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CFD Analyses of Methods to Improve Air Quality and Efficiency of Air Cleaning in Pig Production

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1. Introduction

Release of contaminant gaseous as ammonia, carbon dioxide, sulphur hydrogen, methane and laughing gas is an inevitable consequence of livestock production, and degrades air quality in the production facilities and has a negative impact on both the short and long distance environment. Generally the knowledge on how the content of these gases influence animal performance, animal health and the health's of the farmers is deficient, but it is commonly accepted that the concentrations of especially ammonia, hydrogen sulphide and carbon dioxide should be kept below certain thresholds (CIGR 1984). Ammonia is of special interest because the concentrations inside the housing system in some cases reach critical levels and because it, in large parts of the world, is assumed to be the livestock production gas that has the largest negative impact on the surrounding environment.

Ammonia in livestock housing originates from animal excretion of faeces and urine. Especially urine has a large content of urea which readily is transformed into ammonia upon contact with the enzyme urease:

$$(NH_2)_2CO + H_2O \overset{\text{urease}}{\Rightarrow} 2NH_3 + CO_2 \qquad (1)$$

The required enzyme urease is present in faeces and therefore the generation of ammonium takes place when urine brings together with faeces. Successively a part of the generated ammonia will be transformed into ammonium in the solution:

$$NH_3 + H_2O \Leftrightarrow NH_4^+ + OH^- \qquad (2)$$

The lower pH-value in the solution the larger part of the ammonia will be transformed to ammonium and that part is bound in the solution. The remaining ammonia will evaporate to the air above with a velocity that depends on numerous properties in the solution and in the air above.

Due to the negative influence of ammonia on air quality in the housing system and on the surrounding environment it is of large interests to design housing systems that limit the evaporation of ammonia or enable efficient removal of the evaporated ammonia to maintain low concentration in the room and low emissions to the surrounding.

The purpose of the work presented in this chapter is to demonstrate the possibilities to design ventilation systems that reduce the ammonia concentration in pig housing and simultaneously reduce the required ventilation capacity. In addition it is demonstrated how improved ventilation system design including strategically located exhausts can be utilised to capture a large part of released ammonia in a relative small share of the entire air change, and how cleaning of that minor part of the total air change may contribute to a significant reduction of the total ammonia emission.

The analyses discussed in this work are based on Computational Fluid Dynamics (CFD) which is a branch of modelling tools that use numerical methods and algorithms to analyse problems that involve fluid flow. A general overview of the CFD methods used in relation to ventilated rooms or more specifically related to the agricultural industry lies beyond the scope of this chapter but can beneficially be found in Nielsen et al. (2007) and Norton et al. (2007). In this chapter it is prioritised to give an in depth description of the necessary or preferred methods to solve the challenges related to the special issues treated in this work.

The use of CFD methods involves a geometrical description and delimitation of the fluid volume – often called the domain - that has to be included in order to analyse the required flow phenomena. In pig production it is conmen to use mechanical ventilations system were the outdoor wind conditions have a relatively small influence on the indoor airflow, and therefore it is reasonable to delimitate the analysed spaces to indoor air volume.

In Denmark and a few other European countries it is common to equip pig housings with mechanical under pressure ventilations system with air intake through porous material in the ceiling. Typically these inlets consist of a layer of mineral wool between timber beams with a cement bonded wood wool plate beneath, see Fig. 1.

In such a system, the air is entering the room with a velocity as low as 0.005 to 0.05 m/s, and, consequently, draft will seldom be a problem if the system is designed in accordance

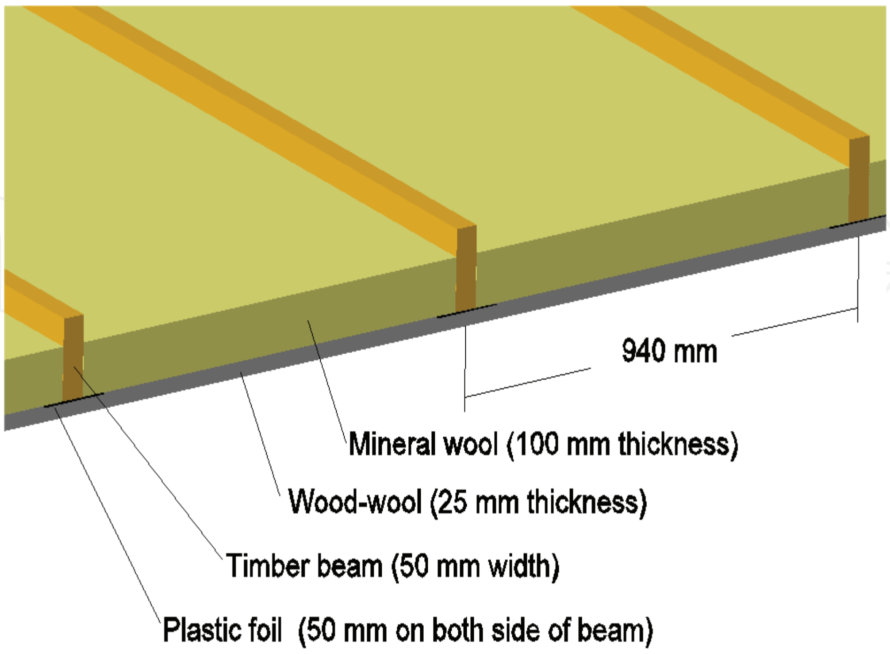


Fig. 1. Typical construction for diffuse air inlet through ceiling.

with the existence empirical knowledge. However, the empirical knowledge is not sufficient to optimize room layout in order to improve air distribution in the animal occupied zone or in order to reduce the release of ammonia and odorants from manure. CFD (Computational Fluid Dynamics) is an obvious tool for such tasks, but until now, the reported experience of using CFD in relation to air intake through porous material in the ceiling is limited.

CFD modeling requires detailed geometrical description of the flow domain and division of the domain into a comprehensive grid. The procedure is very time consuming if it is used in complex setups with pen partitions, equipment, slatted floor and animals. Wu & Gebremedhin (2001) performed CFD simulation of airflow around up to ten geometrically precise models of standing 600 kg Holstein cows. However, to simulate airflow in an animal room under operation, this method has the disadvantages that it is very time consuming to build such models, and that the animals are moving around and place themselves in different positions. A potential way to overcome this is to assume that the occupied zone consists of a porous media with a certain flow resistance. A similar method has been use to model airflow through slatted floor (Sun et al., 2004) and through partly open pen partitions (Wagenberg et al., 2004).

In this work the porous media assumption are utilized to avoid a detail geometrical modeling and complicated subdivision of the space around the animals the animals, and to model the condition in the porous inlet.

2. Analyses of a partly pit ventilation system as method to reduces ammonia emission from a pig production unit

To reduce ammonia and odour emission from livestock housing, the use of air cleaning systems is increasing. Available acid based exhaust air cleaning systems are capable of reducing ammonia emission through ventilation with approximately 95 percent (Melse & Ogink 2005), but due to the large amount of air that must be treated the investment and operating costs are high. In many cases a reduction of ammonia emission of 30 - 70 percent is sufficient to fulfil the requirement from legislation. Under northern Europe climate conditions the ventilation level is relatively low in a large part of the year resulting in high ammonia concentrations in exhaust air in those periods. This makes it possible to obtain a relatively large reduction of total ammonia emission with a cleaning system designed for a relatively small share of the total ventilation capacity.

