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Influences of stack effect and longitudinal ventilation on the movement of buoyancy-driven contaminants in sloping tunnels

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Abstract. Sloping tunnels widely exist in mountainous regions and urban underground traffic systems. The dynamics of buoyancy-driven contaminants in a naturally ventilated sloping tunnel are generally different from that in a horizontal tunnel. Using the brine-water method and the light attenuation technique, we demonstrate that buoyancy-driven source location and source reduced gravity have significant influence on the steady-state density distribution in the sloping tunnel. The results suggest that the stack effect is an important factor influencing the movement of the buoyancy-driven flow in sloping tunnels. Subsequently, the dynamics of the buoyancy-driven flow in a longitudinally ventilated sloping tunnel are investigated. It is found that, under the combined effects of longitudinal ventilation and stack effect, multiple steady states exist for identical boundary conditions.

1. Introduction

As the problem of traffic congestion becomes increasingly serious, the number of the road tunnels increase in the world every year. Owing to the long and narrow structure of the tunnels, the dynamics of contaminants movement become more complicated [1,2]. Therefore, the behaviors of the gaseous contaminants in tunnels have attracted much attention [3,4-6].

Buoyancy can be an economical driving force for gaseous contaminants transport. If the buoyancy source locates at the base of tunnel, a buoyancy-driven flow, including plume region and longitudinal currents, is formed in the space [7]. Morton [8] proposed a plume model to estimate the reduced gravity and buoyancy flux. Additionally, previous literatures, i.e., Refs [9,10], studied the buoyancy-driven longitudinal currents in horizontal channel. However, the characteristics of the buoyancy-driven contaminants in horizontal tunnels are different from that in sloping tunnels. Stack effect induced by accumulating of density difference between contaminants and ambient air in longitudinal direction, is a diving force in sloping tunnels. Yang [11] indicated that the stack effect could be large enough to expel smoke upwards in a sloping tunnel. Because of the limitation of the topographical conditions, sloping tunnels are constructed increasingly in recent years [12]. Therefore, it is necessary to further to explore the characteristics of the buoyancy-driven flow under the influence of the stack effect in naturally ventilated sloping tunnels.

However, in addition to natural ventilation strategy, longitudinal ventilation system is a prevailing contaminants control method in the tunnel. The magnitude of stack effect could be comparable to the pressure rise induced by the mechanical ventilation system, which might significantly increase the difficulty and complexity of the contaminants control in longitudinally ventilated sloping tunnels. Yang et al.[13] have proposed that, in an urban traffic tunnel which contains sloping ramp tunnels, besides the anticipated flow pattern, the competition between the stack effect and mechanical longitudinal



ventilation can lead to other five possible flow patterns. However, it is still unclear that how to achieve the effectively expected flow direction of gaseous contaminants and meet the demands of ventilation. Therefore, it is urgent to investigate the dynamic mechanism of the contaminants flow induced by the combined effects of longitudinal ventilation and stack effect in a sloping tunnel.

This paper is organized as follows. In section 2, the brine-water experiments investigating the effects of the source reduced gravity and source location on the steady-state density distribution in a naturally ventilated sloping tunnel are presented. In section 3, theoretical dynamic analysis to identify the multiple steady flow patterns of contaminants in a longitudinally ventilated sloping tunnel is proposed. In section 4, conclusions are drawn.

2. Distribution of the steady-state density in a naturally ventilated sloping tunnel

In this section, brine-water experiments were carried out to investigate the steady-state density distribution, which is relate to the magnitude of stack effect, in a naturally ventilated sloping tunnel. And the factors, which might influence the steady-state density distribution, were discussed.

