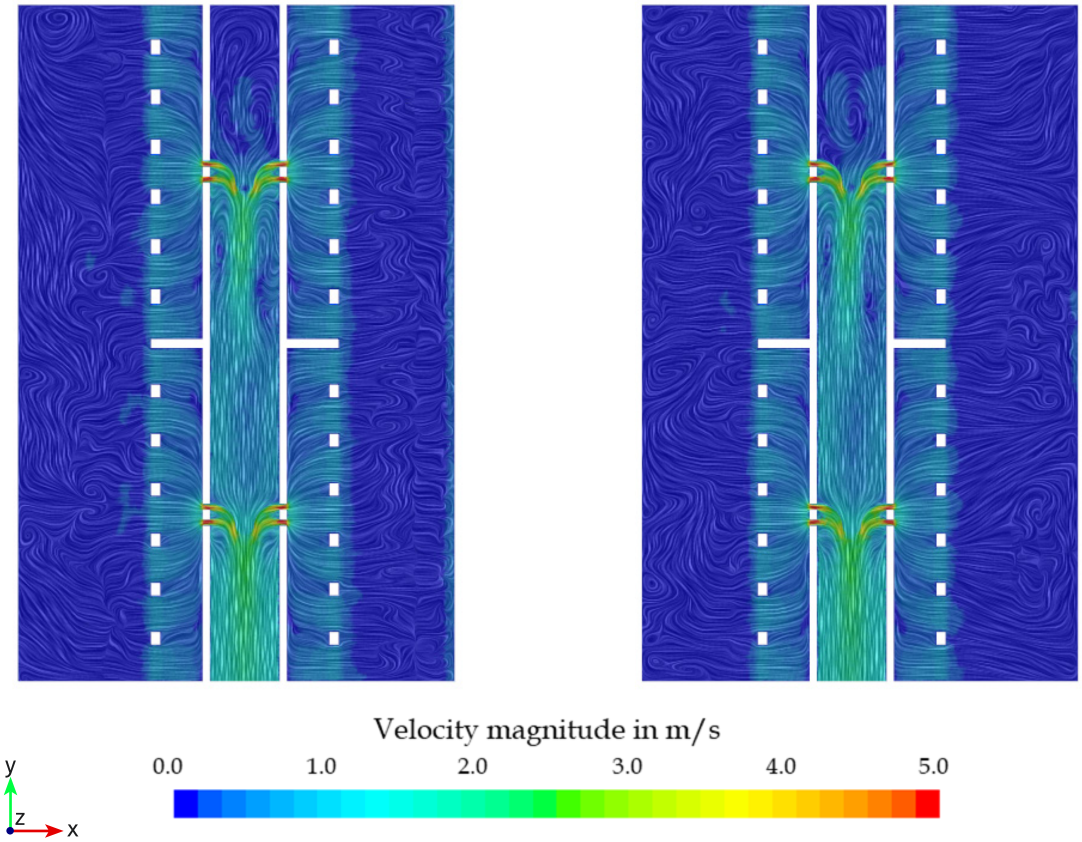


Figure 5: Schlieren pattern with velocity distribution in the underfloor area (detail, z = -0.55 m)

Here it can be seen that the suction is very evenly distributed over the suction slots of the segments. Due to the line sink, a low-pulse and even suction of air is achieved over the entire depth of the barn.

However, the position of the slurry ducts relative to the inflow ensures an uneven suction above the slurry. Figure 6 shows the suctioned air as streamlines. The wind flows from left to right through the barn. In this direction, the slurry ducts below the slatted floors are also numbered 1 - 4. It can be seen that in the slurry ducts 1 and 3 the air flows directly into the segment channel without reversing direction due to the suction, so that the air is sucked in only over a small width of the liquid manure. However, air which strives in these ducts towards the above-floor area (left half of slurry ducts 1 and 3) is carried downwards again by the incoming air, so that a kind of natural barrier is formed. In slurry ducts 2 and 4, the flow must reverse its direction before it enters the segment ducts. As a result, it first flows over the entire slurry surface in the duct, but then supports the underfloor extraction through its correct direction. In all liquid manure ducts, it is ensured that only a minimum amount of air from the underfloor area can return to the animals' living area.

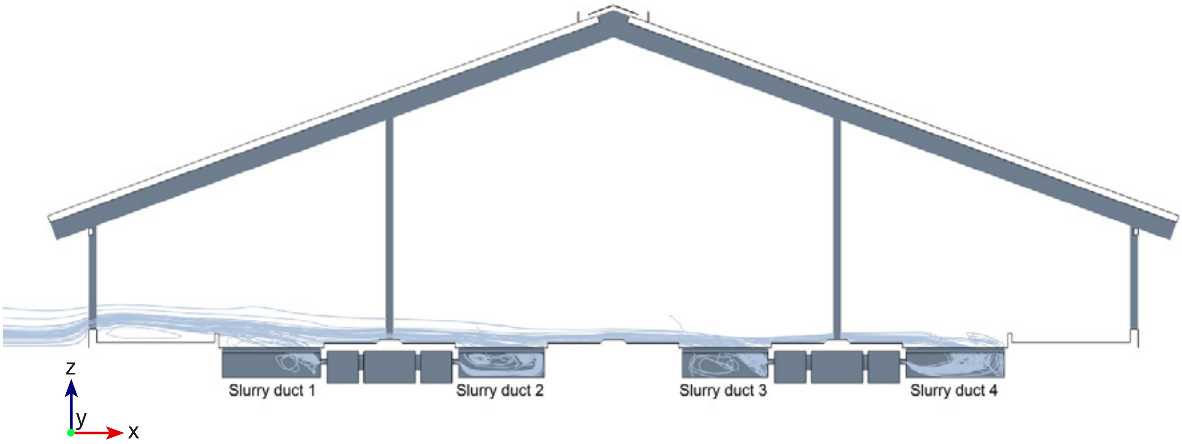
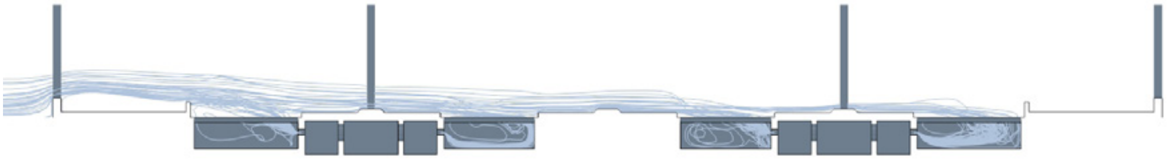
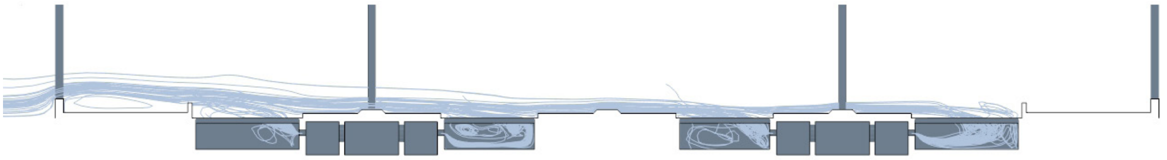


Figure 6: Representation of the streamlines in the slurry ducts

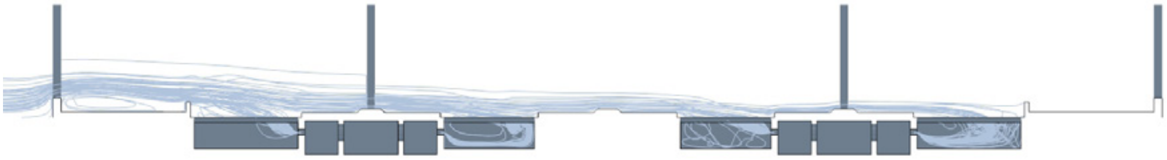
In order to achieve a more uniform extraction over the depth of the slurry ducts, the fan speeds were examined more closely. In addition to the already considered uniform speed of 800 rpm per measuring fan ($\dot{V}$ = 172,000 m^3/h) this distribution was also calculated for the maximum speed of 1,600 rpm ($\dot{V}$ = 345,000 m^3/h). In two further configurations, the suction power for slurry ducts 1 and 3 was set higher than for ducts 2 and 4: firstly, the 800 rpm for ducts 1 and 3 and 600 rpm for ducts 2 and 4 ($\dot{V}$ = 151,000 m^3/h) and, as a further configuration, 1,200 rpm for ducts 1 and 3 and 900 rpm for ducts 2 and 4 ($\dot{V}$ = 226,000 m^3/h). The volume flows in brackets indicate the total volume flow per suction duct. A representation of the streamlines of all four variants is shown in Figures 7a to 7d.