The greater part of ammonia emission from pig production housing systems with slatted floor is released from the slurry surface. In this type of production units pit ventilation has been known as a method to improve indoor air quality, but it is seldom used due to increased energy cost and increased emission of ammonia and odour.

The scope of this work is to investigate the efficiency of a partly pit ventilation system with cleaning of the air exhausted from the pit. The investigation is based on theoretical calculations including CFD methods (Computational Fluid Dynamics) to predict airflow, and ammonia release and distribution in a growing pig unit.

2.1 Methods

The analyses were based on conditions in a typical Danish pig unit for growing pigs from 30 to 100 kg. The assumed unit included two rows of 2.4 m wide and 4.8 m long pens designed for 16 pigs each, see Fig. 2 and 3.

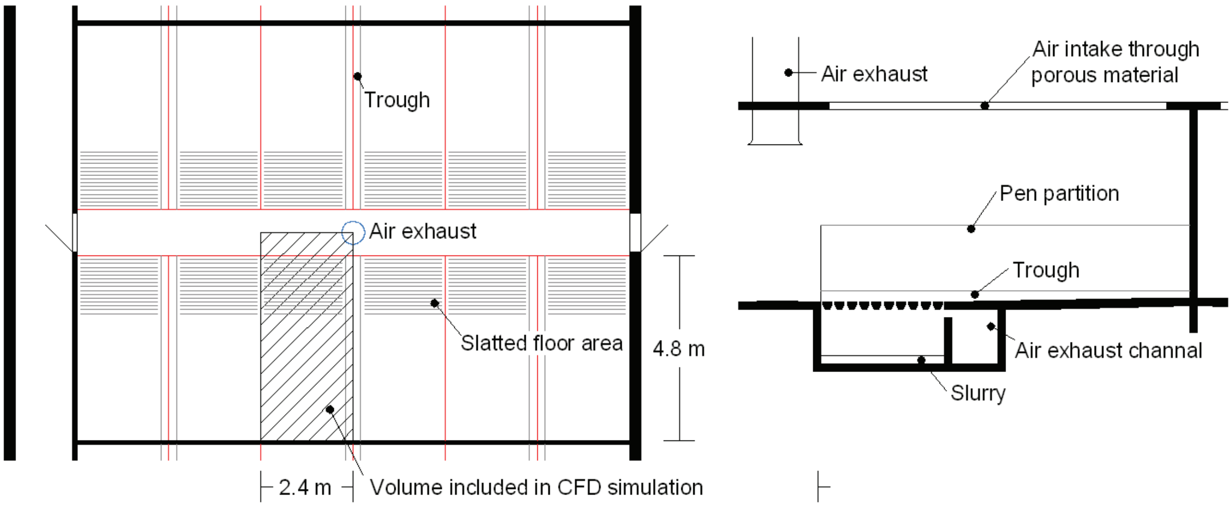


Fig. 2. Plan and cross section of assumed pig production unit.

One third of the pen area consists of slatted floor with a slurry pit beneath and the unit is equipped with negative pressure ventilation system with air intake through porous material in the ceiling. Along the slurry pit an assumed air exhaust channel makes it possible to evacuate a share of total exhaust air directly from pit, see Fig. 5. The maximum ventilation capacity was assumed to be 100 $m^3h^{-1}pig^{-1}$, and StaldVent 5.0© software (Strom & Morsing 2004) were used to calculated the distribution of expected ventilation levels during a year, see Fig. 4.

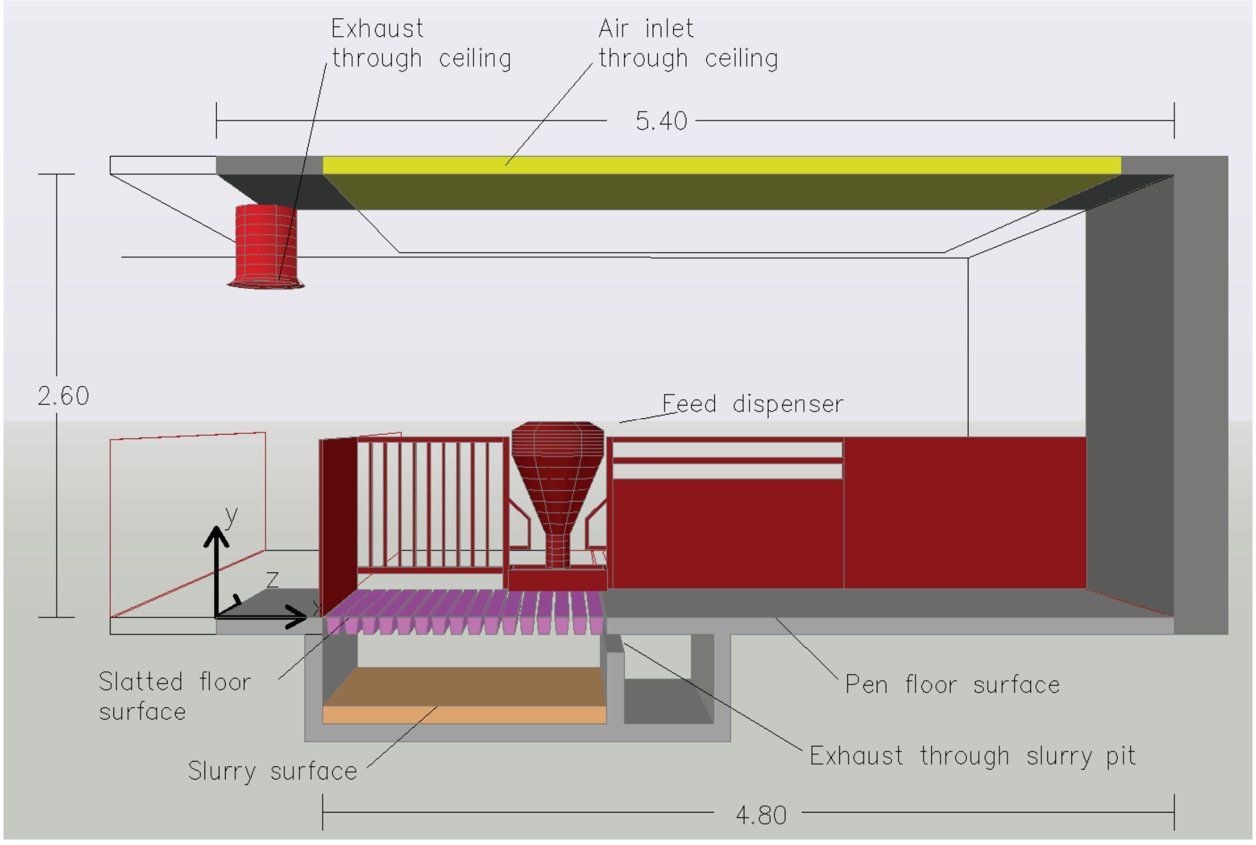


Fig. 3. Perspective and used system of coordinates in the assumed pig production unit.

