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CFD study on effect of the air supply location on the performance of the displacement ventilation system

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Abstract

The purpose of this paper is to investigate using a numerical simulation (computational fluid dynamics or CFD) the effect of the air supply location on the design and performance of the displacement ventilation (DV) system. The results are reported in terms of thermal comfort and indoor air quality. The study focuses on the typical Hong Kong office under local thermal and boundary conditions. This includes the high cooling load used in Hong Kong. Several pollutants typically found in the office such as carbon dioxide and volatile organic compounds (VOCs) were investigated. The results indicate that the supply should be located near the center of the room rather than to one side of the room. This will provide a more uniform thermal condition in the office. The DV system was found to be effective in dispersing VOCs within an office environment for all cases studied. The exhaust was found to have minimal effect on the thermal comfort. For a DV system in Hong Kong, it is possible to use 100% fresh air without extra energy consumption.

Keywords: Displacement ventilation; Thermal comfort; Indoor air quality; Air velocity; Temperature; Percentage of dissatisfied people; Predicted percentage of dissatisfied; Toluene; Benzene; Formaldehyde; Mean age of air; Carbon dioxide; Air supply and exhaust locations

1. Introduction

In today's indoor environment, it is increasingly difficult for conventional centralized heating, ventilating, and air conditioning (HVAC) systems to satisfy the environmental preferences of individual occupants. In Hong Kong, the situation is further complicated by the recent influx of heat generating devices and round the year cooling.

In recent years there has been a growing awareness amongst private firms and government organizations of the importance of the comfort, health, and productivity of individuals, giving rise to an increased demand for a high-quality indoor environment. There has also been an increase in the number of communication cables and wires in offices and workplaces [1]. To respond to these needs, an air-conditioning system must have greater flexibility, better thermal comfort and IAQ, and greater energy savings.

In the past two decades a new type of ventilation system, as an alternative to conventional mixing ventilation, has gained increasing popularity. The displacement ventilation (DV) was first proposed and implemented in the Scandinavian countries about 25 years ago [2]. In 1989 in Nordic countries, it was estimated that DV accounted for a 50% market share of industrial applications and 25% of office applications. The application of a floor-supply DV system in Hong Kong started in the 1980s [3]. However, only a few applications of DV can be found in Hong Kong.

A comprehensive study on the DV system was carried out by a research team in the United States [4–6]. A set of guidelines for designing DV in the United States was also developed [7]. However, direct application of the aforementioned results for Hong Kong design may not

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Nomenclature

A	floor surface area (m^2)
c_e	contaminant concentration at the exhaust air (ppm)
c_s	contaminant concentration at the supply air (ppm)
c	contaminant concentration in the room air (ppm)
f_{cl}	cloth factor (clo)
g	gravitational acceleration rate (m/s)
h	height from the floor (m)
h_c	convective heat transfer coefficient between the cloth and air ($W/m^2 K$)
I_{cl}	clothing insulation ($^\circ C\,m^2/W$)
K	turbulent kinetic energy
L_0	length scale of diffuser outlet equal to hydraulic diameter of outlet (m)
M	metabolism (W/m^2)
P_a	partial water vapor pressure (Pa)
Q_l	heat generated by lighting (kW)
Q_t	total cooling load in the room (kW)
Q_{ex}	heat from exterior walls and windows and transmitted solar radiation (kW)
Q_{oe}	heat generated by occupant, desk lamps, and equipment (kW)
t_0	initial temperature of jet (°C)
t_s	temperature of surrounding air (°C)
T	local air temperature (°C)
T_{cl}	cloth temperature (°C)
T_r	mean radiant temperature (°C)
T_s	room air temperature (K)
Tu	turbulent intensity
u	air velocity (m/s)
V_0	initial air velocity of jet (m/s)
W	external work (W/m^2)
η	ventilation efficiency
ρ	density (kg/m^3)
τ	mean age of air (s)

be feasible because the cooling loads of Hong Kong buildings are higher than those of US buildings, and much higher than those of Scandinavian buildings. Congested land use also results in building layouts different from those in the other places. This paper evaluates the performance of DV systems on the aspect of thermal comfort for offices under Hong Kong thermal and flow boundary conditions such as a very high cooling load.

There are many factors that affect the design and performance of ventilation systems. These include the size and type of building, the air supply velocity and temperature, and the location of the air supplies. In this paper, the investigation looks into the location of the air supply.

Several researchers have looked into the effects of supply location and its impact on thermal comfort. The DV system has long been associated with draft as a result of the close proximity of the supply to the occupants. Both Bauman et al. and Shute stated that occupants should be at least 1–1.5 m away from the supply grilles [8,9]. Loudermilk stated that no occupant should be located within a radius of the diffuser where the air velocities are in excess of 0.25 m/s and the temperatures are more than 0.6 °C lower than the room temperature [10]. The location of the supply in the ceiling was found to lead to poor circulation at the desk in partitioned areas [11].

Gan used computational fluid dynamics (CFD) to investigate local thermal discomfort in an office room [12]. The thermal comfort level and draft risk were predicted using Fanger's comfort equations in the airflow model [13]. He showed that thermal discomfort could be avoided through the optimization of the supply air velocity and temperature. He also showed that optimal supply air conditions depend on the distance between the occupant and the air diffuser.

Wyon and Sandberg [14] performed a series of experiments on the thermal comfort of the DV system using a manikin. They found that the thermal comfort was better above table height and thermal discomfort was mostly observed at the legs and ankles.

Lian investigated the upward DV system to determine the effect of the type of outlet, distance between the occupant and outlet, velocity and temperature of supply air, and the type of outlet [15]. The results show that the main influence on the thermal comfort was the distance between the occupant and the supply.

The recent literature on indoor air pollution indicates that carbon dioxide (CO_2) is a major pollutant. To assess the IAQ of an office building, Cheong monitored a number of indoor pollutants including CO_2 [16]. Fleming in his investigations measured radon, nitrogen dioxide (NO_2), formaldehyde, suspended particles, and carbon monoxide (CO) [17]. Persily pointed out that the indoor concentrations of CO_2 can be useful for understanding IAQ and ventilation [18].

A report by the European committee for standardization (CEN) outlines the dangers to health as a result of exposure to certain types of volatile organic compounds (VOCs) in indoor environments [19]. The report also gives numerical recommendations to reduce human exposure to harmful levels of air pollutants. These involve specifying design ventilation rates for different types of buildings. The pollutant emissions include total volatile organic compounds (TVOCs) such as toluene, xylene, formaldehyde, and ammonia (NH_3). The report