2.1. Brine-water Experiment

A schematic view of the experimental set-up is presented in Figure 1. It consisted of a 200 cm long model tunnel with rectangular cross-section. The width and the height of the tunnel were 5cm and 5cm, respectively, which was suspended rigidly in a large reservoir that was filled with fresh water to imitate the stack effect produced by density difference between the tunnel interior fluid and the ambient fluid. The inclined angle of the tank was approximately 7.9° . Both ends of tank were open freely during the experiments so that brine and water could pass through them. As shown in Fig. 1(b), four brine releasing sources were employed to represent different source locations. The distances between the lower end of the tank and the four different brine releasing sources, i.e., ΔL , were 70cm, 120cm, 170cm and 200cm respectively. The diameters of the brine releasing sources were 1.8cm. The source brine was colored with red dye in order to observe and measure the fluid density. The experiments were performed in a dark room. An LED light panel was covered at the rear of the tank, which was the only light detected by the camera. A Nikon D90 camera fixed in front of the large reservoir was used to record the movement characteristics of the buoyancy-driven flow in the tank.

The dense brine at the volume flow rate was provided by a peristaltic pump. As adopted by Sher and Woods [10], a light attenuation technique was used to measure the distribution of fluid density in the small tank. We firstly carried out a calibration process. A Nikon D90 camera in front of the larger tank recorded the process and the An LED light panel was the only light detected by the camera. Subsequently, the Nikon D90 camera also recorded the formal experiment performance. Then, these images were used to calculate the light intensity of every pixel by post-processed, which determined the distribution of the dye concentration in the tank.

In all tests, the source buoyancy flux B_0 is modified by varing the brine volumetric flux Q_0 :

$$B_0 = g'_0 Q_0 \quad (1)$$

where $g'_0 = g_0(\rho_{s0} - \rho_w)/\rho_w$ is the reduced gravity of source brine, ρ_{s0} and ρ_w are the densities of the source brine and water, respectively, and g_0 is the gravitational acceleration.

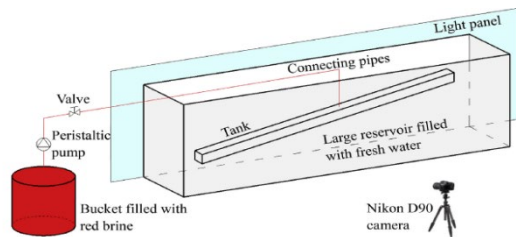
2.2. Factors influencing the steady-state density distribution

The effect of source reduced gravity, g'_0 , and source location, $\Delta L \sin \theta$, on the steady-state density distribution were analyzed in this section. The experimental conditions were listed in Table 1.

