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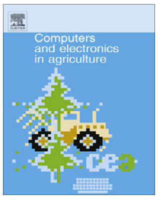

Original papers

Assessment of porous media instead of slatted floor for modelling the airflow and ammonia emission in the pit headspace

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ABSTRACT

In order to reduce the emission, proper understanding of the transportation behaviour of gaseous ammonia inside the slurry pit is required. Numerical simulation by the aid of computational fluid dynamics (CFD) technique can be used for this purpose. However, direct modelling of slatted floors is complicated and may be replaced by the porous media model (PMM) as shown in earlier studies. The objective of our study is to improve the quality of simulation results by PMM, and to assess the effects of air velocity above the slatted floor (as affected by wind), pit headspace height (as affected by amount of slurry in the pit) and sidewall height (as affected by the dairy house sidewall) on the airflow features inside the pit and ammonia emission from the pit. Three different CFD models of a slatted floor were developed to evaluate whether porous media is capable to represent a slatted floor for modelling the airflow inside and ammonia emission from the slurry pit, and to study the effect of turbulence treatment in the porous media on the modelling results: a slatted floor model (SFM) which models the slatted floor as it is, a turbulent porous media model (PMM-T) and a laminar porous media model (PMM-L). Both PMM-T and PMM-L represent the slatted floor by porous media, the PMM-T assumes turbulent airflow and the PMM-L assumes laminar airflow in the porous media. The SFM was verified for a dataset acquired from a 1:8 scale wind tunnel model of the slurry pit. Results showed that the PMM (PMM-T and PMM-L) were able to predict both the airflow features inside the slurry pit and the ammonia emission from the slurry pit if the resistance parameters and flow regime of the porous media were properly set. In comparison to the SFM, the PMM-T predicted the flow pattern better, but overestimated the turbulence intensity and the consequent emission rate. PMM-L performed better in predicting the ammonia emission rate because of the relatively accurate prediction of turbulence intensity. Simulation results also showed that the ammonia emission rate increased with a higher mean airflow velocity, a smaller headspace height and the presence of sidewalls.

1. Introduction

The ammonia emission from dairy cow houses has raised wide concern because of its potential risk in environmental pollution and animal health. In the Netherlands, ammonia emission from the cattle was about 53 kt in 2009, of which 34% originated from dairy cow houses and manure storage facilities (Van Bruggen et al., 2011). Hence, effective control of the ammonia emission from dairy cow houses is very important. Slatted floors above a pit are widely used for slurry management. For such a typical dairy cow house, 60–70% of the ammonia is emitted from the slatted floor surface (Monteny et al., 1998; Braam et al., 1997). Therefore, much effort has been devoted to study the ammonia emission behaviour in the space above the slatted floor, both experimentally and numerically (Norton et al., 2009, 2010; Wu et al., 2012a; Rong et al., 2015; Seo et al., 2012; Snoek et al., 2014). The remaining ammonia emission from the dairy cow house, 30–40% of the total, originates from the slurry pit. The emission rate from the slurry pit is besides slurry characteristics (Monteny et al., 1998), influenced by the air velocity and air flow pattern above the slatted floor (Bjerg et al., 2013), the details of the openings of the slatted floor (Ye et al., 2008), the air velocity and air flow pattern in the headspace of the slurry pit (Wu et al., 2013b). However, the available information is too limited to understand the effects and to develop measures for reduction of pit emission.

So far, only few studies focused on the airflow and mass transfer inside the slurry pit, all of which were carried out on lab-scale (Wu et al., 2013b, 2012b; Zong and Zhang, 2014). Airflow and mass

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Nomenclature

v	velocity (m s^{-1})
T	temperature (K)
P	pressure (Pa)
P_{atm}	pressure (atm) (Table 2)
Y_i	species mass fraction
ρ	density (kg m^{-3})
P_{op}	operating pressure (Pa)
M	molecular weight (kg mol^{-1})
E	ammonia emission rate (kg s^{-1})
Q	flow rate (m^3 s^{-1})
C_{in}	ammonia concentration at the inlet (kg m^{-3})
C_{out}	ammonia concentration at the outlet (kg m^{-3})
R	gas constant (J K^{-1} mol^{-1})
D	viscous coefficient (m^{-2})
C	inertial coefficient (m^{-1})
C_p	specific heat capacity (J kg^{-1} K^{-1})
μ	viscosity (kg m^{-1} s^{-1})
D_{eff}	effective diffusion coefficient (m^2 s^{-1})
D_{bulk}	diffusion coefficient in the bulk air (m^2 s^{-1})
ε	porosity
τ	tortuosity
A_{op}	surface area of slot openings (m^2)
A_{fl}	surface area of entire floor (m^2)
k	thermal conductivity (W m^{-1} K^{-1})

