Energy-saving-orientated ventilation optimization under safely feasible water-gas compartment in urban utility tunnels

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Abstract: Building an independent gas compartment in utility tunnel will require spending additional costs for construction, which is often hindered by the public budget limitations. To lay gas pipelines together with water pipelines compartment in utility tunnel was proposed, forming a water-gas compartment. Persistent ventilation consumes too much energy to cope with small possibility accident. Hence, the diffusion law of potential gas leakage and effect of the present combustible gas detection, alarming and ventilation systems were examined by a numerical simulation using the software Fluent based on computational fluid dynamics (CFD). The volume fraction of leaking methane accumulation law without ventilation were obtained. The results revealed that the present emergency measures for a single gas pipe compartment can be safely applied to the proposed water-gas compartment to guarantee the safety, which provides novel insights into and an important basis for the improvement of the related urban engineering design and relevant standards. Optimization scheme of ventilation was proposed and energy saved was calculated quantitatively.

1. Introduction
The natural gas pipeline leakage has caused problems like accidental fires and explosions due to the construction damage or the natural corrosion in soil [1], which could be effectively minimized by laying the pipeline into an urban utility tunnel [2], which would increase the lifespan of the pipeline and reduce the follow-up maintenance cost [3, 4]. It is also a sustainable design scheme for land-intensive management [5]. The current Chinese standard stipulates that natural gas pipeline should be laid in a separate compartment if placed into the urban utility tunnels and there should be at least 6 times/h ventilation under normal condition[6], which would lead much higher cost and consume too much energy. In the early construction of urban utility tunnels such as those in London and in Hamburg in 19th century, a precedent existed, in which gas pipelines and other pipelines were placed together in a single compartment [2], so water-gas compartment was proposed. Also, if the it could be confirmed that the 6 times/h ventilation is unnecessary, much energy could be saved.

The distance between two compartment doors was at least 200 m [6], while the diameter of the leakage hole was only several millimeters. Hence, it was difficult to conduct an experiment based on small scale, and numerical simulation based on computational fluid dynamics (CFD) is an important research method of leakage. The most common used numerical simulation software is ANSYS Fluent.
The experiments about leakage in utility tunnel, in 3 sizes (length×width×height), were conducted [7]: first one was 25 m×0.3 m×0.3 m, second one was 57 m×0.3 m×0.3 m, third one was 25 m×0.6 m×0.6 m. Totally five SST-9801A methane detectors produced by Shenzhen Suofutong Industrial Co. Ltd. were selected to observe the concentration change of leakage methane. In addition, standard k-ε turbulence model, k-ε RNG model, k-ε Realize model, k-ω model were compared with experimental results [8]. The results showed the standard k-ε turbulence model was the best choice for gas leakage and concentration distribution in such a narrow space with millions of grids, whose simulation results met the requirement of engineering design.

2. Method and simulation model

2.1 Parameter setting

Standard k-ε turbulence model was selected to conduct the simulation. For grid independence check, 2.5 million grids were selected to carry out the simulation with taking into consideration of both the accuracy and the time cost. The time step of 0.5 second was selected with considering the response speed of the methane detectors and the whole simulation time span studied.

The Figure 1 shows that the size of water-gas compartment is 200 m×3.6 m×3.4 m. The X, Y, Z axis are along the length, width, height of compartment respectively. The diameters of both clean water and reclaimed water pipelines were 800 mm, and that of the gas pipeline was 400 mm, which would have the capacity to meet the water and gas demand of a typical big city.

According to the stipulation of the newest installation atlas, the standard distance is 1 m between 800 mm water pipes [9], and also 1 m between 400 mm gas pipes [10]. If all the pipelines were laid horizontally in parallel to each other, the width of the compartment would be too wide and leave the upper space unutilized. Thus, the vertical layout was considered to apply. Since the steel-made gas pipe including transport substance was lighter than that of the water pipe, made by cast iron, the gas pipeline was installed above the water pipeline.