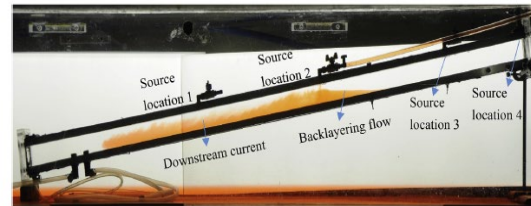
Table 1 Experimental conditions

EXP.	g'_0 (m/s ²)	B_0 ($\times 10^{-4} m^3 / s^3$)	ΔL (m)
1	0.71	1.14	2.0

2	0.35	1.12	2.0
3	0.17	1.10	2.0
4	0.17	2.27	1.2
5	0.17	2.27	1.7
6	0.17	2.27	2.0



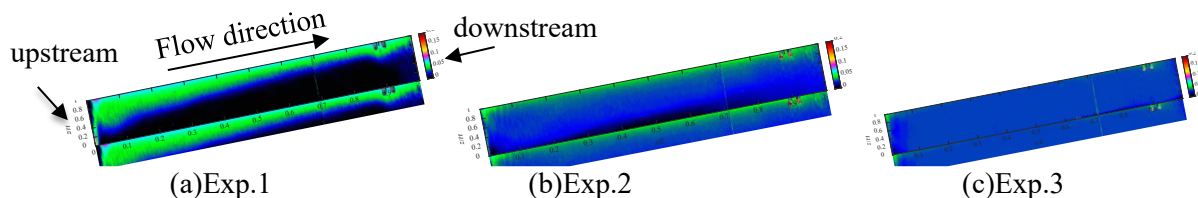
(a) Diagram of experimental setup



(b) Photo of experimental setup

Figure 1. System diagram of brine water experiment

2.2.1. Influence of source reduced gravity. Figure 2(a)–(c) shows the distribution of the density in the steady state in Exp. 1, Exp. 2 and Exp.3. In order to display the characteristics of contaminants movement intuitively, the images have been rotated 180° relative to the experiment situations. In all cases, B_0 and $\Delta L \sin \theta$ remain the same, only source reduced gravity, g'_0 , decreases from Exp.1 to Exp.3. In Exp.1, the stratification is obvious on account of the density of fluid close to the bottom of tank larger than that in Exp.2. However, in Exp.3 the vertical stratification is more uniform than in Exp.1 and Exp.2. Therefore, it can be seen that with the increase of source reduced gravity, the density distribution is more obvious. Additionally, the downstream flow of the source gradually transits from stratified two-way flow to well-mixed one-way flow, when source reduced gravity decreases.



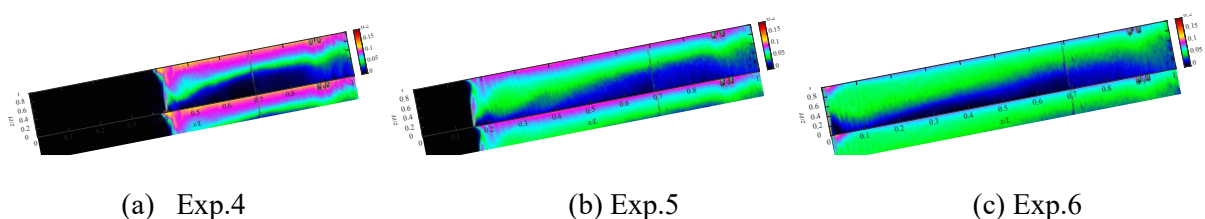
(a)Exp.1

(b)Exp.2

(c)Exp.3

Figure 2. Distribution of steady-state density in tank in Exp.1, Exp. 2, and Exp. 3.

2.2.2. Influence of source location. Figure 3(a)–(c) shows the distribution of the steady-state density in Exp. 4, Exp. 5, Exp. 6. All images have been rotated 180° in Figure.3. In these experiments, $\Delta L \sin \theta$, i.e., source location, is the only variable. As shown in Figure 3, the density distribution in the tank becomes increasingly unapparent as a result of the increase of distance between the buoyancy-driven source and downstream portal of tank. Moreover, when the buoyancy-driven source is located close to the upstream portal of tank, the magnitude of stack effect is larger than that in others positions, which results in the larger volumetric flux of fresh fluid through the upstream portal of tank.



(a) Exp.4

(b) Exp.5

(c) Exp.6

Figure 3. Distribution of steady-state density in tank in Exp.4, Exp.5, and Exp.6.

3. Dynamic analysis of contaminants flow in a longitudinally ventilated sloping tunnel

In section 2, we indicate that stack effect, which depends on the buoyancy source location, is a driving force for contaminants flow in a naturally ventilated sloping tunnel. However, in a longitudinally ventilated downhill tunnel, under the combined influence of the longitudinal ventilation and stack effect, two flow patterns may exist. When the longitudinal ventilation exceeds the stack effect, the effective contaminant flow control is attained, i.e., fan-dominated flow pattern(see Figure 4.(b)), otherwise both the vehicles and pedestrians could be threatened under buoyancy-dominated flow pattern(see Figure 4.(a)).

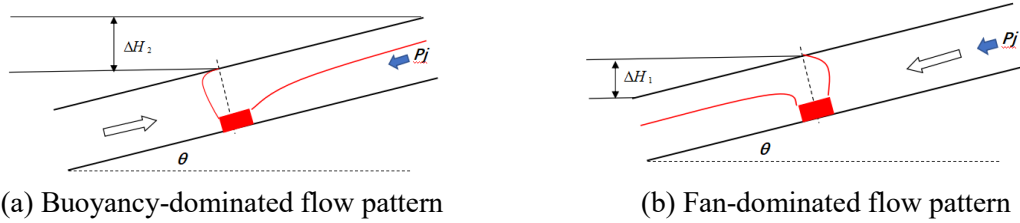


Figure 4. The schematic of two possible steady flow patterns in a longitudinally ventilated tunnel

3.1. System equation

In a longitudinally ventilated sloping tunnel, we assume the contaminants is fully mixed, i.e., the temperature is uniform. The heat balance equation in the tunnel is expressed as

$$MC_p \frac{dT}{dt} = qC_p \rho (T_a - T) + E \quad (2)$$

where M is the mass of the contaminants, T is the contaminants temperature, T_a is the ambient air temperature, q is the volumetric flow rate, E is the heat release rate of source, ρ is the contaminants density.