(a) Streamlines for a speed of rotation of 800/600 rpm



(b) Streamlines for a speed of rotation of 800/800 rpm



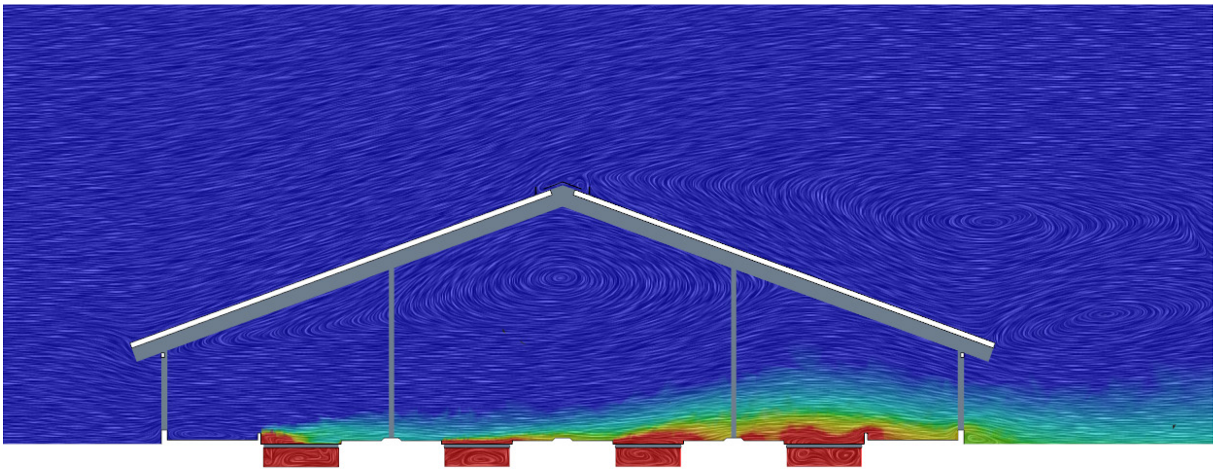
(c) Streamlines for a speed of rotation of 1,200/900 rpm

(d) Streamlines for a speed of rotation of 1,600/1,600 rpm

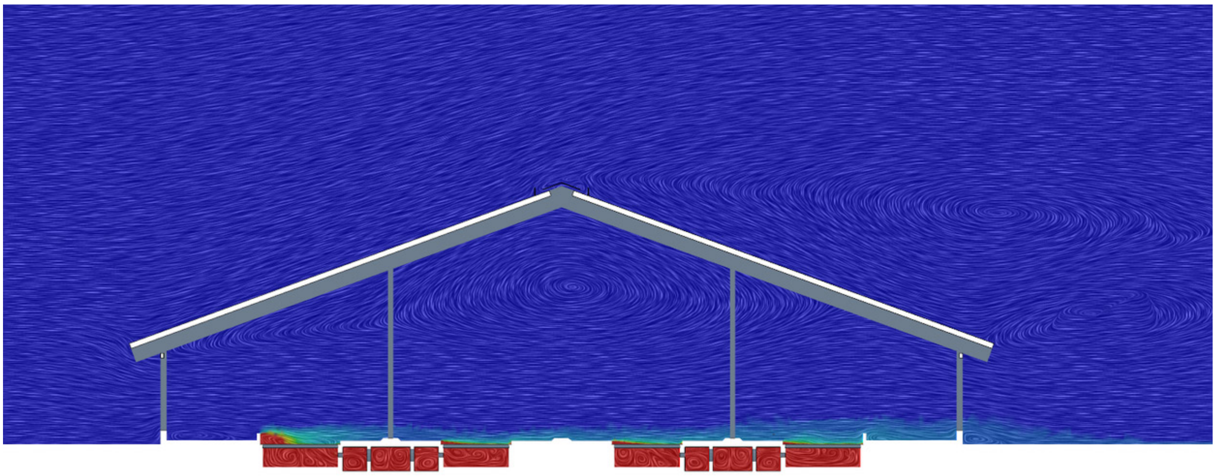
Figure 7: Comparison of the streamlines in the underfloor area for different suction constellations at a flow of v_{10} = 3 m/s

The flow patterns show that the behaviour of the air does not change significantly. The influence of the increased suction volume flow on the NH_3 emissions of the barn is discussed in the following section.

In order to be able to make a comparison with a conventional cattle stable without underfloor suction, such a configuration was simulated for the case of an inflow of v_{10} = 3 m/s. A comparison of the ammonia concentration in the barn without underfloor suction and with a suction volume flow of $\dot{V}$ = 226,000 m^3/h per suction duct is shown in Figures 8a and 8b.



(a) Concentration of ammonia without underfloor suction



(b) Concentration of ammonia with underfloor suction

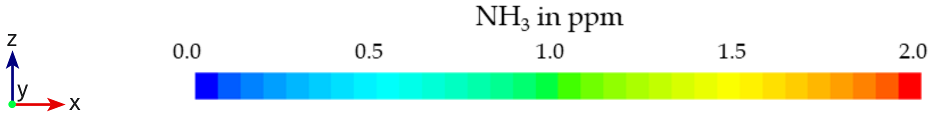


Figure 8: Comparison of the NH_3 concentration in the barn without (a) and with (b) partial underfloor suction at a flow of v_{10} = 3 m/s and a suction volume flow of $\dot{V}$ = 226,000 m^3/h

Without underfloor suction, the ammonia concentration increases in the direction of flow. The air dips into the slurry cellars, swirls and, due to the positive pressure gradient between above- and underfloor area, re-enters the above-floor area. During this process, it has enriched with ammonia from the liquid manure. The partial underfloor suction in Figure 8b prevents such high concentrations from developing in the above-floor area with the same flow. Although the incoming air also dips into the slurry cellar here, it is almost completely kept in the underfloor area by the suction system.

For further evaluation, the above-floor share of the ammonia mass flow $\dot{m}_{NH_3,above-floor}$ was determined at the interfaces of the barn with the environment. It can be calculated according to Equation 2 using the volume flow $\dot{V}_{above-floor}$ of the air in m^3/h leaving the stable at the opening of the eaves side and the concentration of ammonia $C_{NH_3,above-floor}$ determined there in kg/m^3.

$$\dot{m}_{NH_3,above-floor} = \dot{V}_{above-floor} \cdot C_{NH_3,above-floor} \qquad \text{(Equation 2)}$$

The underfloor share of the ammonia mass flow $\dot{m}_{NH_3,underfloor}$ is determined at the interfaces of the suction duct to the exhaust air treatment plant. It can be calculated according to Equation 3 using the volume flow $\dot{V}_{underfloor}$ in m^3/h to the washer and the raw gas concentration of ammonia $C_{NH_3,underfloor}$ in kg/m^3.

$$\dot{m}_{NH_3,underfloor} = \dot{V}_{underfloor} \cdot C_{NH_3,underfloor} \qquad \text{(Equation 3)}$$

The results of the simulations presented below assume a conservative theoretical washer performance of 70 %. It thus reduces the mass flow of ammonia in the clean gas to 30 % of the original mass flow in the raw gas in the underfloor area. For the total mass flow which the stable system emits into the environment, the corresponding proportion from the underfloor area must be added to the ammonia mass flow leaving the stable above ground (Equation 4).

$$\dot{m}_{NH_3} = \dot{m}_{NH_3,above-floor} + 0{,}3 \cdot \dot{m}_{NH_3,underfloor} \qquad \text{(Equation 4)}$$

The simulations described above were also simulated for two other incident flow velocities (v_{10} = 5 m/s and v_{10} = 10 m/s). Figure 9 shows the results relative to the simulation without partial underfloor suction at a wind speed of v_{10} = 3 m/s. The bars of the above-floor part are filled with saturated colours and have black values, the underfloor part is shown in pastel colours and labelled in grey.