In this model, other obstacles like props of pipes were ignored, because the volume and the number of them, compared with the pipes, were limited. The methane detectors were installed above the single gas pipe or above the center of the few parallel pipes, as illustrated by triangle (not selected) and roundness (selected) in Figure 1. The installation height of detector is 3.3 m, where is 0.1 m away from the ceiling. Leakage in right operating gas pipe was conducted. The positions of the leakage holes were set back to methane detectors, including 3 directions of the holes: right-sided, right-down-sided, and down-sided.

According to the current product information, the T(BT)35-11-6.3 model axial flow ventilator (its blade angle is 25° and rotate speed is 1450 rpm with the airflow volume of 15,683 m³/h) was chosen to meet the requirement for ventilation performed at least 6 times per hour (normal ventilation) which exceeded the flow rate of 14,688 m³/h for this water-gas compartment. The ventilation opening and the door had to be over 10 m apart [11], so two 2 m×1 m ventilation openings were set at X=10 m-12 m and X=188 m-190 m, shown in green in Figure 1.

![Figure 1 Sketch of the gas leakage in water-gas compartment.](image-url)
The 200-m-long fire protection zone between the two fire doors of the compartment was divided into one ventilation region between the ventilation openings and two ventilation corners between the openings and the fire doors. The locations of leakage holes are presented in Figure 1, the holes at X=47.5 m and at X=92.5 m were located in the middle of the two methane detectors. As for the boundary conditions, the air inlet and air outlet were set as velocity boundary, where the ventilation volume should be converted into flow velocity. Also, the leakage hole is mass flow boundary and the others are wall boundary. Pure methane was selected to replace complex constituent of natural gas, and its density is lower than that of air, considering gravity and buoyancy [1, 12].

2.2 Calculation of the leakage mass rate
Because of the perfect protection of urban utility tunnel, there was not any damage by external force and the maximum operating pressure of gas pipeline was 1.6 MPa [6]. The sizes of the leakage holes caused by natural corrosion would not be too large, so 2/4-mm-diameter holes were chosen to study the persistent leakage, and a large 10-mm-diameter hole was employed to investigate the protective effect of the existing emergency measures against leakage. The mass flow boundary condition for leakage holes was adopted and the leakage mass flow rate was calculated by Equation 1 [13].

\[
q_m = C_{dg} A P_g \left( \frac{k}{k+1} \right)^{\frac{1}{k-1}} \left( \frac{2}{k+1} \right)^{\frac{k+1}{2(k-1)}}
\]

Where the \(q_m\) is mass flow rate, unit is kg/s; gas flow parameter \(C_{dg} = 0.98\); \(A\) is area of leakage hole (diameter=2 or 4 or 10 mm, \(\pi = 3.1416\)), absolute pressure \(P_g = 1.7 \text{ MPa}\), methane isentropic index \(k = C_p/C_v = 1.29\); \(M\) is molar mass of methane and the value is \(16 \times 10^{-3} \text{ kg/mol}\); gas constant \(R = 8.134 \text{ J/(mol·K)}\), gas temperature \(T_g = 293 \text{ K}\). Therefore, the mass flow rate of 2/4/10-mm-diameter hole is 0.008926 kg/s, 0.03570 kg/s, and 0.2231 kg/s respectively.

3. Research subject and results
3.1 Gas accumulation without ventilation
Exploration of the situation without any ventilation was necessary in case the normal ventilation facilities failed. The time limit of 2-mm-holes leakage was set at 60 min, which was also the limit for the emergency management department to repair the facilities after the fault happened, and allowing longer failure time would be meaningless. The leakage rate of the 4-mm-diameter holes was four times that of the 2-mm-diameter holes, and thus the 30 min was set as the time limit. The holes at X=92.5 m were chosen and the change of maximum concentrations of methane detectors at X=85 m and at X=100 m were compared (Figure 2 and Figure 3).