The pressure balance equations for two flow pattern are

$$P_j - \Delta \rho g \Delta H_1 = sq_l^2 \text{ (for fan-dominated)} \quad (3)$$

$$\Delta \rho g \Delta H_2 - P_j = sq_u^2 \text{ (for buoyancy-dominated)} \quad (4)$$

where P_j is the fan-induced pressure rise, s is the flow impedance coefficient and can be defined as

$$s = (\lambda l / D + \sum \xi) \rho / (2A^2) \quad (5)$$

Here, l is the total length of the tunnel, λ is the friction factor, which is considered as 0.02 here, ξ is the local resistance coefficient. If the resistance resulting from the gas expansion in the near-fire region is neglected, the total local resistance coefficient of the tunnel is approximately $\sum \xi = 1.6$.

Substituting Eq.(2) into Eq.(3) and (4), the temporal variation of dimensionless temperature rise are:

$$f(T^{**}) = \frac{dT^{**}}{dt} = \frac{\beta E}{MC_p} - \frac{T^{**} \rho_a}{M(T^{**} + 1)} \sqrt{((T^{**} + 1)P_j - T^{**} \rho_a g \Delta H_1) / (s \rho_a) / \rho} \quad \text{(for fan-dominated)} \quad (6)$$

$$f(T^{**}) = \frac{dT^{**}}{dt} = \frac{\beta E}{MC_p} - \frac{T^{**} \rho_a}{(T^{**} + 1)M} \sqrt{(\rho_a g \Delta H_2 T^{**} - (T^{**} + 1)P_j) / (s \rho_a) / \rho} \quad \text{(for buoyancy-dominated)} \quad (7)$$

where $T^{**} = \beta(T - T_a) = (T - T_a) / T_a$ is the dimensionless temperature rise for the contaminants.

3.2. System characteristics and dynamic behavior

In this section, a slopping tunnel with 300 m long, 9 m wide, 7.8 m high, was considered as the example to illustrate the dynamic behavior of contaminants. The strength of source was 7.5MW, which was located in the middle of tunnel. The slope of tunnel was 5° . There are three points (marked as 1, 2, 3) locating on the position where the dT^{**} / dt equals to 0, which are the steady states of the systems in Figure.5(b). Point 1 and 2 and the profile located on the left of Point A, correspond to fan-dominated flow pattern, which are derived from Eq.(6). Point 3 and the profile located on the right of point A, correspond to the buoyancy-dominated flow pattern, which are derived from Eq.(7). Moreover, it is evident that point 1 and 3 are mathematically stable but point 2 is unstable. For point 1, when T^{**} increases a little bit from it, $f(T^{**}) = dT^{**} / dt$ becomes negative. Then, T^{**} decreases until it comes back to

point 1. Therefore, point 1 represents a fan-dominated steady flow state. Similarly, point 3 is a stable state of buoyancy-dominated pattern. However, when T^{**} increases a little bit from point 2, T^{**} increases until reaches the new steady states, i.e. point 3. When T^{**} decreases from point 2, point 1 finally would be reached as T^{**} decreases continuously. Therefore, either point 1 or 3 is the final steady state under the mechanical longitudinal ventilation circumstance in a sloping tunnel.

In addition, fan-induced pressure rise is a significant factor to the final steady state of contaminants flow. If the magnitude of fan-induced pressure rise is smaller than that of stack effect, only the buoyancy-dominated flow pattern is achieved (see Figure 5(a), in which point 1 disappears). If the fan-induced pressure rise is large enough to surpass the stack effect, only the fan-dominated flow pattern exists (see Figure 5(c), in which point 3 disappears). However, if there is slight difference between the magnitude of fan-induced pressure rise and stack effect, the multiple flow solutions occur even under identical boundary condition (see Figure 5(b)), which results in a great challenge to contaminants control.