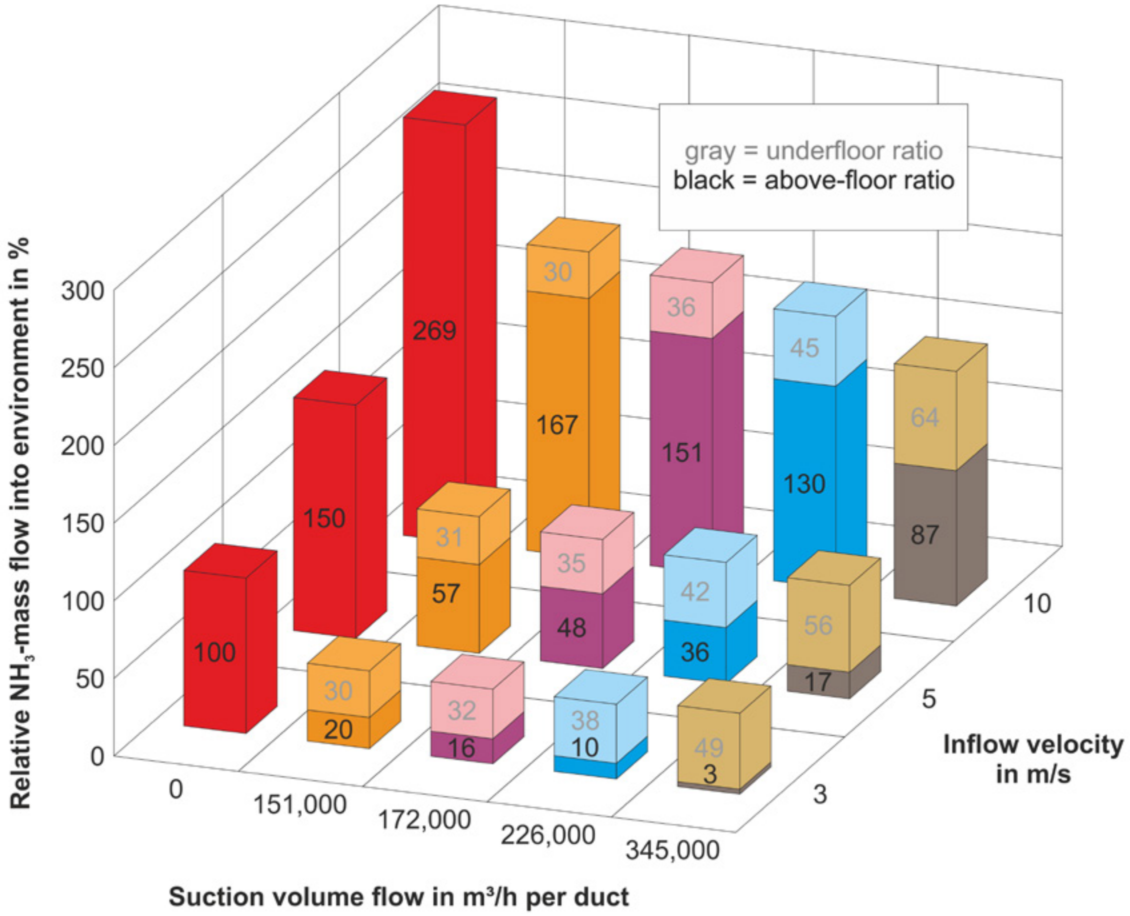


Figure 9: Bar chart showing the relative ammonia mass flow into the environment of a naturally ventilated cattle stable with and without partial underfloor suction at different inflow velocities v_{10} and suction volume flows and a cleaning performance of the downstream air washer of 70 %

The suction volume flows apply per duct. For a moderate inflow velocity of v_{10} = 3 m/s, the NH_3 mass flow into the environment is almost independent of the suction volume flow. Partial underfloor suction can halve the emissions of the stable system here. This also shows, however, that the increase in ammonia emissions from the liquid manure by increasing the suction volume flow corresponds approximately to the expected reduction in the above-floor area. It can also be seen that at higher wind speeds, less ammonia is released into the environment as the power of the suction fans increases. Here, the overall reduction of emissions by the suction outweighs the increase in the underfloor emissions due to the higher impulse above the slurry. With constant suction power and increasing wind speed, the mass flow into the environment increases according to Equation 2, since the volume flow through the barn increases, but the concentration of ammonia remains at a similar level.

The theoretical potential and effectiveness of partial underfloor suction in combination with a downstream air washer for reducing ammonia emissions from a naturally ventilated cattle stable could already be demonstrated here based on a few simulations.

The influence of the flow direction

The flow perpendicular to the ridge is usually the main wind direction in the design and positioning of a naturally ventilated cattle barn and should ensure good ventilation of the barn interior. In reality, however, the wind directions change more or less dynamically. For this reason, partial underfloor suction must also function, e. g. in the case of an inclined flow. In the simulations carried out, six different incident angles α were considered (Figure 10).

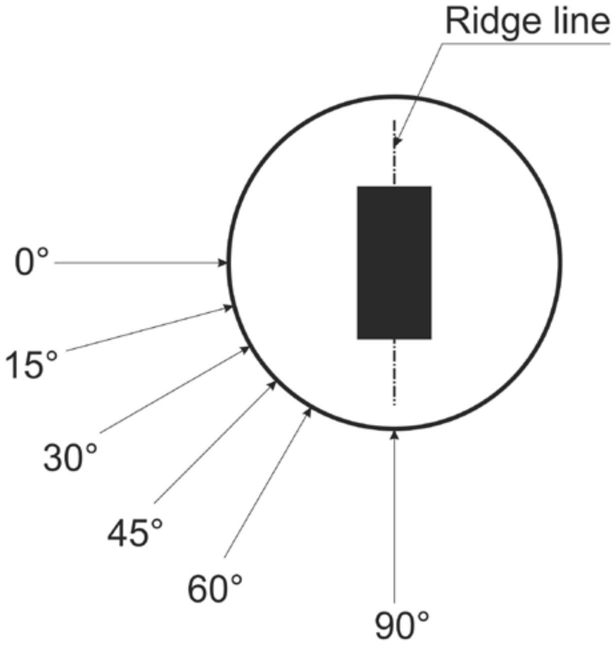
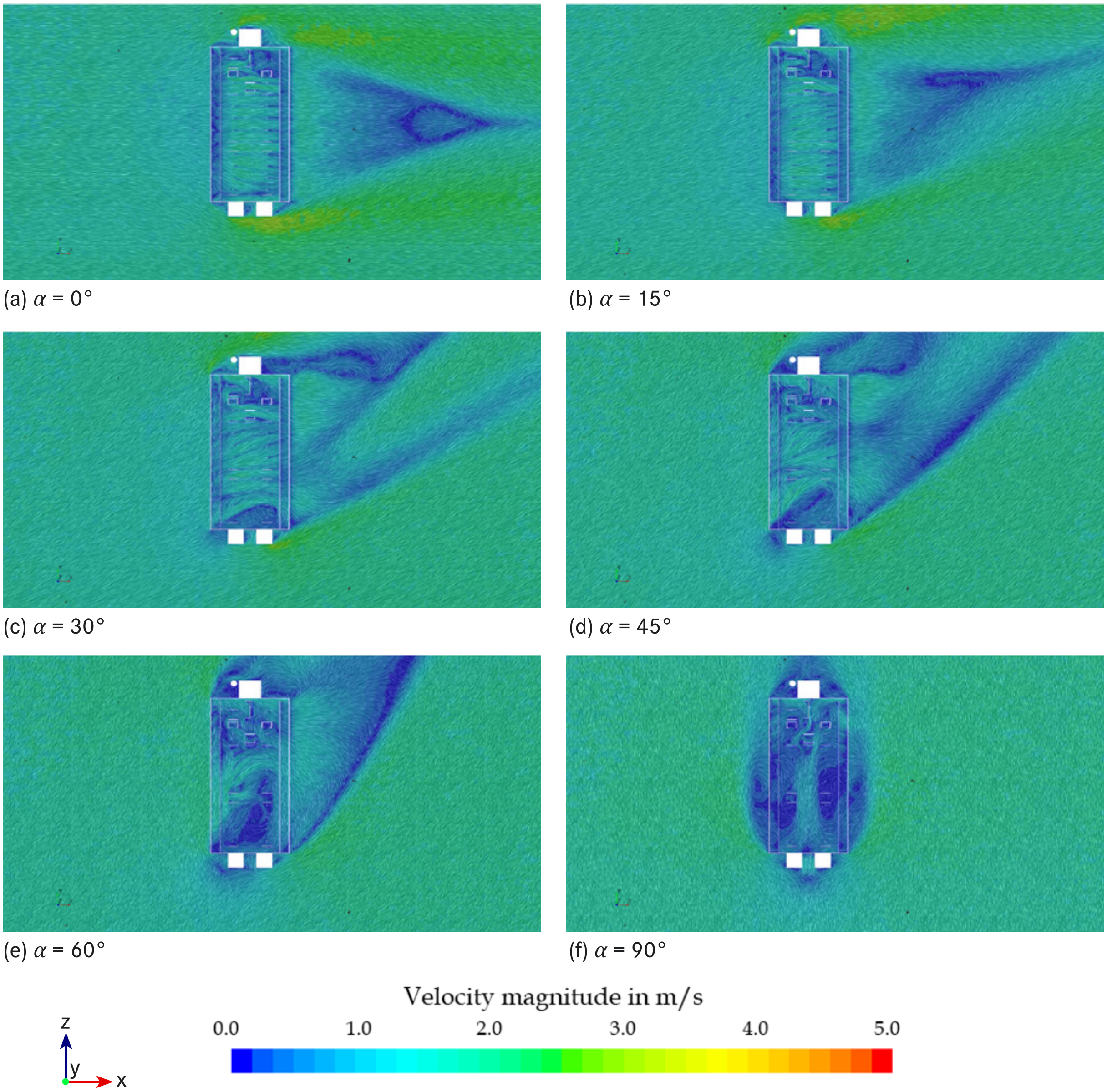


