Control of methane gas concentration in sewage tank reactor

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Abstract. In order to solve the safety hazard of methane gas explosion in dry toilets, the control of methane gas concentration in sewage tank reactor was carried out. The numerical simulation method was applied to study the concentration field of methane gas in the dry septic tank reactor. The main influence parameters considered here are the ventilation pipe diameter and the fan pressure drop. The optimum ventilation condition found by Fluent software is that the diameter of ventilation pipe is 300 mm and the pressure drop of draining fan is 20 Pa.

1. Introduction
Among the 17 sustainable development goals proposed by the World Health Organization [1], the construction of sanitary latrines has far-reaching significance. Especially for China with a large population and lack of water resources, toilet development research will be a major direction for the future environmental ecological construction.

In the past many ventilation studies, people often pay attention to comfort and air quality problems. Liu, J., et al. [2] used numerical simulation to study the thermal comfort of ventilation in the cabin environment. Murga, A., et al. [3] studied the influence of ventilation on indoor air quality. Few people proceeded from the safety of dry privies by considering the control of flammable gas methane in dry toilets. Based on the construction of public aqua privies in agricultural and pastoral areas in Qinghai Province, the present paper studies the control of methane gas concentration in the septic tank reactor of dry privies in order to provide guidance for the construction of dry privies.

2. Ventilation model
The model was established based on the actual size of the dry septic tank reactor (length 1.8 m, width 1.8 m, height 3.3 m). The manure in the reactor is fermented and methane gas is continuously produced. The model is partially simplified by considering the gas-liquid interface of the reactor that released methane set as the input boundary. The length of the reactor exhaust pipe and the intake pipe were 6 m and 6.45 m, respectively. The model considers installed a hood (0.4 m high and 0.5 m in diameter) 0.2 m at the upper end of the exhaust pipe and the intake pipe to prevent air backflow and rainwater intrusion. In order to improve the ventilation capacity inside the reactor, an exhaust fan is added at the upper end of the exhaust pipe to promote methane emission. A schematic diagram of the reactor ventilation system is shown in Figure 1. When studying the reactor ventilation, the possibility of the discharged methane flows back to the reactor through the intake pipe is considered and the calculation domain is added to include the intake and the exhaust port.

2.1. Control equations and boundary conditions
The basic control equations are the continuity (1) and the momentum (2) in the following:
\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = S_m
\]  
(1)

\[
\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) = -\nabla p + \nabla \cdot (\mathbf{\tau}) + \rho \mathbf{g} + \mathbf{F}
\]  
(2)

where is \( \rho \mathbf{v} \) convection term, \( S_m \) is mass source, \( p \) is the static pressure, \( \mathbf{\tau} \) is the stress tensor, and \( \rho \mathbf{g} \) and \( \mathbf{F} \) are the gravitational body force and external body forces. Turbulence k-e two-equation model is chosen and it is suitable in engineering applications [4-7]. The component transport model of methane gas is written as:

\[
\frac{\partial (\rho c_s)}{\partial t} + \nabla \cdot (\rho \mathbf{u} c_s) = \nabla \cdot (D_s \nabla (\rho c_s)) + S_s
\]  
(3)

where \( c_s \) is the volume concentration of the component \( s \), \( \rho c_s \) is the mass concentration of the component, \( D_s \) is the diffusion coefficient of the component, \( S_s \) is the component source.

Figure 1. The scheme of flow field.

Methane gas is produced in the reactor and continuously released from the interface of water and gas. In order to simulate the release process, a thin layer of 10 mm is added to the liquid side of the septic tank reactor as a source of methane. The release rate of Methane gas is determined to be \( 9.25 \times 10^{-6} \) kg/s. The exhaust port is set to be the fan internal boundary condition and the pressure outlet boundary condition is set at each side of the added calculation domain shown in Figure 1. The initial pressure is atmospheric pressure and the initial temperature is 261.75 K for outdoor air temperature. The temperature at the interface of liquid and gas of the septic tank reactor is 278.15 K. The other boundary is set to be the wall boundary.

