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Performance evaluation of different air distribution systems for removal of concentrated emission contaminants by using vortex flow ventilation system

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ABSTRACT

An excellent air distribution system is a key factor to maintain indoor air quality, particularly in high-concentration contaminant-released buildings such as industrial halls. This study evaluated the performance of a new type of air distribution system, the vortex flow system, for contaminant removal and compared it with three other commonly used air distribution systems. The airflow fields and distribution of contaminants in large-space buildings with concentrated contaminant sources were studied. In addition, the mean age of air (MAA), air change efficiency, ventilation effectiveness, and mean residence time (MRT) of the contaminants were used to evaluate the four air distribution systems. The results of this study illustrated the significance of the air distribution system on the ventilation performance. Owing to the flow characteristics of the column vortex, the contaminants released from the source in the vortex flow system were limited by the negative pressure gradient near the center of the vortex zone and rapidly moved upward along the vortex core, resulting in a higher ventilation efficiency of contaminant removal with a lower ventilation flow rate. The results demonstrated the application potential of the vortex flow system in large-space buildings with concentrated emission contaminants.

1. Introduction

The effective control of concentrated emission is a challenging issue for maintaining indoor air quality, particularly in industrial settings [1]. Compared with residential buildings, significant concentrated emissions are commonly generated during various processes such as hot metal melting, welding, electroplating, and paint spraying [2]. A contaminant usually consists of fine particulates and gases [3–5], which can be hazardous to human health and the indoor environment. To meet the increasingly stringent health and environmental regulations as well as reduce the capital investment and operating costs associated with ventilation systems, an in-depth understanding of the complex movements of the airflows within an indoor environment is needed. This information would also assist in optimizing the ventilation system performance.

The performance of a ventilation system largely depends on its air distribution system. Many research studies have proven that only increasing the ventilation rate without an appropriate air distribution system cannot effectively remove indoor pollutants [6,7]. Furthermore, an efficient air distribution system will not only improve indoor air quality but also effectively reduce the energy consumption. There are two approaches by which an efficient air distribution system reduces the energy consumption: (1) reduction in the airflow volume of the ventilation system and (2) decrease in the system operating time. The energy consumption of the fans, dust collector, and air-handling unit will also be reduced by lowering the ventilation airflow volume and system operating time. To improve the performance of a ventilation system, various types of air distribution systems have been developed for different room configurations and contaminant emission characteristics such as downside air supply [8,9], upside air supply [10,11], and lateral air supply [12,13] systems.

Generally, the principle of ventilation for contaminant removal includes two primary methods: dilution and displacement. However, these methods have some limitations with respect to contaminant removal. For the dilution method, first, it is hard to ensure dilution and mixing in a large-space building with economic ventilation rates [14], which leads to a poor energy efficiency. Second, a contaminant may diffuse widely in the room during the dilution process, leading to the contamination of clean areas [15]. Finally, according to the dilution method principle, the contaminant concentration near an exhaust opening is usually low, which implies that the ventilation effectiveness (VE) for contaminant removal is relatively poor [16]. There are also

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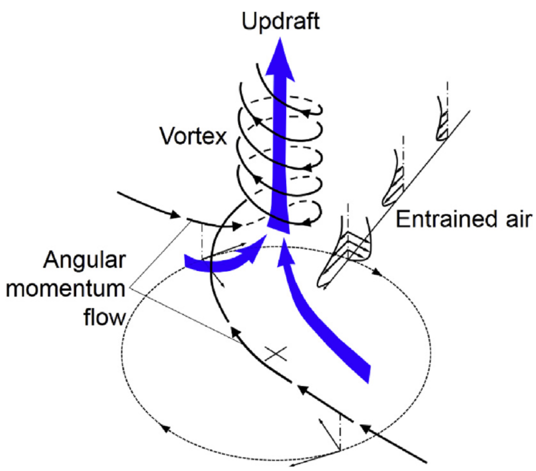

Fig. 1. Schematic of the column vortex flow.

deficiencies associated with using the displacement method. One limitation is that in large or complex indoor environments it is difficult to generate the ideal displacement effect because the clean supply air may be heated or polluted before filling the occupied zone [17–19]. Another drawback is the long response time for contaminant exhaust, which causes the exhausts to remain for a longer duration in the room [20–23]. Consequently, high-efficiency air distribution systems still need to be developed.