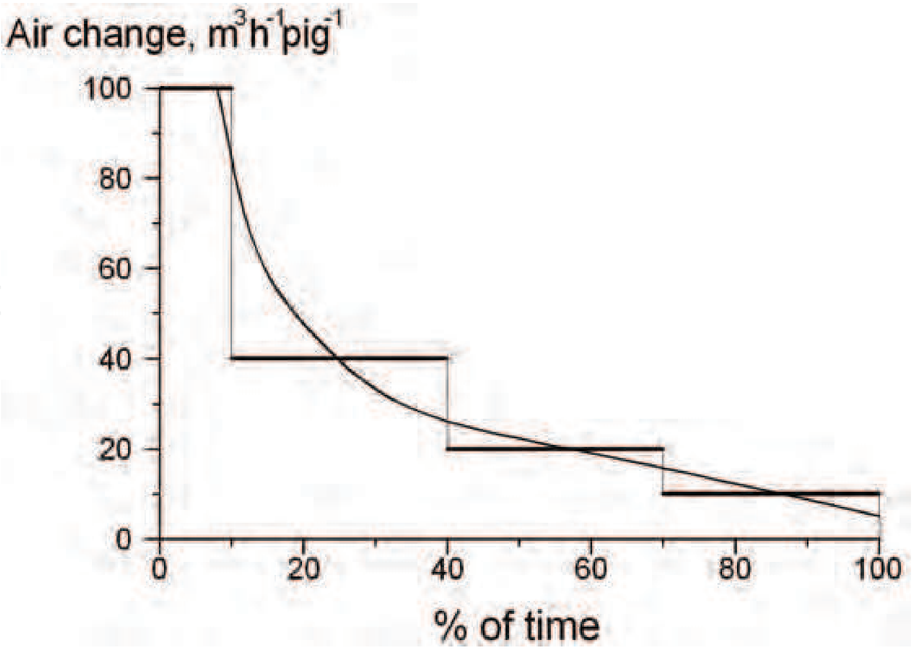


Fig. 4. Expected distribution of ventilation levels in a growing pig unit under Danish conditions (smooth curve), and four representative levels of ventilation (step curve) used in modelling of ammonia release and emission.

2.1.1 CFD modelling

The commercial CFD (Computational fluid Dynamic) code Fluent 6 (Anonymous 2006) were used to calculated air flow and ammonia distribution in one pen section of the room, see Fig. 2. The chosen section was divided into 37722 hexahedral cells and the grid on surfaces is shown in Fig. 5.

2.1.1.1 Porous media assumptions

Porous media boundary conditions were utilised to model airflow in three special regions of the used geometrical model:

- Porous material for air intake in the ceiling,
- Slatted floor partly covered with pigs, and
- Pigs in animal occupied zone pigs up to 0.6 m above floor level.

The flow resistance in each of the three directions (x, y and z) in the porous media regions were calculated using equation 1 (Bjerg et al., 2008; anonymous 2006).

$$\Delta p = 0.5 \cdot R_1 \cdot \rho \cdot \ v^2 + \mu \cdot R_2 \ v \tag{3}$$

where

Δp is pressure drop over the porous media, Pa,

R_1 internal risistance factor,

R_2 viscus risistance coefficient

ρ air density, kg/m^3 (1.2 kg m^{-3} at 20 °C)

v air velocity, through porous media, m/s

μ air viscosity, kg m^{-1}s^{-1} (1.8 · 10^{-5} kg m^{-1}s^{-1} at 20 °C)

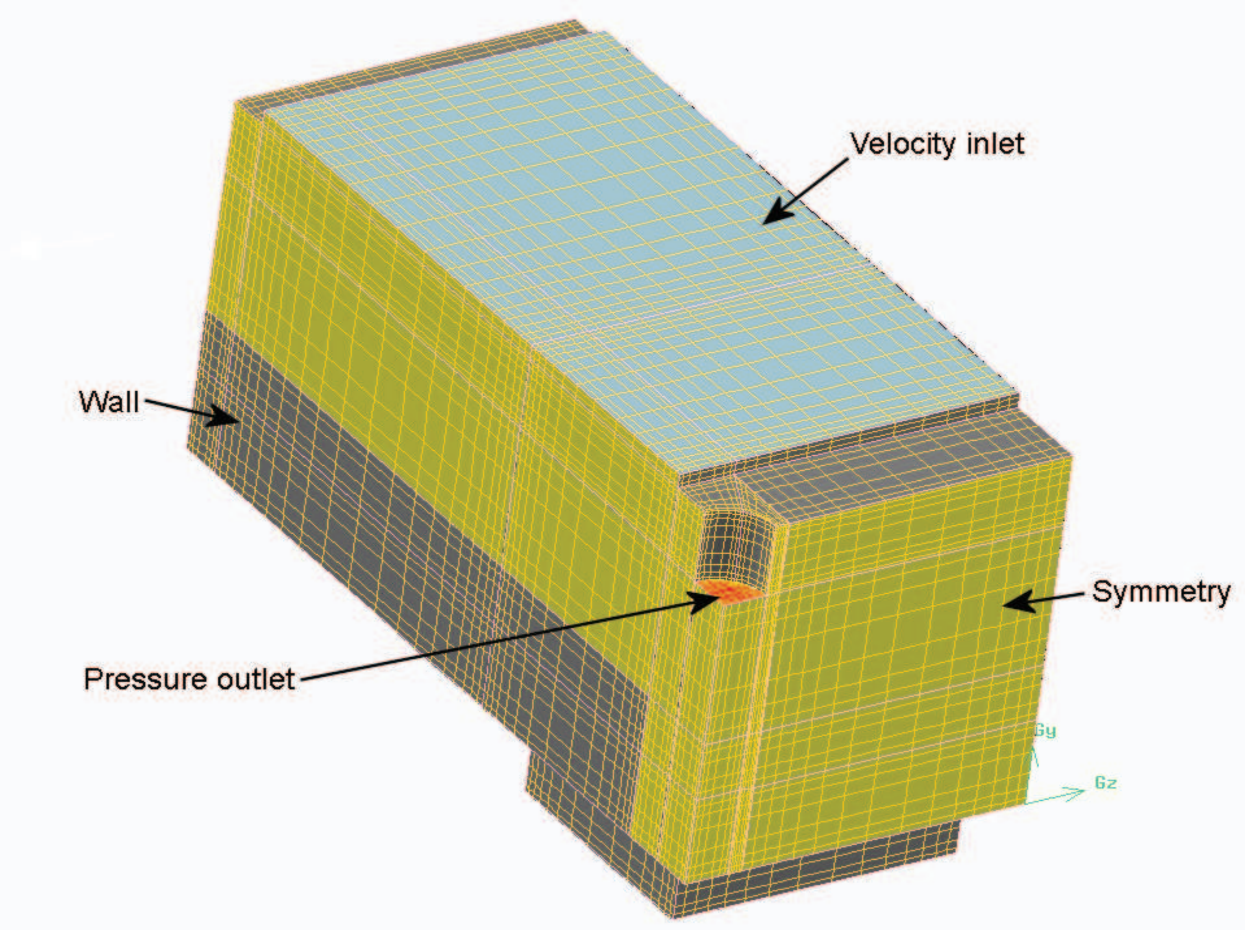


Fig. 5. Grid and boundary conditions on surfaces of the volume included in CFD modelling.