2.2. Model discretization

The control equation of continuity, momentum, energy and composition are discretized by the second-order upwind scheme, and the control equations are solved by the simple algorithm of pressure velocity coupling. The flow field is meshed by the Gambit software. The mesh is hybrid mesh, and local encryption processing is performed at the fan outlet and the hood to improve the simulation accuracy, shown in Figure 2.
2.3. Grid independence
For the case of 20 Pa pressure drop of the outlet fan, the model with the grids of 1, 2, 3, and 4 million is calculated and the air velocity at six checking points in the exhaust pipe is selected to check the grid independent. The results are shown in Figure 3. When the number of meshes is 2 million, the results are less independent on the number of grid. The grid of 2 million is selected for subsequent numerical simulation.

3. Simulation results and analysis

3.1. Analysis of velocity and methane concentration
The pipe diameter 200 mm and the fan pressure drop 20 Pa are selected, and the simulation results of the velocity and the composition field on the cross-section of Y=1.9 m are shown in Figure 4. It can be seen that the velocity in the exhaust pipe, the hood and the intake pipe are relatively large. At the lower left of the reactor, due to the effect of the intake air, there is a velocity gradient, which results in the composition gradient. The composition distribution is basically consistent with the velocity distribution and the reliability of the simulation results is obtained.
3.2. Analysis of influencing factors

The main influence parameters of reactor ventilation are the diameter of ventilation pipe and the pressure drop of fan. Three ventilation pipe diameters of 200 mm, 300 mm and 400 mm and four fan pressure drops of 5 pa, 10 pa, 15 pa and 20 pa are selected in this study. The ventilation requirement of the reactor is up to 12 times/h (99 m$^3$/h), and the effects of ventilation pipe diameter and fan pressure drop on methane emissions in the reactor are investigated.

The reliability of the simulation is analyzed in Subsection 3.1. Considering the target value of the ventilation design, the gas exchange rate is not less than 0.0275 kg/s, and the methane mass fraction in the reactor is not more than 6.93×10$^{-3}$.

When considering the effects of the influencing factors on the amount of ventilation in the reactor, the simulation results under each working condition are placed in Figure 5. Under the existing working conditions, the gas exchange capacity requirement of the reactor has been reached (greater than 0.0275 kg/s), and the gas exchange rate increases with the increase of pipe diameter and fan pressure drop.

When considering the effects of the influencing factors on the mass fraction of methane in the reactor, the simulation results under each working condition are placed in Figure 6. The methane mass fraction requirement (less than 6.93×10$^{-3}$) in the reactor is achieved under all existing operating conditions. The methane mass fraction in the reactor decreases with the increase of the fan pressure drop, and finally gradually becomes gentle. On the other hand, the methane mass fraction in the reactor does decrease with the increase of the ventilation pipe diameter for small diameter and the methane mass fraction is almost independent on the pipe diameter when it is larger than 300 mm. The amount of methane imported and exported with different pipe diameters under the condition of fan pressure drop 20 pa is shown in Figure 7. It can be found that as the pipe diameter increases, the amount of methane reflux in the intake pipe is increased.
Figure 5. Effect of various working conditions on the ventilation.

Figure 6. Effect of various operating conditions on the methane mass fraction.

Figure 7. Import and export of methane for different diameters with respect to fan pressure drop 20 pa.

4. Conclusions
Through the simulation study of the septic tank reactor, it is concluded that the effect of the fan pressure drop on the methane mass fraction in the reactor is positively correlated, but the fan pressure drop has a certain limit. When the fan pressure drop is larger than 20 pa, the influence of the pressure drop becomes tiny and cannot improve the methane discharge better. The ventilation pipe diameter has a recirculation effect, where the methane mass fraction of the 300 mm pipe diameter is smaller than that of the pipe diameter of 400 mm in the studied working conditions. For the ventilation and public toilet construction projects in Qinghai Province, the best conditions for ventilation are ventilation pipe diameter 300 mm and fan pressure drop 20 pa.

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