Numerical simulation on heat transfer characteristics of gas pipeline in urban utility tunnel

G Q Wang1*, H M Wang1, Yan Cai2, G H Feng1 and Z Q Kang1

1 School of Municipal and Environmental Engineering, Shenyang Jianzhu University, Shenyang, China
2 CCCC Gas and Heat Research and Design Institute

* guiq.wang@sjzu.edu.cn

Abstract. Recent years, more and more utility tunnels are adopted in China with the development of urbanization. Compared to the conventional method for utility installation, the utility tunnel that co-locates more than one utility underground eliminates the need for frequent excavation and reinstatement of roads. Ventilation systems are essential in utility tunnel for safety reasons, especially for gas compartments. This paper aims to evaluate effect of the longitudinal ventilation on gas temperature field by investigating the heat transfer process on gas pipeline. Numerical models including convection, conduction and radiation were established and then used to simulate the heat transfer process on gas pipeline. Results show that the ventilation has a great impact on gas temperature. In case of low inlet air temperature, the gas temperature may drop below -10°C, which is too low to guarantee a normal operation.

1. Introduction

A utility tunnel is defined as an underground structure containing one or more utilities, permitting the installation, maintenance and removal of the systems without the necessity of making road cuts or excavations [1]. The utility tunnel has a long history of application around the world, which considered to be more effective on facilitating subsequent repair and renewal. Unfortunately, higher initial costs remain a significant barrier to its adoption [2]. In China, direct buried installation is still the most widely adopted solution for urban utility placement due to its lower short-term construction costs. Recent years, with the promotion of a series of policies, more utility tunnels are invested and built in major cities of China [3].

The utility tunnel is a relative enclosed space with poor ventilation. In order to ensure the normal operation of various municipal pipelines and to provide the maintenance personnel with a safe and sanitary environment, it is necessary to ventilate the utility tunnel to eliminate internal exhaust gas and heat [4-6]. Especially when a fire occurs in the tunnel, the ventilation system should be able to help control the spread of the fire and remove the toxic fumes accumulated in time [7]. However, introducing untreated air may result in changes of ambient temperature in utility tunnel, especially during the coldest weather in winter. Lower temperature may lead to excessive heat exchange between gas pipeline and indoor air, and thus cause the gas temperature to drop.

In this paper, a complete set of numerical models governing the heat transfer process was established, which considers heat convection, conduction and radiation. The simulation on a actual project was conducted to investigate the influence of various boundary conditions.
2. Method

The utility tunnel studied here locates in Shenyang of China with a climate of severe cold winter. The cross section and geometries of the tunnel are shown in figure 1. The upper part of the tunnel is the gas cabin, and the lower part is used for heating pipe installation.

The gas pipeline is made of steel, coated with polystyrene film. The tunnel is buried 5.3 m to 22.2 m underground.

![Cross section of utility tunnel.](image)

Figure 1. Cross section of utility tunnel.

The full length of the utility tunnel is 10 km, which is segmented every 0.5 km. The entire utility tunnel is divided into 20 segments. For each segment, two ventilation fans were used to circulate the air in tunnel at the start and end positions of the segment. The velocities of gas and air are 9 m/s and 0.5 m/s, respectively.

2.1. Numerical model

As illustrated in figure 2, the heat transfer process between the gas pipeline and the utility tunnel consists of four parts: convection between gas and inner surface of pipeline ($Q_g$), conduction through the pipeline ($Q_w$), convection between ambient air and outer surface of pipeline ($Q_a$), radiation between outer surface of pipeline and the tunnel structure ($Q_r$).

As heat exchange reaches a steady state, the thermal equilibrium was established and used to simulate the heat transfer between components.
2.2. Convection between gas and inner surface of pipeline \((Q_g)\)

Gas flow inside the pipeline is pressurized flow, which ensures the heat transfer between gas and pipeline to be forced convection. Dittus-Boelter Equation was used to calculate the convective heat transfer:

\[
Nu_f = 0.023Re_f^{0.8}Pr_f^n \tag{1}
\]

Gnielinski equation was also used to calculate the convective heat transfer for comparison.