Figure 10: Definition of the investigated incident angles at the stable

The inflow velocity for the angle variations was kept constant at v_{10} = 3 m/s and the suction volume flow was $\dot{V}$ = 104,000 m^3/h per duct. Figure 11 shows for each angle the magnitude of the velocity and the flow lines in the x-y-plane at a height of 0.5 m to illustrate the change in flow with progressive deviation from the flow with α = 0° (perpendicular to the ridge). The clear influence of the angle on the flow in the barn but also on the flow downstream of the barn can be seen. The difference between the flow with α = 0° and that with α = 15° is minimal in the stable. Only the position of the eddy area downstream of the stable shifts according to the changed flow. From an angle of α = 30°, a stationary vortex forms on the lower, wind-facing stable wall, which becomes larger as α rises, but already begins to disintegrate at α = 60°. At α = 90° (flow parallel to the ridge), two eddy areas form on the long sides of the barn due to the stall on the gable wall facing the wind.



(a) α = 0°

(b) α = 15°

(c) α = 30°

(d) α = 45°

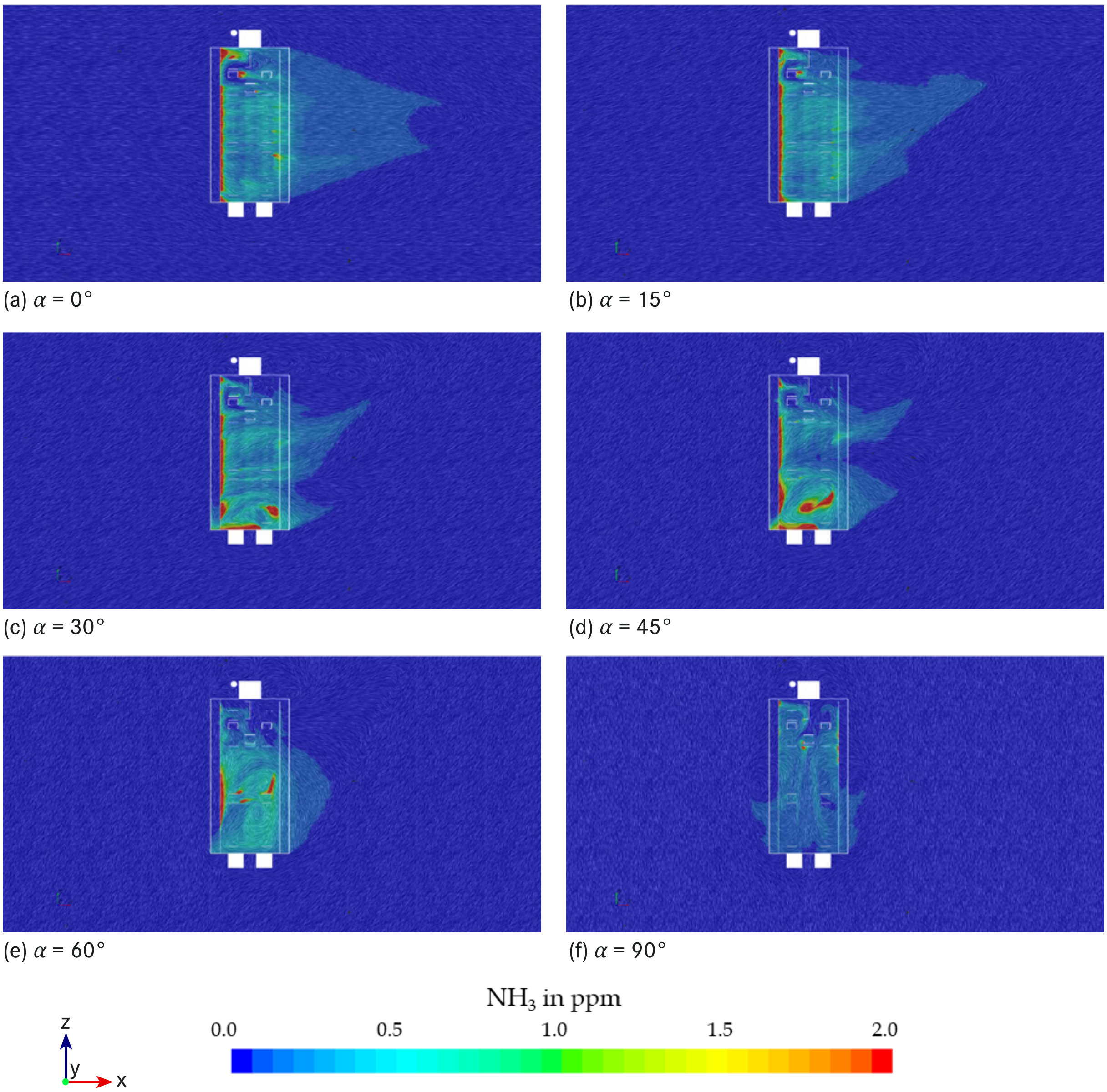
(e) α = 60°

(f) α = 90°

Figure 11: Comparison of the velocity magnitude on a section at z = 0.5 m with varying flow angle, a flow velocity of v_{10} = 3 m/s and a suction volume flow of $\dot{V}$ =104,000 m^3/h per suction duct

It can also be seen that the more the air comes from the direction of the flow angle of α = 90° and thus hits the closed gable wall, the slower the flow in the barn. As a result, there is also less air exchange in the stable. This shows the importance of positioning a new barn already in the planning phase. A wrong orientation towards the wind, e. g. due to the orientation for optimal use of a photovoltaic system, can have strong negative effects on the animals and emissions.

Looking at the corresponding ammonia distributions in Figure 12, there is a clear correlation between the vortex formation and a local increase of the pollutant gas concentration.