2.1.1.2 Flow resistance properties for air inlet

Internal resistance factor (R_1) and viscous resistance coefficient (R_2) through air inlet was determined from existing measurement of pressure drop through 100 mm mineral wool and 25 mm wood-wool (Anonymous, 1999). It appears from Fig. 1 that the plastic foil beneath the timber beams reduces the effective inlet area. But to avoid modelling each separate part of the inlet area in the subsequent CFD simulation the determined flow resistance parameters were adjusted to assure a realistic pressure drop if the inlet was modelled as a coherent area. Those adjusted flow resistance parameters appears from Table 1.

2.1.1.3 Flow resistance properties for slatted floor

Vertical flow resistance properties through slatted with and without assumed partly covering with pigs was determined in CFD simulation of airflow through detailed geometrical models of a segment of the floor, see Fig. 5.

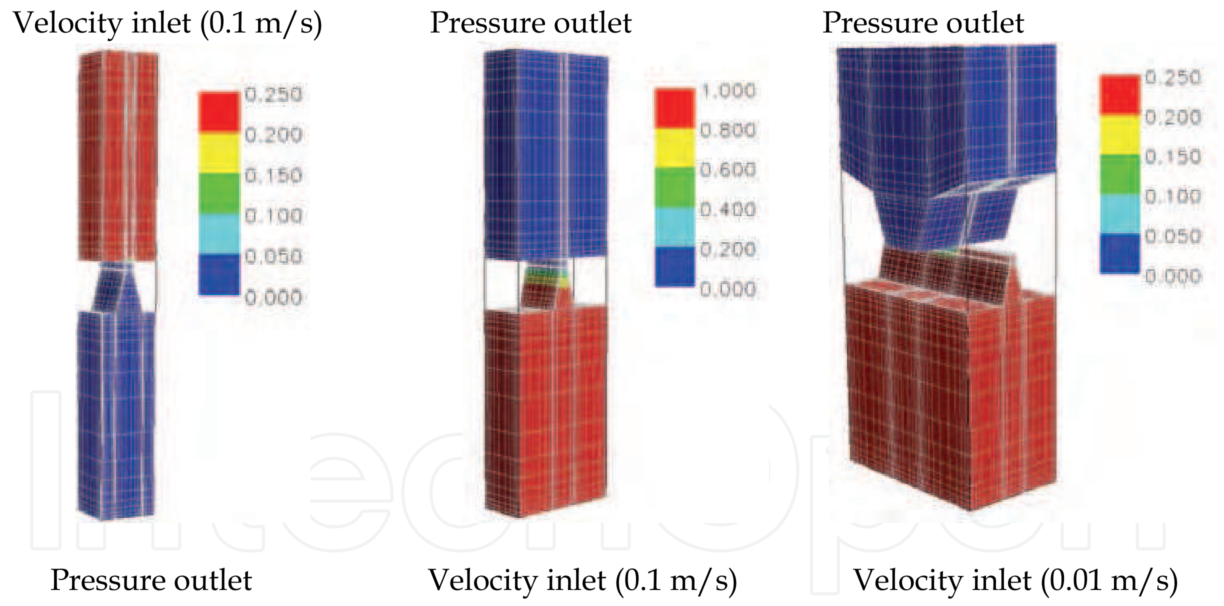
The resulting relation between inlet velocity and the pressure drop over the floors were used for determination of the values of R_1 and R_2 using equation 3. The found values appear from Table 1.

	x-direction[1]		y-direction		z-direction	
	R_1	R_2	R_1	R_2	R_1	R_2
Porous ceiling[2]	4000	$5.4 \cdot 10^6$	4000	$5.4 \cdot 10^6$	4000	$5.4 \cdot 10^6$
Slatted floor[3]	-	-	40	11000	40	11000
Slatted floor with pigs[3]	-	-	80	15000	80	15000
Drained floor[3]	-	-	160	22000	160	22000
Drained floor with pigs[3]	-	-	4400	60000	4400	60000
AOZ, activity area[4]	0.4	400	0.4	400	0.4	400
AOZ, resting area[4]	1.3	1500	1.3	1500	1.3	1500

[1] System of coordinate orientation appears from Fig. 2.
[2] Resistance in horizontal directions assumed to be equal to resistance in vertical direction.
[3] Slats blocks for flow in x-direction and resistance in z-direction assumed to be equal to resistance in y-direction.
[4] Resistance in vertical direction assumed to be equal to resistance in horizontal directions.

Table 1. Overview over used flow resistance properties.

Slatted floor | **Drained floor[1]** | **Drained floor[1] with pigs**



[1] Danish animal welfare legislation do not allow slatted floor with opening ratio of more than 10 % in the animal resting area, and the phrase "drained floor" is used for floor with opening ratio below 10 %.

Fig. 6. Grid and pressure distribution (Pa) on surfaces of simulation models for determination of flow resistance through slatted floor drained floor and drained floor with pigs.

2.1.1.4 Flow resistance properties for animal occupied zone.

The presence of animals will restrict the air flow in the Animal Occupied Zone (AOZ). The defined height of the AOZ is related to the expected height of a standing pig. Height of standing pigs can be calculated as 0.16(animal weight, kg)$^{0.33}$, m (Baxter 1984). For growing finishing pigs from 30 to 100 kg this results in heights from 0.49 to 0.73 m. In this work the determination of flow resistances is based on an assumed animal weight of 50 kg and a height of animal occupied zone of 0.6 m. The AOZ is assumed to be divided into resting including the third of the pen in largest distance from the slatted floor and an activity area including the remaining two thirds of the pen area. Based on 16 pigs in the pen following distribution of animal on staying and laying positions in resting area and activity area was assumed:

8 pigs laying in resting area corresponding to 2.1 pigs/m^2
1 pig standing in resting area corresponding to 0.26 pigs/m^2
5 pigs laying in activity area corresponding to 0.65 pigs/m^2
2 pigs standing in activity area corresponding to 0.26 pigs/m^2

The flow resistance parameter for flow through the AOZ was determined in CFD simulation on geometrically fairly detailed models as shown in Fig. 7. The model illustrates assumed conditions in the resting area with the density of 2.1 laying pigs and 0.26 standing pigs per m^2. The magnitude of the pigs corresponds to an average body weight of 50 kg. The pigs are constructed as the intersection of two dimensional silhouettes from three different directions. Unstructured grid was used in simulation of airflow around the pigs. Air velocity boundary conditions were assumed at the left end face and pressure outlet conditions were assumed in the right end face of model in Fig. 7.