2.3. Conduction through the pipeline \((Q_w)\)

A steady model based on Fourier's law was employed to simulate the heat conduction through the pipe wall:

\[
q = \frac{t_i - t_o}{\sum_{i=1}^{n} \frac{\delta_i}{\lambda_i}} \tag{2}
\]

2.4. Convection between ambient air and outer surface of pipeline \((Q_a)\)

The ventilated air in the tunnel was driven by the ventilation fans, which circulate the air at a certain velocity to exhaust excess heat. A forced convection heat transfer correlation for non-circular cross-section channel was used to the heat convection between pipeline and ambient air:

\[
Nu_f = \frac{(f/8)(Re-1000)Pr_f}{1+12.7\sqrt{f/8(Pr_f^{2/3}-1)}}[1+(\frac{d}{l})^{2/3}]c_i \tag{3}
\]

For liquid:

\[
c_i = (\frac{Pr_f}{Pr_w})^{0.11} \quad (\frac{Pr_f}{Pr_w} = 0.05 \sim 20) \tag{4}
\]

For gas:

\[
c_i = (\frac{T_f}{T_w})^{0.45} \quad (\frac{T_f}{T_w} = 0.5 \sim 1.5) \tag{5}
\]

![Figure 2. Heat transfer process in utility tunnel.](image-url)
2.5. Radiation between outer surface of pipeline and the tunnel structure \((Q_r)\)

Radiation happens between outer surface of pipe and the inner surface of tunnel, in which the heat exchange was calculated by Stephen Boltzmann’s law:

\[
\Phi = \frac{E_{\alpha 1} - E_{\alpha 2}}{\frac{1}{A_1} + \frac{1}{A_2X_{1,2}} + \frac{1}{\delta_2 A_2}}
\]

(6)

2.6. Governing equations

The governing equation set includes the heat balance for gas and air as follows:

\[
(C_{pg} \rho_g A_g) \frac{\partial T_g}{\partial t} + (C_{pg} \rho_g A_g v_g) \frac{\partial T_g}{\partial X} - \alpha_g \pi D_i (T_i - T_g) = 0
\]

(7)

\[
(C_{pa} \rho_a A_a) \frac{\partial T_a}{\partial t} + (C_{pa} \rho_a A_a v_a) \frac{\partial T_a}{\partial X} - \alpha_a \pi D_o (T_o - T_a) - \alpha_a S_a (T_w - T_a) = 0
\]

(8)

\[
\alpha_g \pi D_i (T_i - T_g) = \pi \frac{D_i + D_o \bullet \frac{T_o - T_i}{2}}{\sum_{i=1}^{n} \delta_i / \lambda_i}
\]

(9)

\[
\alpha_a \pi D_o (T_o - T_a) + \frac{\pi D_o \sigma \left[ \frac{1}{100} \left( \frac{T_o + 273.15}{100} \right)^4 - \left( \frac{T_w + 273.15}{100} \right)^4 \right]}{\frac{1}{\delta_o} + \frac{\pi D_o}{S_w} \left( \frac{1}{\delta_v} - 1 \right)} = \pi \frac{D_i + D_o \bullet \frac{T_i - T_o}{2}}{\sum_{i=1}^{n} \delta_i / \lambda_i}
\]

(10)

The transient terms in equations were neglected and a steady simulation was conducted. Finite volume discretization was applied for governing equations, and 4 sets of nonlinear equations including 4 unknown variables \((T_g, T_a, T_o, T_i)\) were obtained at each control volume as follows.

