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Experimental study on mixing and stratification of buoyancy-driven flows produced by continuous buoyant source in narrow inclined tank

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ABSTRACT

In this study, a series of experiments are performed to investigate the mixing and stratification of buoyancy-driven flows in a narrow inclined tank. The buoyancy-driven flow is produced by continuously releasing dense brine into an inclined tank filled with fresh water. Two distinct mixing regimes are identified. In one of the regimes, fresh water enters the tank because of the negative pressure induced by the brine plume. In the other regime, the fresh water inflow is mainly caused by the stack effect. A light attenuation technique is used to measure the density stratification and distribution in the tank. The effects of the buoyant source volume flow rate, source buoyancy flux, and source location on the mixing and stratification are investigated. The results indicate that the mixing between the buoyant and ambient fluids is strengthened by the increase in the source volume flow rate and the height difference between the source location and the lower end of the tank. However, the current downstream of the source becomes more stratified as the source buoyancy flux increases. A dimensionless parameter, λ, is proposed to evaluate the overall mixing intensity in the tank. As λ increases, the flow changes from a bidirectional one to a unidirectional one. The evolution of reduced gravity along the longitudinal direction is also investigated. The results indicate that fresh water is entrained into the brine layer if the thickness of the brine layer is less than the tank height. Otherwise, the reduced gravity remains constant along the longitudinal direction of the tank.

1. Introduction

Buoyancy is one of the fundamental forces driving flows in many geophysical and environmental processes such as buoyancy-driven natural ventilation [1–3], gravity currents [4,5], and thermal smoke propagation [6,7]. Therefore, it is necessary to explore the characteristics of buoyancy-driven flows for gaining a better understanding of many industrial and natural phenomena.

The interaction between the buoyant flow and the ambient fluid is very complicated. Vertical plumes and gravity currents are the two most common types of buoyancy-driven flows. Turbulent mixing involved in vertical plumes was initially modeled by Morton et al. [8]. They assumed that the rate of entrainment was proportional to the characteristic velocity of the buoyant fluid. The plume theory has been widely used to estimate the ventilation flow rate in the natural ventilation of buildings [9–13]. In addition, the classical plume model proposed by Morton et al. can be applied to describe the motion of a plume in uniform environments. Caulfield and Woods [14] developed a model to illustrate the behavior of a turbulent plume in an environment with non-uniform density stratification.

In contrast to vertical plumes, gravity currents are primarily gravitational flows driven by horizontal density differences. A typical gravity current consists of two parts: the frontal wavelike region called the head and the following stratified current called the tail. Many studies have demonstrated that a considerable mass of ambient fluid is entrained into a current, especially through the head [15–19]. Moreover, mixing occurs at the rearward side of the head because of Kelvin–Helmholtz instability. Using a pH indicator and an acid, Hallworth et al. [17] observed three different flow regimes in the evolution process of the lock-release gravity current. In the first regime, the head of the current progressed at a constant speed. In the following regime, the flow was dominated by both buoyancy and inertia, and the velocity of the head was proportional to $t^{-1/3}$, where t represents the time. As the flow continued, the Reynolds number declined significantly, and therefore, viscous force dominated the flow in the third regime. As the brine mixed with the ambient fluid, the internal structure of the gravity

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current changed gradually. Hacker et al. [18] found that the tail of a lock-release current was stratified in the first regime, and then, the stratification extended to the head in later regimes. Recently, using a light attenuation technique, Sher and Woods [19] confirmed that mixing mainly occurred at the head of a lock-release gravity current. However, for a continuous gravity current, mixing occurs not only at the head of the current but also in a region near the buoyant source [20]. In a word, the mixing between the buoyant fluid and the ambient fluid depends on the local density and velocity gradients in the flow [21].

Thermal gas propagation in a tunnel can be considered as a combination of a vertical plume and a continuous gravity current. Buoyant gases move upward from the source as a vertical plume. After the rising plume is deflected by the tunnel ceiling, the gas propagates along the tunnel ceiling as a gravity current. The stratification of the hot gas layer directly affects the safety of the passengers and rescuers in the tunnel. Therefore, some studies have been conducted on smoke stratification in horizontal tunnels [22–25]. However, for a gravity current moving downhill, the extra weight of the current contributes to the driving force. Chow et al. [26] studied the smoke movement in an inclined tunnel under natural ventilation. Their results indicated that the gas temperature in inclined tunnels decayed at different rates on the two sides of the heat source. This observation was very different from that in horizontal tunnels. Britter and Linden [27] studied the motion of a continuous gravity current moving down an inclined surface. They found that the velocity of the head was proportional to 1/3rd of the power of the buoyancy flux and was independent of time. However, the velocity of the head of a horizontal gravity current decreased with time in the later regimes. Therefore, the dynamics of an inclined gravity current can be different from that of a horizontal gravity current. Previous experimental results for hot gas stratification in horizontal tunnels cannot be directly extended to that in inclined tunnels. Considering that the number of inclined tunnels being constructed in recent years is steadily increasing [26,28,29], it is necessary to further explore the characteristics of buoyancy-driven flows in inclined tunnels.