(a) $\alpha = 0°$

(b) $\alpha = 15°$

(c) $\alpha = 30°$

(d) $\alpha = 45°$

(e) $\alpha = 60°$

(f) $\alpha = 90°$

Figure 12: Comparison of the ammonia distribution on a section at z = 0.5 m with varying flow angle, a flow velocity of v_{10} = 3 m/s and a suction volume flow of $\dot{V}$ =104,000 m^3/h

There are only minimal differences between the ammonia concentrations at the flow angles $\alpha = 0°$ and $\alpha = 15°$, as the flow through the barn does not change significantly. From $\alpha = 30°$, several smaller areas with a higher concentration of ammonia form in the vortex on the wind facing stable wall described above. These increase further as the angle of inflow increases and reach their maximum at $\alpha = 45°$. Due to the vortex structure, an area of stronger negative pressure is created here, so that the underfloor suction system can build up less local counterpressure for the same performance.

As a comparison, a simulation was carried out in which no partial underfloor suction for an incidence angle of $\alpha = 45°$ (Figure 13). By that the area with a strongly increased ammonia concentration occupies almost the entire wind-facing half of the stable. This accumulation not only results in an extreme deterioration of the air quality inside the barn, but also in a strong increase in ammonia emissions into the environment.

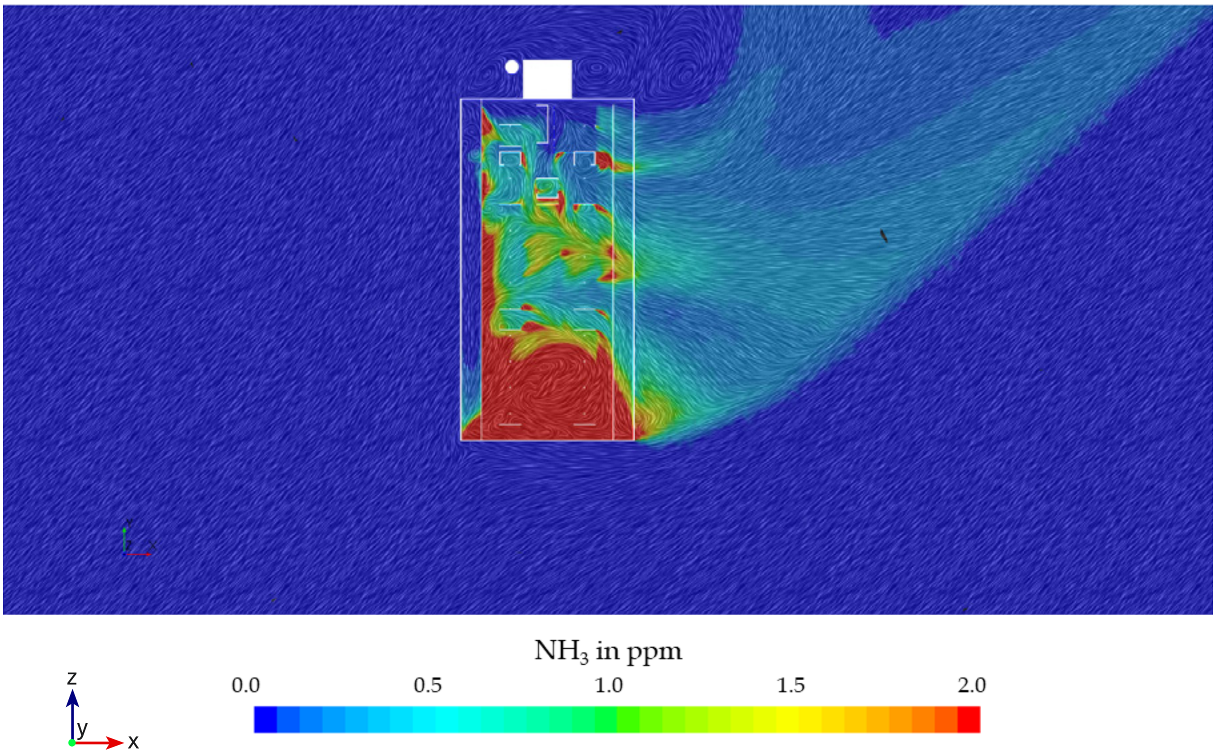


Figure 13: Ammonia distribution on a section at z = 0.5 m with a flow angle α = 45°, a flow velocity of v_{10} = 3 m/s and no partial underfloor suction

The evaluation of the ammonia mass flows leaving the barn is shown in Figure 14, considering the mass flow from the air washer. A strong reduction of the ammonia mass flows is shown, independent of the angle of inflow.

The reduction in the above-floor area increases with a flow angle that is more parallel to the ridge line, since the pressure gradient between the above- and underfloor areas is reduced while the suction power remains the same. The underfloor portion remains almost constant. This points to a very good effectiveness of the partial underfloor suction.

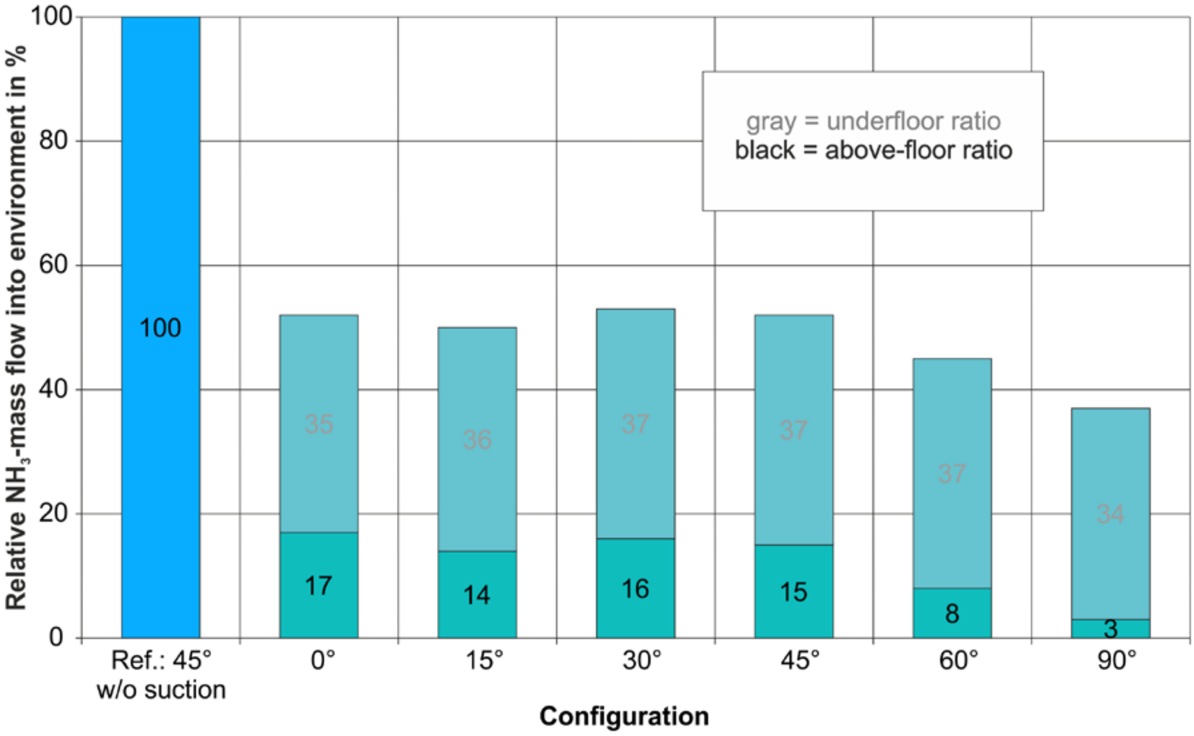
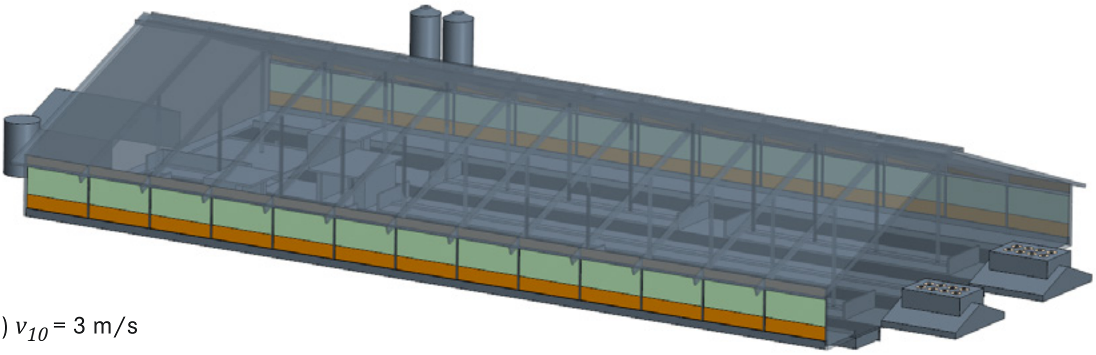