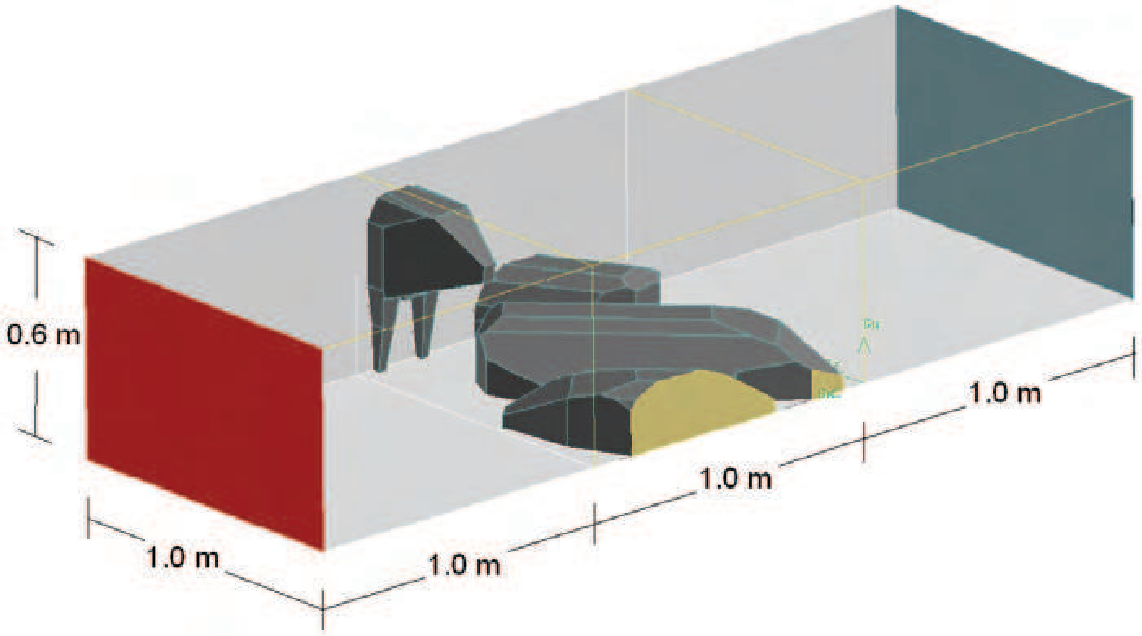


Fig. 7. Geometrical model used in simulation for determination of flow resistance through animal occupied zone with animal density of 2.1 laying and 0.26 standing 50 kg pig pr m^2. Velocity inlet and pressure outlet boundary condition were assumed at the left and right face, respectively.

The resulting relation between inlet velocity and the pressure drop around the animals were used for determination of the values of R_1 and R_2 using Equation 3. The found values appear from Table 1.

2.1.1.4 Ventilation configurations

Simulations were carried out with air intake of 10, 20, 40 and 100 $m^3h^{-1}Pig^{-1}$ corresponding to inlet velocities of 0.00411, 0.00822, 0.01644 and 0.0411 m/s, respectively. For each ventilation level simulations were carried out with 0, 5, 10 and 20 $m^3h^{-1}Pig^{-1}$ air exhaust from the pit.

For room exhaust pressure outlet conditions were assumed on the entry to the ventilation shaft through the ceiling, see Fig. 5. For pit exhaust velocity outlet conditions were assumed on the entry surface on the connections between the slurry pit and the under floor exhaust channel, see Fig. 2 and 3. Fig. 5 illustrates that symmetry boundary conditions were assumed at the surface where the modelled section was cut out of the entire room.

2.1.1.5 Ammonia release

As ammonia source were assumed a constant concentration on slurry surface, and a level of 340 ppm were chosen in order to obtain realistic ammonia concentrations in the room. Griskey (2002) state the diffusivity for ammonia in air at 295 ºK and 101325 Pa to 1.8 x $10^{-5}m^2s^{-1}$, and this value was utilized in the CFD calculations.

2.1.1.6 Heat release

Releasing of convective heat due to animal heat production in animal occupied zone was included in simulations as a heat source of 200 Wm^{-3} in the volume from 0-0.6 m above the solid floor and of 100 Wm^{-3} above the slatted floor, corresponding to a total heat supply of 54 W per pig. Radiation heat release from pigs and transmission heat loss from the building was not taken into account.

2.1.1.7 Modeling of turbulence

Compared to the widely used Standard k-ε turbulence model (Launder & Spalding, 1974) the realizable k-ε turbulence model (Shih et al. 1995) has in earlier works (Bjerg et al., 2008) shown to be more suitable to handle turbulence in a room with air intake through porous material in the ceiling and, consequently, the realizable k-ε turbulence model was used in this work.

2.1.2 Calculation of ammonia emission

In estimation of yearly average ammonia concentrations and emissions it was assumed that the ventilation system runs with 100 percent of its capacity in 10 percent of time and with 40, 20 and 10 percent of capacity in 30 percent of time each, see Fig 4.

Calculation of air cleaning efficiency was based on the assumption that the ammonia will be removed to a level of 1 ppm in the treated air, which corresponds to the performance of commercial systems. A setup with treatment of all air from a unit without pit ventilation is used as reference case for estimating the efficiency of treating of pit exhaust or treating of a minor part of room (ceiling) exhaust.

2.2 Results and discussion

Fig. 8 shows simulated airflow and ammonia concentration distribution for the case with total ventilation of 40 $m^3h^{-1}Pig^{-1}$. The left picture show the case with a pit ventilation of 10 $m^3h^{-1}Pig^{-1}$, and the right picture show the case without pit ventilation.

It is clear that pit ventilation creates a significant reduction of ammonia concentration in the entire room. In the animal occupied zone (0 to 0.6 m above floor) the average concentration was reduced from 13.5 to 5.5 ppm corresponding to a reduction of nearly 60 percent.

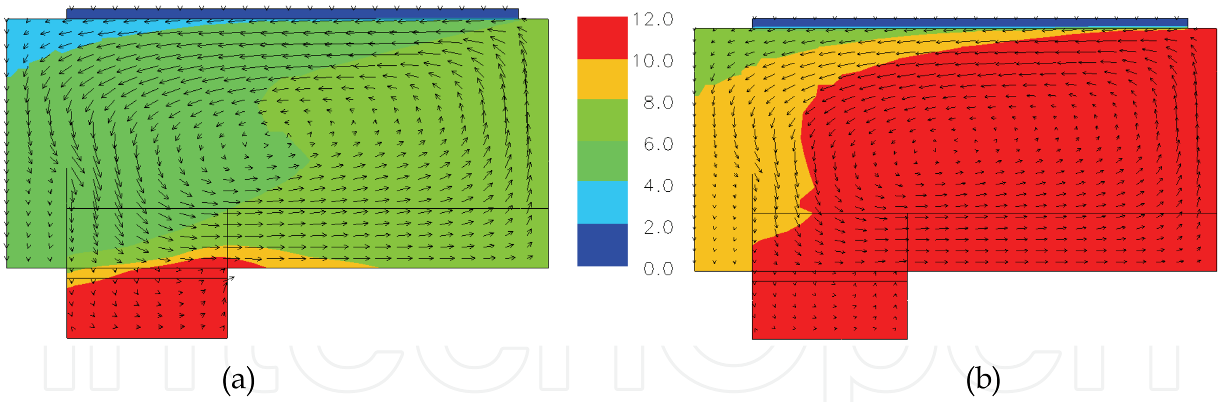


Fig. 8. Simulated airflow and ammonia distributions (ppm) at total ventilation of 40 $m^3h^{-1}Pig^{-1}$, (a) with pit ventilation of 10 $m^3h^{-1}Pig^{-1}$, and (b) without pit ventilation.