Python was used to implement the algorithm and solve the final equation set.

\[\text{Figure 3. Finite volume discretization of utility tunnel.}\]

2.7. Boundary condition

The utility tunnel studied in this paper was located in Shenyang City. The annual outdoor air temperature was shown in figure 4. It can be seen that the outdoor temperature in Shenyang can be as low as -20°C.
3. Results and discussion
The gas temperature profiles with different correlations is shown in figure 6. The correlation equations were used to calculate heat transfer inside gas pipes. Both the temperature differences and surface roughness meet the application condition of correlations. There are not significant differences between temperature profiles calculated with Gnielinski equation and Dittus Boelter equation.
The temperature profile for the first segment is illustrated in figure 7. As the gas flows in the forward direction, the ventilation air flows inversely.

Gas transfers heat to ambient air through conduction and convection, accompanied by a slight drop in temperature. The ventilation air receives not only the heat from gas, but also the heat from the utility tunnel. Therefore, the air temperature has increased greatly.

![Temperature profile at the first segment](image)

**Figure 7.** Temperature profile at the first segment.

Figure 8 shows the temperature profiles when the inlet air temperature is -20°C. The gas temperature changes continuously and air temperature change are discontinuous due to the segmentation for ventilation. At each segment of tunnel, the air temperature gradually approaches the temperature of tunnel wall due to the large contact area between the air and the tunnel wall.

As the gas flows, the gas loses heat to air and the temperature decreases to a steady state. Figure 9 shows the gas temperature profiles with different inlet air temperature. The outlet temperature of gas decreases as air inlet temperature decreases. For lowest inlet air temperature, the gas temperature at the exit can be reduced to below -10°C, which is too low to guarantee a normal operation.

![Temperature profiles when inlet air temperature is -20°C](image)

**Figure 8.** Temperature profiles when inlet air temperature is -20°C.
Figure 9. Temperature profiles with different inlet air temperature.

4. Conclusion
Ventilation is an effective way to ensure a safe operating environment in utility tunnel, which also has impact on gas temperature. The studied utility tunnel was segmented for ventilation. At each segment, the temperature of ventilated air increases greatly as the air absorbs the heat from pipeline and tunnel wall. The air temperature depends mainly on the temperature of tunnel wall due to the much large contact area. Different from the discontinuous change of air temperature, the gas temperature is continuously reduced to a relatively stable value along the flow direction. For lower inlet air temperature, the outlet gas temperature may be lower than -10°C, which cannot guarantee a normal operation. More attention needs to be paid on inlet air temperature when operating ventilation.

Acknowledgments
The authors wish to acknowledge the support of Natural Science Foundation of Liaoning Province of China (Grant No. 2019-ZD-0300) and Fundamental Research Project for Higher Education Institution of Liaoning Province (Grant No. LJZ2017032).

References
[1] Sun F, Liu C and Zhou X 2017 Utilities tunnel’s finance design for the process of construction and operation Tunnelling and Underground Space Technology 69 182–186
[2] Hunt D V L, Nash D and Rogers C D F 2014 Sustainable utility placement via Multi-Utility Tunnels Tunnelling and Underground Space Technology 39 15–26
[3] Yang C and Peng F-L 2016 Discussion on the development of underground utility tunnels in China Procedia Engineering 165 540–548
[4] Wu D, Zhang Y, Li A, Kong Q, Li Y, Geng S, Dong X, Liu Y and Chen P 2019 Indoor airborne fungal levels in selected comprehensive compartments of the urban utility tunnel in Nanjing, Southeast China Sustainable Cities and Society 51 101723
[5] Yang C, Peng F-L, Xu K and Zheng L-N 2019 Feasibility study on the geothermal utility tunnel system Sustainable Cities and Society 46 101445
[6] Li S, Liu X, Wang J, Fang G, Chen W and Deng S 2019 Reduced scale experimental study and CFD analysis on the resistance characteristic of utility tunnel’s ventilation system Energy Procedia 158 2756–2761
[7] Liu H, Zhu G, Pan R, Yu M and Liang Z 2019 Experimental investigation of fire temperature distribution and ceiling temperature prediction in closed utility tunnel Case Studies in Thermal Engineering 14 100493