Figure 14: Bar chart comparing the ammonia mass flow into the environment for the different incident angles α at a flow velocity of v_{10} = 3 m/s, a suction volume flow of $\dot{V}$=104,000 m^3/h and a cleaning efficiency of the downstream air washer of 70 %; reference: incident angle α = 45° without partial underfloor suction

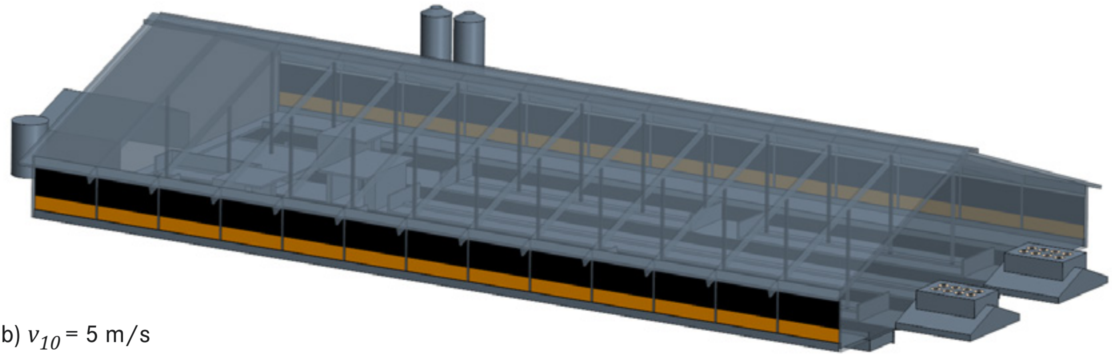
The influence of the wind break mechanism

In current practice, the control and use of blinds is dependent on climate parameters. At high wind speeds, the cross-section of the side wall is reduced to minimise draughts in the barn, especially in winter (Etlinger 2017, Caduff 2020). Modern side ventilation systems use a combination of blinds which block 100 % of the wind and wind protection nets with different permeabilities (Huesker Synthetic GmbH 2020).

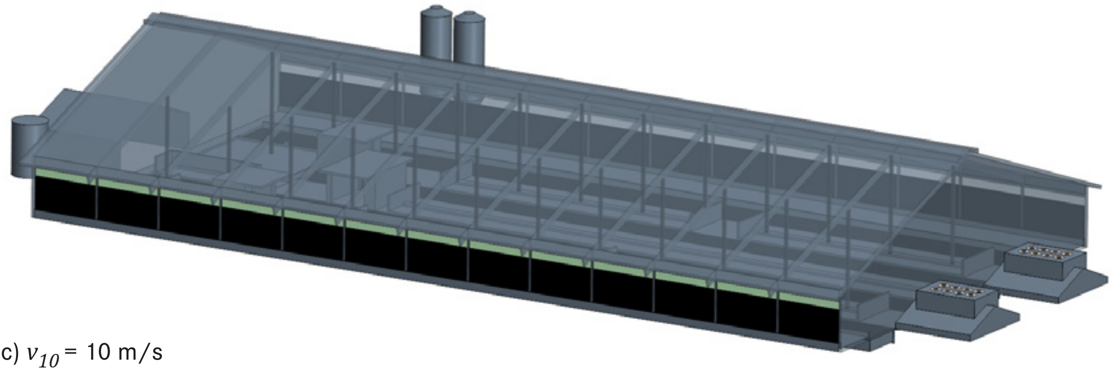
In the numerical model, this was illustrated in the following way: No blinds are used at low wind speeds (v_{10} = 3 m/s). For this reason, a wind protection mesh with a weak braking effect for the upper two thirds of the side wall was modelled in the simulations. In the lower third, the permeability was halved to reduce the flow velocity above the slatted floors. At medium wind speeds (v_{10} = 5 m/s), the upper, highly permeable area is completely closed with blinds so that the air can only enter the barn through the low-permeability net in the lower third of the side wall. At even higher wind speeds (v_{10} = 10 m/s), the blinds are raised from below until only about 1/5 of the side wall is open with a high-permeability net with a weak braking effect. A graphic representation of these three models is shown in Figure 15.



(a) v_{10} = 3 m/s



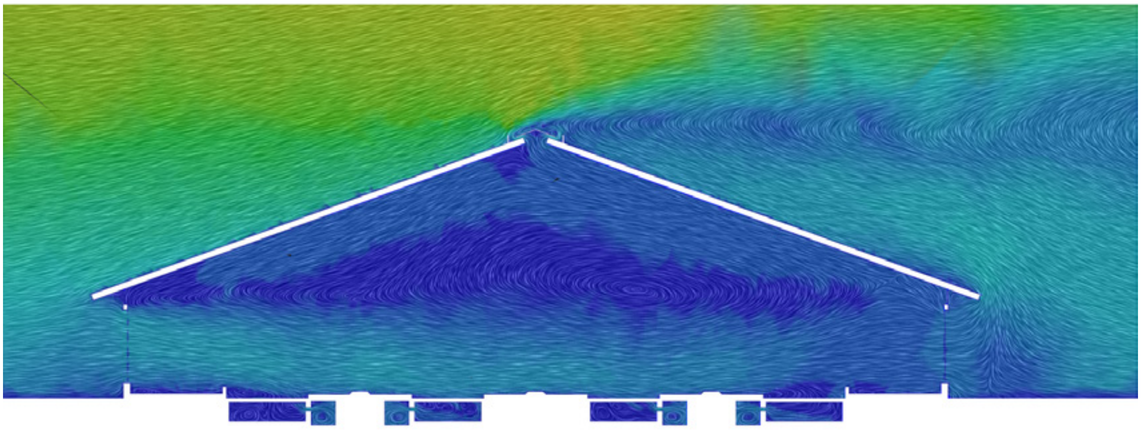
(b) v_{10} = 5 m/s



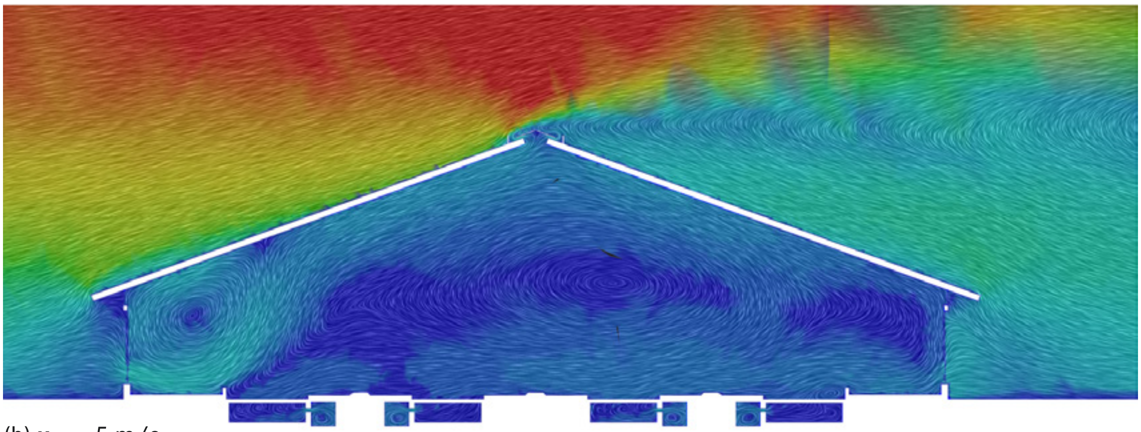
(c) v_{10} = 10 m/s

Figure 15: Configuration of the windbreak nets and blinds for different inflow speeds