Fig. 9 shows ammonia concentration in the exhaust air from the room at different levels of air change from the pit and totally.

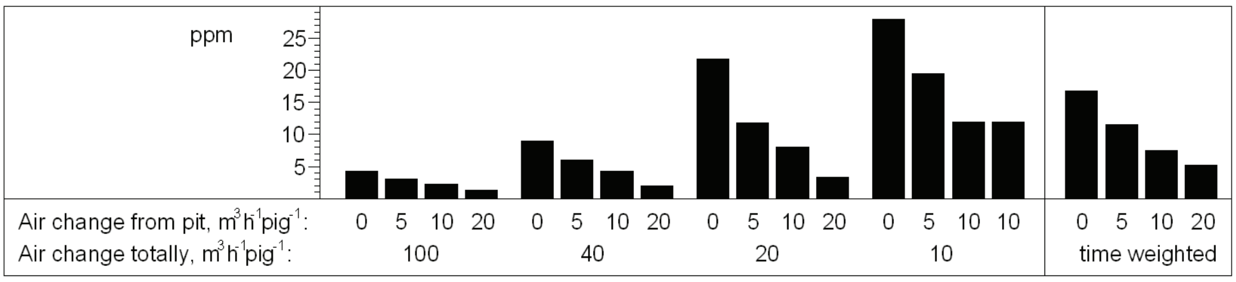


Fig. 9. Ammonia concentration in room exhaust at different pit ventilation and entire unit ventilation. Time weighted values, shown to the right in the graph, assumes total air change of 100 $m^3h^{-1}Pig^{-1}$ in 10 percent of time, and 40, 20 and 10 $m^3h^{-1}Pig^{-1}$ in 30 percent of time each.

As average during a year it is estimated that pit ventilation of 5, 10 and 20 $m^3h^{-1}Pig^{-1}$ will reduce ammonia concentration in the exhaust with 31, 55 and 68 percent, respectively, and inside the room the ammonia concentration will be reduced correspondently.
Fig. 10 shows total ammonia release and the emission from the room at different levels of air change from the pit and totally.

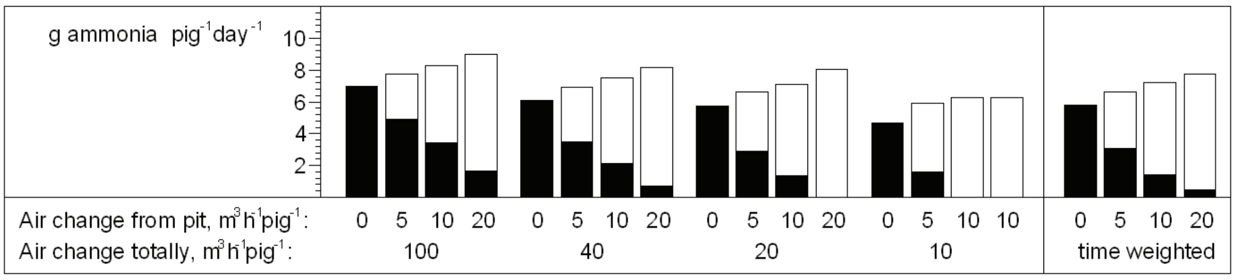


Fig. 10. Total ammonia release (aggregated bars) and emission from the room (black part of bars) at different levels of pit ventilation and entire unit ventilation. White part of bars show emission through pit exhaust assuming no air cleaning.

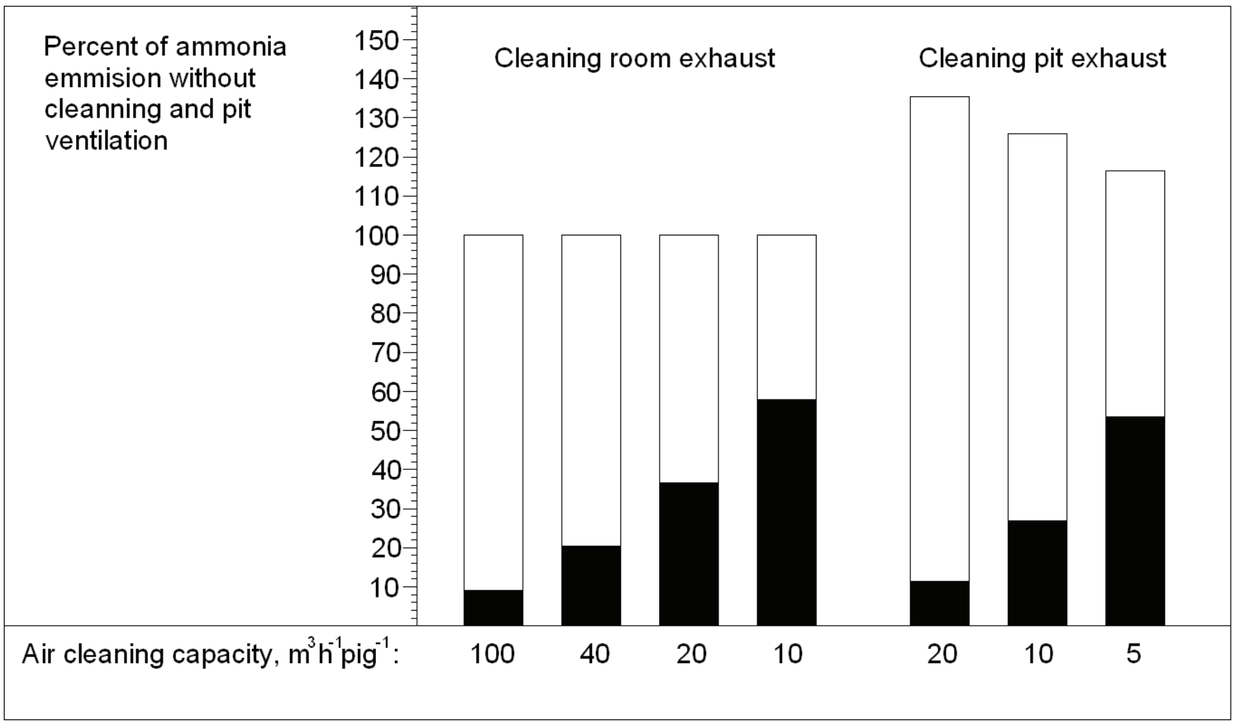


Fig. 11. Ammonia release (aggregated bars) and ammonia emission to the surroundings (black bars) at different air cleaning strategies. 100 percent corresponds to the ammonia emission from a unit with no air cleaning or pit ventilation. White part of bars shows removed ammonia.

It can be seen that an increased level of pit ventilation increased the ammonia release if cleaning system is not available. Using pit ventilations of 5, 10 and 20 $m^3h^{-1}Pig^{-1}$ during a year will result in increased ammonia emission of 16, 26 and 35 percent, respectively.