![Figure 2 Maximum methane volume fraction at methane detectors (2 mm hole)](image2)

![Figure 3 Maximum methane volume fraction at methane detectors (4 mm hole)](image3)

From the results of the three leakage directions of the 2-mm-diameter holes, it indicated that the direction did influence the accumulation of methane, and all the values of volume fraction were too
low to cause any explosion. Besides the situation of ventilation suspended for an hour would rarely happen, the results showed that the water-gas compartment without ventilation can still be regarded as safe with a diameter of the leakage holes of 2 mm.

The maximum volume fraction at methane detectors in the leakage from the 4-mm-diameter holes exceeded the lowest explosive limit in could be ignited during the time after 1045 s. Even if the compartment was spacious enough for the leakage methane to diffuse, there was the possibility to cause explosion, which was dangerous and it meant that these ventilation facilities should be fixed and restarted soon to maintain the safety of the water-gas compartment.

The result showed that the down-side leakage had the least methane accumulation near the leakage site, because the low-density gas diffused upwards to the top of the compartment, and was also obstructed by the pipeline itself. Thus, the volume fraction in that point was lower than those in the other directions. The right-side or right-down-side leakage, compared with the down-side one, had an insignificant effect on the diffusion, but both the offside wall and gas pipelines above affected the diffusion. Hence, the pipeline as an obstacle exerted enormous impact on the gas leakage simulation in utility tunnel which should be considered in research.

As for the corrosion perforation on the pipeline, the leakage was found quite soon for both the 2-mm and 4-mm-diameter holes. No explosive risk was established within 60 min for the 2-mm-hole leakage and 15 min for 4-mm-hole leakage respectively, because the leakage methane was not accumulated effectively to reach the lowest explosive limit, which was attributed to the large installation space distance between the water or reclaimed water pipelines. Under these conditions, the speed of diffusion the leakage gas was much higher than that of its accumulation.

According to these results, even if the ventilation is suspended, the compartment is still safe in at least 15 min, which means that if the ventilators do not work in normal time, there is no risk with the normal work of methane detector. This would be a suggested design for future design standard because it can save much energy, and the detail will be discussed in fourth quarter.

3.2 Effect of current emergency measures on water-gas compartment

Under current emergency measures, after the alarm, the ventilation volume increased to 12 times/h (double ventilation), which would discharge the leakage methane rapidly and guarantee safety. In case the leakage gas volume fraction continued to rise and reached 1.25%, the gas cut-off valve would be activated, concurrently emptying the content of gas pipeline. The relationship between the pressure in the pipe and the time to vent the gas is given in Equation 2 [14]:

$$\ln \left(\frac{P_1}{P_2}\right) = \frac{4}{k+1} \left[ k \left(\frac{2}{k+1}\right)^{\frac{k+1}{k}} \left(\frac{B g Z}{M \rho T_g}\right)^{\frac{1}{2}} \right]$$

Where the initial absolute pressure $P_1$ is 1.7 MPa, $P_2$ is the target absolute pressure, MPa, $t$ is the venting time, s, $S$ is the flow area of venting pipe (diameter is 100 mm) with valve parameter $\mu = 1$ and $V$ is the volume of pipeline between two cutting-off valves (length is 2 km, diameter is 400 mm), methane isentropic index $k = C_p/C_v = 1.29$, and gravity acceleration $g = 9.81$ m/s$^2$, relative molecular mass of methane $M_r = 16$, gas compressibility factor $Z = 1$, empirical value $B = 848$ kg·m/(kmol·K), gas temperature $T_g = 293$ K.

The venting pipe and facility met the design requirement of the venting time: the gas pressure ($P_2$) decreases to below 50% of the designed value ($P_1$) within 15 min like Figure 4 showed. Therefore, the time span was 15 min.
Figure 4 Dynamic pressure and leakage rate with venting time

In the leakage from the large, 10-mm-diameter holes, the alarm response time was only several seconds, and the volume fraction soon exceeds 1.25%, which was exceedingly dangerous. Thus, double ventilation would start immediately with a cut-off valve activated to vent gas into the open air. The condition of normal ventilation was compared with the down-side, 10-mm-hole leakage at X=47.5 m because of the one-way ventilation wind direction along X axis, and the methane volume fraction under this emergency condition can be observed in Figure 5.