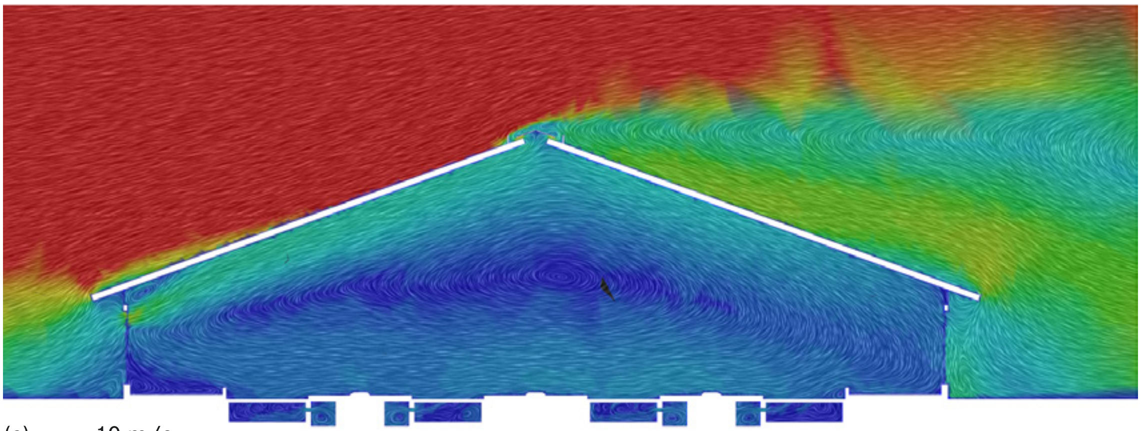
Figure 16 shows the resulting velocity distributions for the respective configurations of the wind protection nets and blinds from Figure 15. The simulations were carried out at a constant suction volume flow of $\dot{V}$ = 104,000 m^3/h and a constant angle of incidence of α = 0°.



(a) v_{10} = 3 m/s



(b) v_{10} = 5 m/s



(c) v_{10} = 10 m/s

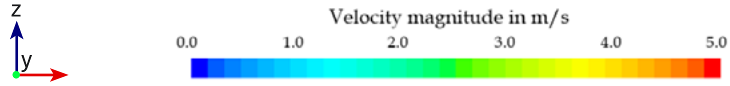
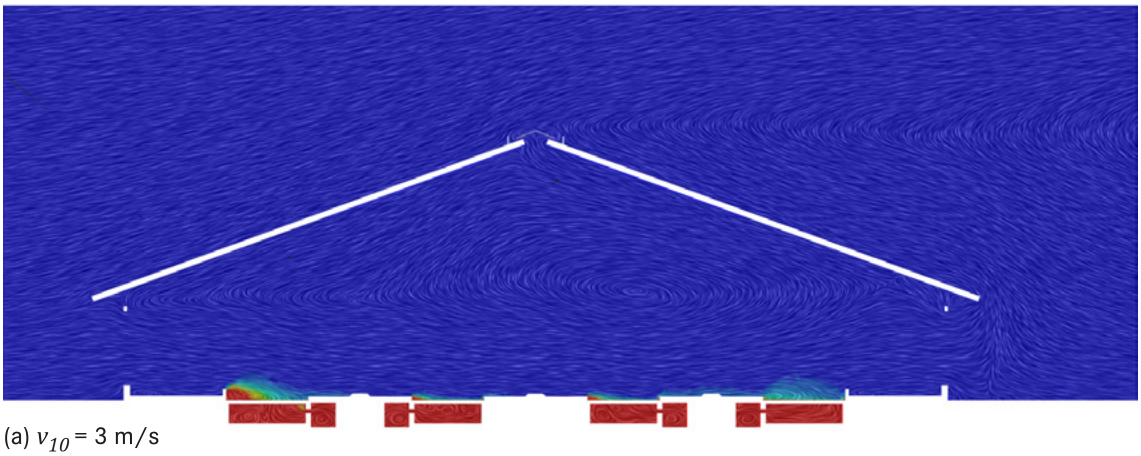
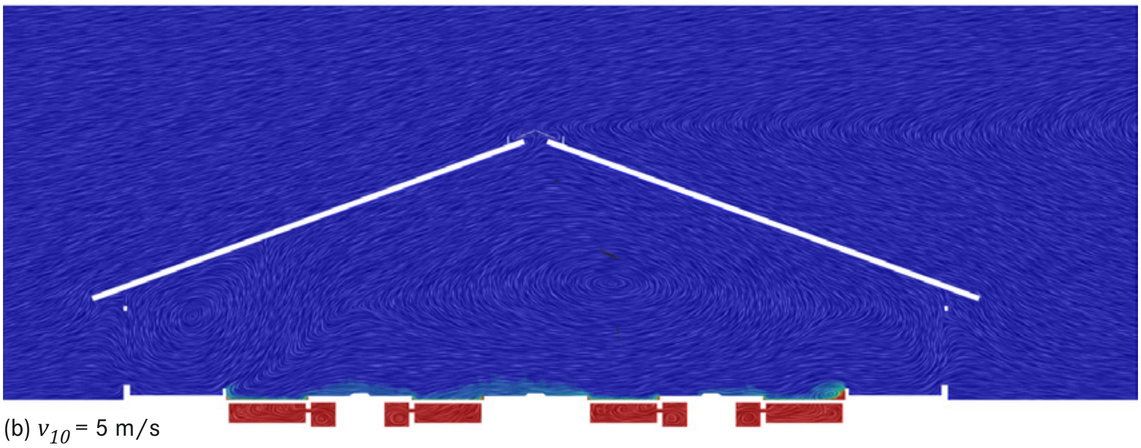


Figure 16: Representation of the schlieren pattern and velocity distribution in the central section of the barn for the three optimised combinations of windbreak nets and blinds at a varying inflow velocity, a suction volume flow of $\dot{V}$ =104,000 m^3/h and a constant incident angle of α = 0°

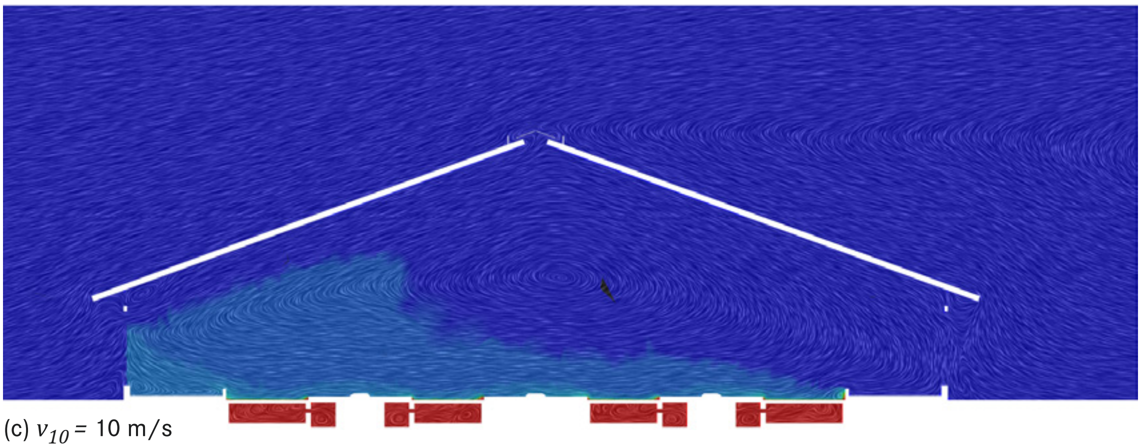
It can be seen that in all three configurations, the air speed inside the barn is approximately the same, despite the widely varying external climatic conditions. This results in a similar ammonia distribution for the same suction volume flow (Figure 17).