The simulation without pit ventilation showed that a decreased air change from 100 to 40 $m^3h^{-1}Pig^{-1}$ resulted in 13 percent decreased in ammonia emission. This can be compared with the result of a Danish investigation of the influence of air change on ammonia emission where the average air change were reduced from 80 to 40 $m^3h^{-1}Pig^{-1}$ (Lyngbye et al., 2006). In that investigation the room temperature was maintained by cooling the air inlet resulting in a reduction of the ammonia emission of 10 percent. The agreement with this investigation supports the assumption that a constant ammonia concentration on pit bottom surface is a reasonable simplification in CFD-modelling for analyzing the influence of ventilation strategy on ammonia emission.

Fig. 11 shows calculated performance of different cleaning strategies. For a unit with no pit ventilation it appears that cleaning of all exhaust air (100 $m^3h^{-1}Pig^{-1}$) reduce ammonia emission with about 90 percent. If the cleaning system is designed to handle 10 percent of the ventilation capacity the reduction of ammonia emission is 41 percent, and measured in relation to the capacity of cleanings system this strategy is 4.5 times as efficient as cleaning all the air. Cleaning of 10 percent of the air exhausted directly from the pit removes 73 percent of the ammonia emission and related to the cleaning capacity this is 8 times as efficient as cleaning all the air from the room. But due to increased ammonia release in the pit ventilated system the consumption of acid to reduce the ammonia emission with a certain amount will increase with about 35 percent.

3. Airflow pattern and ventilation efficiency

Ventilation systems in livestock buildings are designed to remove heat, moisture and containment gases in order to maintain temperatures and concentrations that are suitable for the animals. The airflow in pig units with diffuse air inlet through the ceiling is characterised by low air velocities primarily generated by the buoyancy force due to the convective heath release from the animals, and CFD-analyses have shown relative large spatial difference in temperature and concentrations in these systems, and consequently, there exists a potential to improve the ventilation effectiveness if the exhausts can be moved to locations with higher temperatures or concentrations.

Pigs are usually resting more than 80 percent of the time and the therefore the heat release will be most concentrated and generate a higher temperature and an upward air stream above the resting area. This has inspired to conduct an analysis of the influence of moving the exhaust to a location immediately above the resting area as it appears from Fig. 12.

The result presented in Fig. 13 shows that if the air change is maintained at 40 $m^3pig^{-1}h^{-1}$ then the general air temperature level will drop about three degrees. Ventilation systems in modern pig production facilities are usually designed to control the air change in a way that maintains a predefined temperature measured by a temperature sensor above the animals.

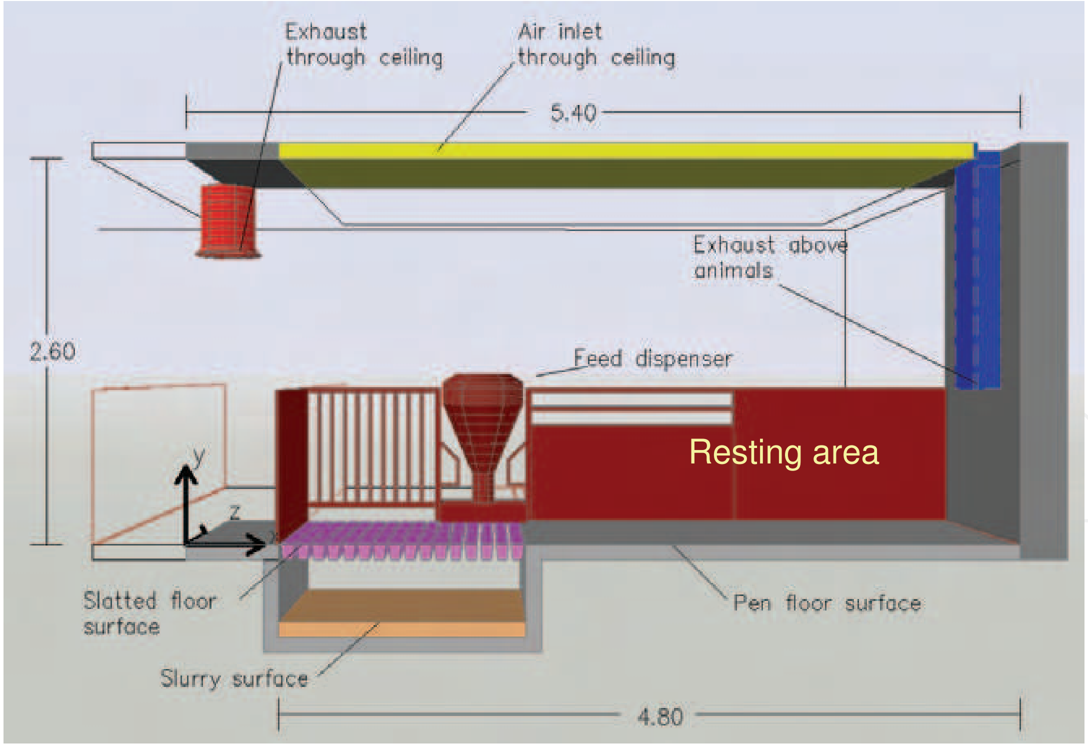


Fig. 12. Pig unit with two alternative ventilation exhausts (through ceiling or above animals).

The lower picture in Fig. 13 shows that the air temperature distribution becomes very similar to the ceiling exhaust case if the air change is reduced 40 % in the case with exhaust above the resting area. Additional analysis shows that a 40 % reduction of air change in combination with location of the exhaust above the resting area will not degrade the condition in relation to carbon dioxide or ammonia concentrations in the room. Potential benefits of such an arrangement will be reduced energy consumption for running the ventilation system, reduced emissions - where especially odour emission can be expected to decrease with decreased air change and finally if air cleaning of the entire air change are required it may result in significant savings in both investments and operation cost.