In this study, a new air distribution system, the vortex flow (VF) system, is evaluated. The VF system is a type of general ventilation flow system based on the column vortex principle. As shown in Fig. 1, a column VF is formed by combining the angular momentum supply airflow and updraft flow, which have been studied by both experimental [24–28] and numerical simulation methods [29–32]. The supply airflow converges near the ground and the nearby ambient air/contaminant will be entrained into vortex because of the formation of a column vortex. A column vortex-like tornado has a strong suction force and long control distance, which has tremendous potential for applications in ventilation. In recent years, preliminary studies have examined the VF for a local exhaust ventilation [33,34] and in a three-dimensional ventilated cavity [35]. However, the performance of the VF system for contaminant removal under actual room conditions has not been fully studied, which is more complicated and chanllenging due to the effects of room configurations, ventilated inlets design, supplied airflow patterns etc.

In this study, the performance of the VF system for the contaminant removal from large-space buildings with a concentrated contaminant source was numerically evaluated and compared with three commonly used air distribution systems: the downside supply–upside exhaust (DU), upside supply–downside exhaust (UD), and lateral supply–lateral exhaust (LL) systems. The airflow fields and distribution of different contaminants were studied. Furthermore, the mean age of air (MAA), air change efficiency (ACE), VE, and mean residence time (MRT) of the contaminants were used as indices to evaluate the performance of the different air distribution systems.

2. Computational Fluid Dynamics method

2.1. Geometric model and grid generation

The geometries of the four air distribution systems with different configurations of the inlet and outlet ports are shown in Fig. 2. All the cases are set in a same size room with dimensions of 20 m (*L*) × 10 m (*W*) × 6 m (*H*). A contaminant source of 2 m (*L*) × 2 m (*W*) × 0.6 m (*H*) is located near one side of the room to make the room asymmetrical on the long side, which is more universal for the actual room conditions. As illustrated in Fig. 2, the VF, DU, and UD systems comprise the total inlet area, and the direction of the two supply airflows in the VF system (① and ③) are at 30° to the wall to provide the angular momentum supply airflow in the same direction. The details of the configurations of the inlet/outlet ports are listed in Table 1.

In this study, the computational grid is generated using pre-processor Gambit 2.4.6 with the maximum number of 1,197,600 cells and maximum stretching ratio of 1.2 in the four air distribution systems.

2.2. Governing equations

A commercial computational fluid dynamics (CFD) software (ANSYS FLUENT) [36] is used to compute the airflow inside the room. In the current study, the airflow is assumed to be unsteady and incompressible with constant temperature (300 K). The contaminant

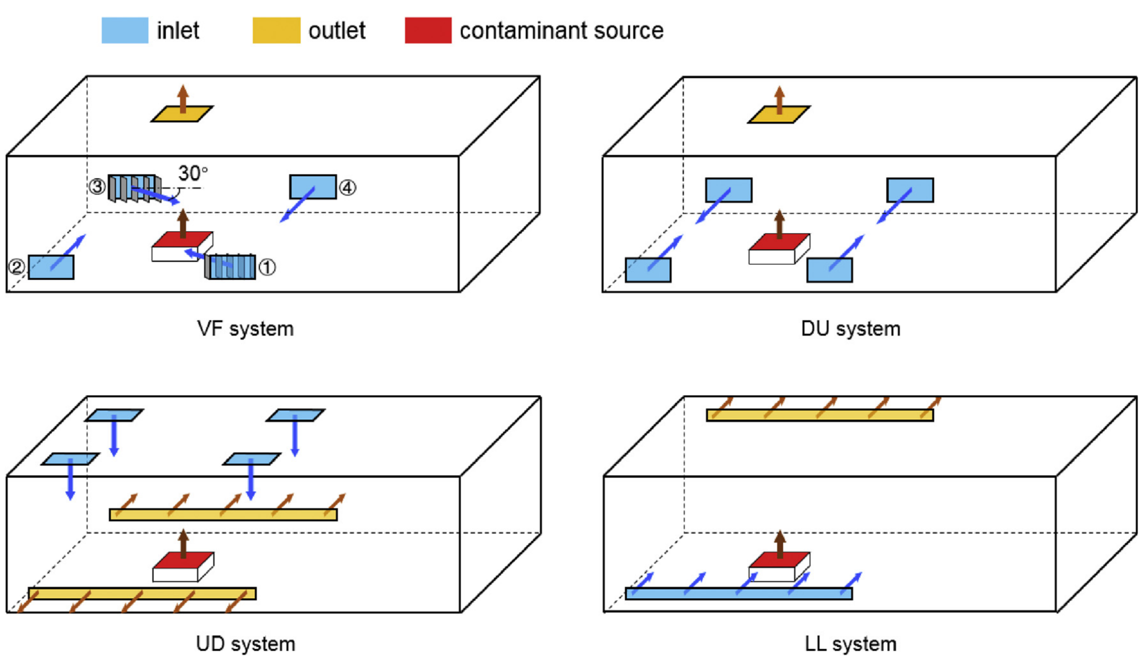

Fig. 2. Schematics of the four air distribution systems.