4. Conclusion

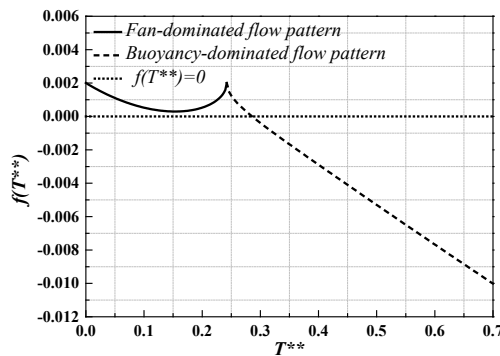
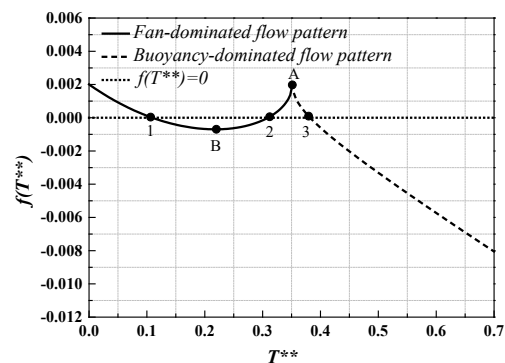
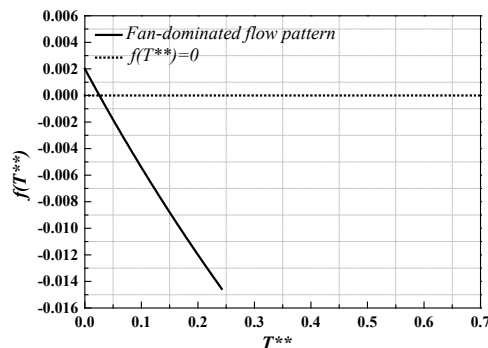
In this study, the dynamic mechanism of the gaseous contaminant flow in a sloping tunnel was investigated. The results may be helpful to further explore the characteristics of contaminants flow in sloping tunnels. The following conclusions can be drawn:

1. In a naturally ventilated sloping tunnel, source reduced gravity, g'_0 and source location, $\Delta L \sin \theta$ have influence on the steady-state density distribution and mixing characteristics of contaminants flow. With the increase of source reduced gravity, the density distribution is more obvious. Moreover, the downstream flow of the source gradually transits from stratified two-way flow to well-mixed one-way flow as the source reduced gravity decreases. Additionally, when the distance between the buoyancy-driven source location and downstream portal of the tank increases, the steady-state density distribution becomes increasingly unapparent. Meanwhile, the results shown in Figure 3 indicate that stack effect is a driving force for the buoyancy-driven flow in a naturally ventilated sloping tunnel. Furthermore, the thermal pressure difference induced by the stack effect is dependant on the buoyancy source location.

2. The theoretical analysis was explored to explain the behavior of contaminants flow in a longitudinally ventilated sloping tunnel. As shown in Figure 5(b), there are three points locating on the position where the dT^{**}/dt equals to 0. Point 1 and point 3 are the final steady points of fan-dominated flow pattern and buoyancy-dominated flow pattern, respectively. Point 2 is physically unstable. Moreover, fan-induced pressure rise is a vital factor influencing final contaminants flow pattern. If the magnitude of fan-induced pressure rise is lesser than that of stack effect, the buoyancy-dominated flow pattern is achieved alone (see Figure 5(a), in which point 1 disappears). If the fan-induced pressure rise strongly surpasses the stack effect, the fan-dominated flow pattern exists alone (see Figure 5(c), in which point 3 disappears). However, if there is slight difference between the magnitude of fan-induced pressure rise and stack effect, multiple flow states may appear even under identical boundary condition (see Figure 5(b)) and more effective strategy is needed to satisfy ventilation requirements.

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(a) $P_j = 18 Pa$ (b) $P_j = 24 Pa$ (c) $P_j = 250 Pa$ **Figure 5.** The possible scenarios for the dynamic profiles of dT^{**}/dt vs. T^{**} under different P_j .

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