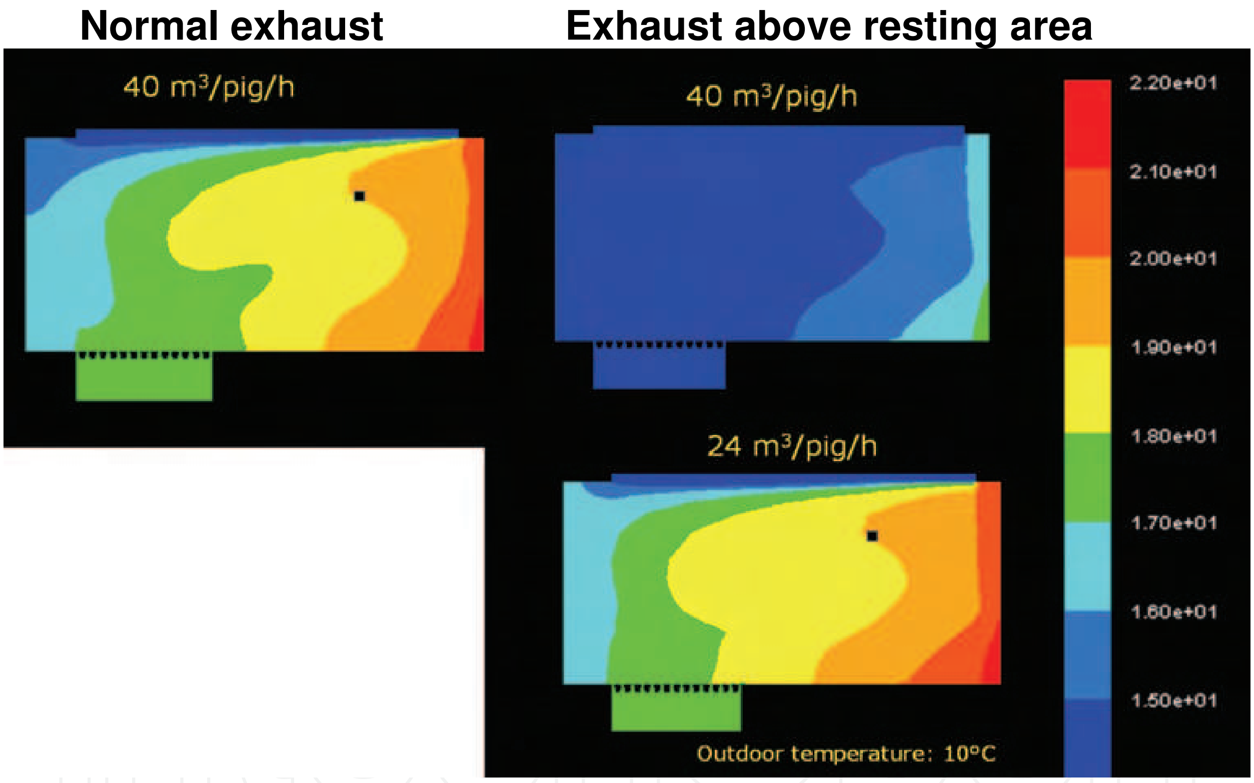


Fig. 13. CFD prediction of temperature distributions (°C) in a pig pen at different exhaust locations and air changes.

The CFD models discussed in this chapter have until this point been delimited to the condition in one pen only, and this simplification may naturally cause that important interactions between pens will be lost. As it is indicated in Fig. 2 a normal ceiling exhaust are usually design to remove air from a number of pens. To visualize the consequences of air streams between pens Fig. 14 show results from an analysis of 3 pens corresponding to one quarter of the pig unit shown in Fig. 2.

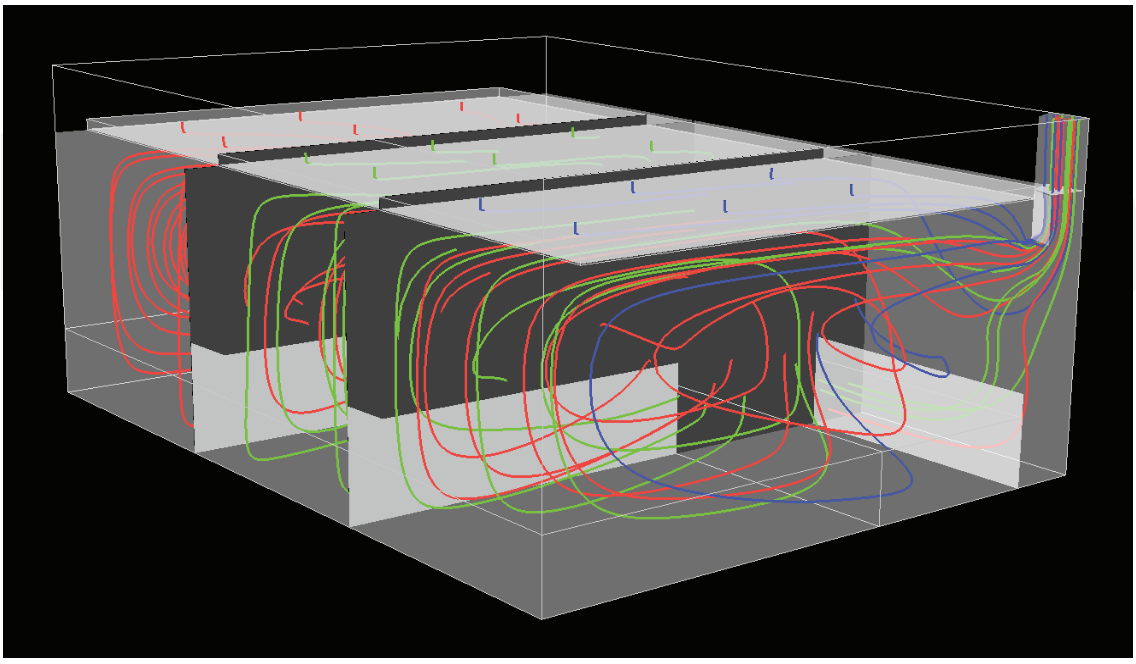


Fig. 14. Simulated air stream lines from inlet to exhaust for air entering a pig unit at 6 different locations above each of 3 pens.

The graph shows simulated stream lines for air entering the room at six locations above each pen. It appears that red stream lines entering the room above the pen in the largest distance from the exhaust pass through the animal occupied zone of al three pens, which has the negative consequence that pigs in one pen become exposed to airborne pathogens that might be released from pigs in another pen. The figure also shows that a large part of the air entering the room above the pen closet to the exhaust leaves without reaching the animal occupied zone, and as result significant difference in temperatures and concentrations between pens may occur. Subsequent analyses have shown that both problems can be avoided by installing an exhaust above the resting area in each pen.

4. Conclusions

The analyses, including CFD-methods (Computational Fluid Dynamics), showed that evacuating and cleaning of 10 percent of the total ventilation capacity from the pit may reduce the ammonia emission of the system with 73 percent, and the ammonia concentration in the room is significantly reduced. In a similar production system without pit ventilation cleaning of 10 percent of the ventilation capacity reduced the ammonia emission with 41 percent compared to no cleaning.

In addition analyses illustrated that CFD methods can be a very useful tool in the development of improved and more efficient ventilation systems.

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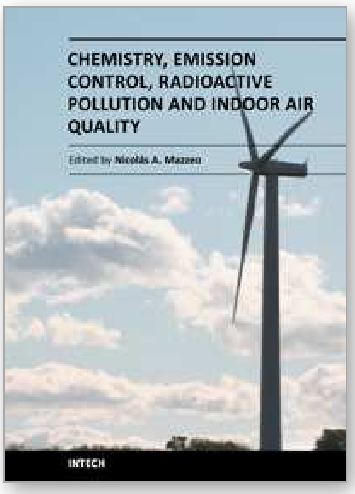

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The atmosphere may be our most precious resource. Accordingly, the balance between its use and protection is a high priority for our civilization. While many of us would consider air pollution to be an issue that the modern world has resolved to a greater extent, it still appears to have considerable influence on the global environment. In many countries with ambitious economic growth targets the acceptable levels of air pollution have been transgressed. Serious respiratory disease related problems have been identified with both indoor and outdoor pollution throughout the world. The 25 chapters of this book deal with several air pollution issues grouped into the following sections: a) air pollution chemistry; b) air pollutant emission control; c) radioactive pollution and d) indoor air quality.

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