It was shown obviously that although a part of the leakage methane would flow out through the outlet even in the absence of emergency measures, a large amount of methane would accumulate at the ventilation downstream and exceed the lowest explosive limit if the ventilation facilities did not work properly with a sufficiently high ventilation rate. The outcome confirmed that the normal emergency measures were indispensable, including the cutting off and venting of the gas pipeline and the action of ventilation facilities. After emergency venting for 5 min, the gas volume fraction dropped to a safe level; 15 min later, there was virtually no detectable methane residue in the compartment.

As for 10-mm-diameter hole, the transverse distribution of methane was slightly altered, because the transverse diffusion speed was far below the leakage rate. The lowest explosive limit was reached at several methane detectors. Hence, an explosion would likely occur under the existence and action of any igniting source, which was dangerous.
Figure 5 Comparison of methane volume fraction with or without emergency measures.

Therefore, the double ventilation and pipeline cutting-off measures should be taken immediately after the alarm has been triggered by the leakage methane and the volume fraction has reached 1%-1.25% to ensure safety. The comparison also confirmed that the present study design and emergency settings could ensure the operational safety of urban utility tunnels if the gas pipelines are laid together with water pipelines into one single compartment.

4. Optimization design of ventilation

For T(BT)35-11-6.3 model axial flow ventilator, the rated power of motor is 1500 w, which means the energy consumption for each ventilator is 36 kWh/day; there are 4 ventilators in a compartment (200 m), 2 for blowing in and 2 for exhausting. However, only two of them will work under normal condition. Nowadays, there are more than 4700 km utility tunnels have been constructed by the end of 2017 [15], with the target length of 8000 km. Consider the air quality in the compartment and the health for patrolling people, 2 or 3 times/h of ventilation is necessary to keep the air fresh and dry, which makes people feel comfortable when they enter in the compartment. If 2 times/h ventilation was selected, 411.72 GWh energy will be saved annually. Also, if 3 times/h ventilation was selected, 308.79 GWh energy will be saved annually.

If long-term effect is considered in life cycle of utility tunnel, at least 50 years and up to 100 years, the energy that could and should be saved is substantial.

\[
\begin{align*}
1.5kW \times \frac{(6-2) \text{ times/h}}{6 \text{ times/h}} \times 2 \times 4700km \times \frac{1000m}{200m} \times 24 \times 365 &= 411.72 \text{ GWh} \\
1.5kW \times \frac{(6-3) \text{ times/h}}{6 \text{ times/h}} \times 2 \times 4700km \times \frac{1000m}{200m} \times 24 \times 365 &= 308.79 \text{ GWh}
\end{align*}
\]

Hence, for future design of gas compartment, it is unnecessary to require previous 6 times/h ventilation in normal condition in future, because the leakage is small probability event and the current emergency system is enough to ensure safety. If the methane detectors detect that there is gas leakage that volume fraction of methane exceeds 1%, the ventilation scheme keeps the same as 12 times/h.
5. Conclusion
In the present study, the potential explosion risk and safety issues caused by methane leakage were investigated. The evaluations were performed by CFD simulation against using the currently novel design and emergency standards. Based on the findings, the utilization of a combined water-gas compartment can be applied in urban utility tunnels. Even when the ventilation measures failed, there was no risk of explosion in the compartment within 15 min (regardless of 2 mm or 4 mm hole). This would provide sufficient time for the maintenance team to locate the problem, and then restart the emergency system back to normal working condition. These measures can ensure the urban utility tunnel is safe under proper management.

Even for large leakage holes with a diameter of 10 mm, explosion accidents could still not be caused in the compartment under the protection of the normal emergency system. The practical implementation of the present findings will be helpful for the safe operation of water-gas compartments in the current utility tunnel system. Moreover, it will contribute to improving the related urban engineering design and standards, and more effectively meeting the requirements for sustainable urban development.

For related ventilation optimization, it could be still safe that the ventilators are used for urgent condition and keep 2 or 3 times/h ventilation under normal condition. If such a new standard was accepted, substantial energy could be saved.

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