transfer measurements inside a slurry pit are difficult due to the harsh conditions and limitations of devices to capture the very low air velocity and its distribution in space as well as distribution of ammonia concentration in space. Alternatively, numerical modelling based on computational fluid dynamics (CFD) is able to realize this objective, but the large number of slats and slots of a concrete floor pose a challenge; it is hard to directly involve all the slats and slots in a full-scale dairy house model due to the massive time-consumption for building the computational domain. To deal with this problem, porous media was used in some studies to represent the slatted floor for modelling the airflow and mass transfer inside the slurry pit (Wu et al., 2013b; Zong and Zhang, 2014; Sun et al., 2004). A comparison between a porous media model (PMM), a slatted floor model (SFM) and experimental results of a 1:8 scale wind tunnel model of the slurry pit showed that the PMM has potential to represent the SFM for assessing the airflow in the pit headspace (Wu et al., 2013b; Zong and Zhang, 2014). However, a number of aspects in the applied PMM need further attention: (1) the single-slot sub-model for calculating the static pressure drop over the slatted floor and resistance coefficients was not validated, neither numerically nor experimentally; (2) the resistance coefficients for airflow parallel to the slats were assumed to be the same as the assessed coefficients for airflow perpendicular to the slats; (3) the turbulence transportation inside the porous media was not discussed; and (4) the experimental data resulted from a scale model. Each of these assumptions may enlarge the difference between the PMM and the real life circumstance. The goal of our study is to improve the quality of simulation results by the PMM, and assess the effect of easily controllable external factors: (1) the air velocity parallel to slats above the floor (as affected by wind), (2) the pit headspace height (as affected by the amount of slurry in the pit), and (3) the height of sidewalls above the floor, adjacent to the slatted floor, and perpendicular to slats (referring to the sidewalls of the building) on the airflow features inside and ammonia emission from the pit.

The current applied PMM was improved as follows: Firstly, the CFD sub-models for calculating the static pressure drop over the slatted floor were carefully designed to guarantee the estimation accuracy of the resistance coefficients. Secondly, the resistance coefficients parallel and perpendicular to the slats were calculated separately for correct processing of decomposed velocity vectors. And thirdly, the effect of the turbulence model (T or L) in the porous media on the modelling results were taken into account. Section 2 describes the modelling methods and materials. In Section 3 the new PMM was used to determine the effect of the controllable external factors, mean air velocity (Section 3.1), pit headspace height (Section 3.2), and sidewall height (Section 3.3) on the airflow features and the ammonia emission rate.

2. Modelling methods and materials

This section describes the modelling methods and the data used for model validation. Intermediate result in support of modelling decisions and validation is discussed in this section as well.

2.1. Geometry and boundary conditions

The geometry defined in CFD in this study was equal to that of the wind tunnel and slatted floor used in the work of Wu et al. (2013b). The 1:8 scale wind tunnel had a length of 3.67 m with a cross-sectional area of 0.35 m×0.35 m. The pit with a surface area of 0.35 m×0.35 m was installed at the middle section of the wind tunnel. Wu et al. (2013b) gives a detailed description of the wind tunnel and slurry pit. Numerical simulations were implemented using Ansys-Fluent 15.1 (Ansys-Fluent 15.1, 2014). Three-dimensional (3D) symmetric models were used to accurately capture the complicated swirl flow in the headspace. The orientation of floor slats was parallel to the wind direction. The schematic, dimensions and boundaries of the computational domain of the SFM and PMM used in this work are shown in Fig. 1. The computational domains were meshed by quadrilateral cells with the refinement at the viscosity-affected near-wall region. A grid-independence test was carried out using the SFM with three different grid systems. The total number of cells for each grid system was 304464, 607850 and 889880, respectively. The test result shown in Fig. 2 indicated that medium grid size was sufficient to guarantee an accurate prediction. The inlet and outlet of the computational domain were treated as velocity inlet and pressure outlet, respectively. The no-slip wall condition was imposed to all solid walls (wind tunnel, pit and slatted floor). The emission surface was also modelled as no-slip wall, and the gaseous ammonia mass fraction at the emission boundary was assumed constant at 360 mg m^{-3}, the average of a range according to De Paepe (2014). The effect of the liquid solution on the ammonia emission was not included in the current study. In order to save computational time, the top boundary of the wind tunnel was considered as free surface and imposed as symmetry boundary. The height of the top boundary was set as 0.175 m. When the sidewalls were included in the model, the top boundary was raised. Depending on the height of the sidewalls, the height of the top boundary varied between 0.175 and 0.260 m. The symmetry plane of the computational domain was highlighted by the dotted line. The detailed mathematic description of the boundary conditions is listed in Table 1. The central plane of the near-centre slot was selected as the characteristic plane to show the flow features in the pit headspace. Three lines on the characteristic plane (0.08, 0.18 and 0.28 m