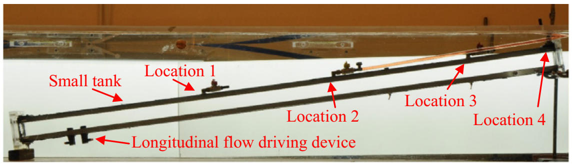
According to the above literature review, even though mixing in buoyancy-driven flows has been widely studied, little effort has been made to investigate the buoyancy-driven flow in a confined inclined tank. As demonstrated by previous studies [26,30], buoyancy-driven flow in a confined inclined tank is affected by the stack effect. Two contributing factors affect the magnitude of the stack effect: the density difference between the working fluid and the ambient fluid, and the net height in the region occupied by the working fluid. The height difference between the portals of the inclined configuration could be sufficiently large in real building configurations. However, the height difference between the two portals of a small-scale inclined tank is limited. Because air density is relatively low, it is difficult to create an obvious stack effect in a small-scale air system. Water density is considerably higher than air density, and thus, the larger density differences between the source brine and the ambient fresh water can create an obvious stack effect in a small-scale experimental platform. In addition, when air is employed as the working fluid, thermocouples are normally used to measure the local temperatures in the tank. Here, it is difficult to obtain the distribution of reduced gravity in the entire tank without interfering with the fluid fields of the measured spaces. The reduced gravity distribution in the water tank can be measured using a light attenuation technique, in which the fluid field is not disturbed by the measurements. Therefore, a brine–water system rather than an air system is chosen as the experimental platform in the present study. This paper is arranged as follows. In Section 2, the experimental setup is briefly introduced and experimental conditions are listed. Section 3 presents the experimental results and their discussion. In Section 3.1, some qualitative results are presented to show different mixing regimes in inclined tank configurations. In Section 3.2, the distributions of reduced gravity are shown to reflect the effects of the source volume flow rate, source buoyancy flux, and source location on the flow stratification. In addition, the longitudinal evolution of the reduced gravity is discussed. In Section 3.3, a non-dimensional parameter is proposed to evaluate the overall mixing in the tank and is used to explain the phenomena observed in the experiments. Conclusions are drawn in Section 4.

2. Experiments

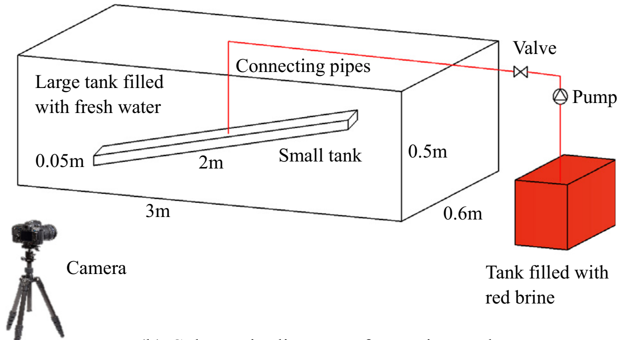
The brine–water experimental technique is widely used to study buoyancy-driven flows [1,15–21,30,31]. Our experiments were performed in a small tank whose dimensions were 2 (length) × 0.05 (width) × 0.05 (height) m. Fig. 1 shows the experimental setup. There were four source locations at the ceiling of the tank, and brine was introduced into the tank from one of the source locations. The longitudinal distance from Location 1, Location 2, Location 3, and Location 4 to the lower end of the tank, ΔL, was 0.7, 1.2, 1.7, and 2 m, respectively. The small tank was immersed in a big tank filled with fresh water. The dimensions of the big tank were 3 (length) × 0.6 (width) × 0.5 (height) m. Both the ends of the small tank were open to ensure that the fluids could enter or leave the small tank freely. A longitudinal flow driving device could have been used to generate forced longitudinal flow within the small tank. However, in the present study, because we aimed to investigate the buoyancy-driven flow under natural conditions, the mechanical driving device was not activated during any of the experiments. A light sheet was placed behind the big tank to provide uniform light for light attenuation measurements. Both the small and big tanks were made of Perspex, and therefore, light could pass through the tank walls. In Exp. 1 to Exp. 25, the tilted angle of the small tank, θ, was 7.9°. In Exp. 26 to Exp. 30, θ was 5.4°.

The source volume flow rate, source buoyancy flux, and source location are three critical parameters influencing the flow in the narrow inclined tank.

$$B_0 = g_0' Q_0 \tag{1}$$



(a) Photograph of experimental setup



(b) Schematic diagram of experimental setup

Fig. 1. Experimental setup.