(a) v_{10} = 3 m/s



(b) v_{10} = 5 m/s



(c) v_{10} = 10 m/s

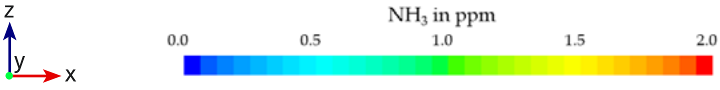


Figure 17: Representation of the schlieren pattern and ammonia distribution in the middle section of the barn for the three optimised combinations of windbreak nets and blinds at a varying inflow velocity, an extraction volume flow of $\dot{V}$ =104,000 m³⁄h and a constant inflow angle of α = 0°

The bar chart in Figure 18 shows the resulting ammonia mass flows into the environment.

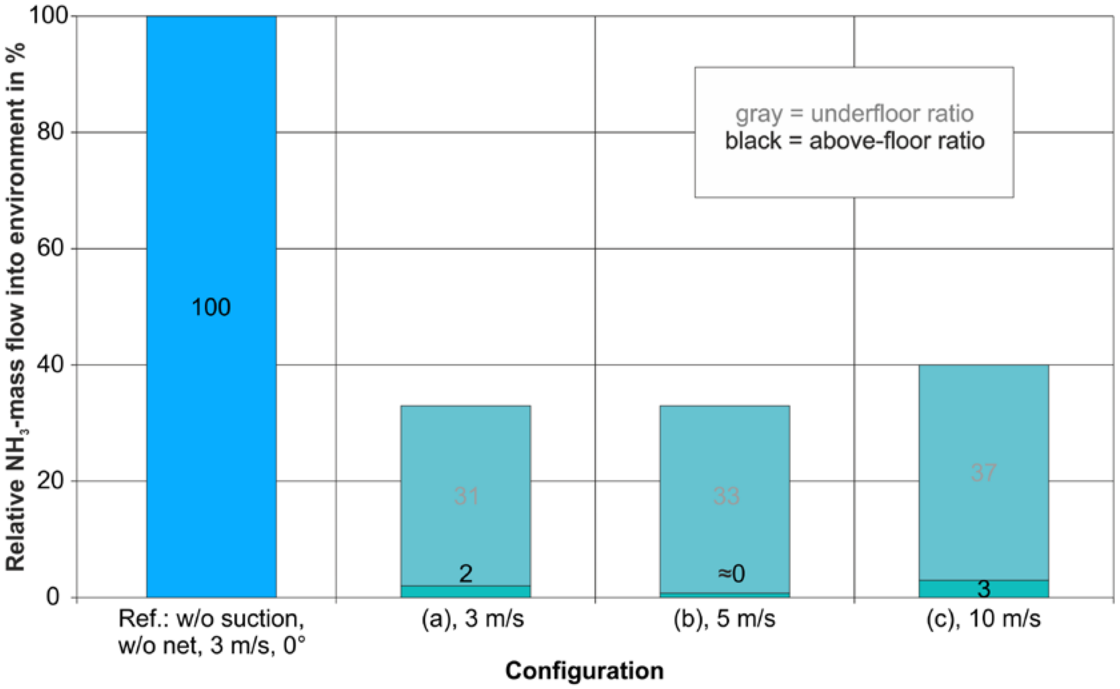


Figure 18: Bar chart comparing the ammonia mass flow into the environment for the three combinations of windbreak nets and blinds optimised for underfloor suction at a varying inflow velocity, a suction volume flow of $\dot{V}$ = 104,000 m³/h, a constant incident angle of α = 0° u and an air washer cleaning performance of 70 %; reference: no partial underfloor suction, no windbreak nets or blinds, v_{10} = 3 m/s, α = 0°

It has been shown that a combination of partial underfloor suction, exhaust air treatment and intelligent control of the wind breaking mechanisms can lead to a considerable reduction of the ammonia mass flow (the above-floor share is reduced to almost zero) from a naturally ventilated cattle stable at different wind speeds without significantly worsening the air quality inside the barn.

Discussion

The reduction possibilities found in this work for the ammonia emissions of a naturally ventilated cattle barn by means of partial underfloor suction clearly exceed those found in other simulation studies on this subject without taking the air washer into account. In their simulations, Bjerg and Andersen (2010) found reductions of 33 % to slightly more than 50 % and Sapounas et al (2009) of 8 % to 48 % depending on the weather conditions. The former considered a maximum suction volume flow of 160 m³/h/HPU (simplified: 1 HPU = ¾ cow) in their simulations. Transferred to the barn considered in this study with a capacity of 255 cows, this would correspond to a suction volume flow of 30,600 m³/h. Sapounas et al (2009) simulated two suction volume flows of 250 m³/h/cow and 500 m³/h/cow in their investigations. Transferred to the barn examined here, this results in volume flows of 63,750 m³/h and 127,500 m³/h. However, the suction volume flows simulated in this study are significantly higher, which explains the large difference. Aftertreatment of the exhaust air is also not considered in the two studies, so that the reductions achieved are overestimated. It can be assumed, however, that a further increase in the suction volume flow to the magnitude of the present study could also lead to a further increase in the reduction performance, which would bring the results of these studies and this study closer together again. Furthermore, Sapounas et al. (2009) found a fundamental improvement in the ventilation of the barn with operation of a partial underfloor suction system. This topic was not dealt with in the present study, but offers potential for further investigations. Especially when considering the air exchange rate of a naturally ventilated barn, underfloor suction can play a major role. Since there is no ventilation of the stable during windless periods, partial underfloor suction in combination with a reduction in emissions can make an important contribution to this. Thus, it could work as a supplement or replacement for the large ventilators used today in the above-floor area, which have no emission-reducing effect whatsoever. However, the exact potential must first be investigated in further work.

In both studies cited above, the animals were simulated in the barn as a porous volume. No animals were simulated in the present simulations. De Paepe (2014) found, both in the wind tunnel and with numerical models, that obstacles in the barn increase the ammonia concentration above the slatted floor by deflecting the air downwards into the slurry cellar and increasing turbulence, which also increases emissions. Against this background, it can be expected that, taking the animals into account, emissions from the barn will increase again somewhat even with partial underfloor suction. However, the basic relationship between the external wind speed, the suction volume flow and the ammonia mass flow is the same in all the above-mentioned studies, including the present study: the higher the external wind speed with which the air enters the barn, the lower the reductions achieved by partial underfloor suction at the same volume flow. Bjerg and Andersen (2010) also found in accordance with this study that the efficiency of partial underfloor suction can be increased by intelligent control of the side wall openings (wind protection nets and blinds in this simulation).

Also, the basic flow processes inside the barn without consideration of the partial underfloor suction but under the influence of varying side wall openings and angles of incidence could be found in other studies, which mainly deal with wind tunnel tests and thus allow a validation of the simulation results (Choinière und Munroe 1994, Qianying et al. 2018, Morsing et al. 2002).

Conclusion

With the help of flow simulation on a numerical model of a cattle barn, it was shown that partial underfloor suction can have a significant influence on the ammonia emissions of a naturally ventilated cattle stable. In combination with a downstream exhaust air treatment system, these can be significantly reduced. With a flow perpendicular to the ridge, opened blinds and a theoretical washer efficiency of 70 %, the reduction of the NH_3 mass flow into the environment can be up to 52 %. However, this value can be further improved by increasing the washer efficiency. A theoretical washer efficiency of 85 % could, for example, reduce emissions by up to 72 %. High emission reduction potentials and a reduction of the harmful gas load in the breathing zone of the animals were also found for changing conditions, be it different wind directions and speeds or different positions of combinations of wind protection nets and blinds. In this respect, however, it must be noted that the use of wind-braking mechanisms must preserve the character of an open stable. The optimisations carried out here were primarily carried out against the background of minimising ammonia emissions.

It should also be remembered that the results of the numerical simulation only show the theoretical potential of such a suction system. The results must therefore be validated by practical tests. With the help of the numerical model, however, it was possible to investigate a large number of different boundary conditions in a short time on a created geometric model and to save long and expensive preliminary test series.

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