System Performance Evaluation and Design Guidelines for Displacement Ventilation

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Qingyan Chen

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Preface

This book presents system performance evaluation and design guidelines for displacement ventilation.

The authors first reviewed the literature concerning the performance of traditional displacement ventilation. Since U.S. buildings have different layouts and larger internal heat gains than those studied in the literature, it was necessary to develop design guidelines for displacement ventilation for U.S. buildings under different climatic conditions.

The design guidelines present two important models that were not available in the literature: a model to calculate the temperature difference between the head and foot level of an occupant and a model to determine the ventilation effectiveness at the breathing level. The investigation developed the models from the results of 56 cases of displacement ventilation obtained by a computational fluid dynamics (CFD) program. Those cases include a wide range of thermal and flow conditions similar to those found in U.S. offices, classrooms, and workshops. The CFD program was validated by six sets of detailed experimental data obtained from a full-scale environmental chamber simulating a small office, a quarter of a large office with partition, and a quarter of a classroom. The data include airflow patterns and distribution of air velocity, temperature, contaminant concentration, and turbulence. The validation also used some data obtained from the literature. The CFD program was also used to assess the performance of displacement ventilation, such as airflow pattern and distributions of air temperature, percentage dissatisfied due to draft, predicted percentage dissatisfied, contaminant concentration, mean age of air, and ventilation effectiveness. The investigation also conducted energy and first costs analysis.

The results show that a displacement ventilation system can provide a thermally comfortable indoor environment at a high cooling load through careful design. The indoor air quality in a space with displacement ventilation is better if the contaminant sources are associated with the heat sources. The displacement ventilation system can also save energy but requires a separate heating system if it is applied to building perimeter zones. This book presents a ten-step design guideline to design the displacement ventilation system for U.S. buildings.

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CHAPTER 1

Introduction

Since the energy crisis in the 1970s, the insulation of buildings has been improved in order to reduce heat loss in winter, heat gain in summer, and the infiltration of outdoor air. As a consequence, the heat extracted from or supplied to a room for maintaining a comfortable air temperature is reduced and the ventilation rate is also reduced by a corresponding amount, sometimes much more if the building envelope is made tighter. However, such a reduction of air supply causes an increase in the concentration of indoor pollutants and sometimes generates a nonuniform distribution of air temperature and contaminant concentration. Draft (thermal comfort problems) and "sick building" syndrome (indoor air quality problems) are very familiar ailments today that are the direct results of the poor distribution of airflow, temperature, and contaminant concentrations. Solving these thermal comfort and indoor air quality (IAQ) problems without consuming too much energy is a challenge for both ventilation engineers and architects.

Currently, the United States consumes more than one-third of its energy in buildings, and there is a possibility of saving up to 20% of this energy. Saving energy may result in the reduction of the fresh air supply. This may cause poorer IAQ. Since people spend up to 90% of their time indoors, IAQ is increasingly recognized as an essential factor for the prevention of human diseases and the promotion of people's comfort and welfare. In the United States, about 800,000 to 1,200,000 commercial buildings with 30 to 70 million people have problems related to IAQ (Woods 1989). The problems include eye, nose, and throat irritation, headache, recurrent fatigue, drowsiness or dizziness, and reduced powers of concentration (Spengler 1995). Dissatisfaction with the working environment could result in reduced productivity and economic loss. A survey conducted in the New England area of 94 state government office buildings showed an average productivity loss of 3%, which is attributed to poor IAQ (Axelrad 1989). Fisk (2000) estimated that the economic impact related to respiratory illness, allergies and asthma, and sick building syndrome is $20 to $200 billion. Therefore, it is necessary to provide a good ventilation system that can provide good IAQ and save energy.

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1.1 DISPLACEMENT VENTILATION

Displacement ventilation has been used quite commonly in Scandinavia during the past twenty years. It was first applied to the welding industry in 1978 (Belin 1978) and has since been increasingly used as a means of ventilation in industrial facilities to provide good indoor air quality and save energy. More recently, its use has been extended to ventilation in offices and other commercial spaces where, in addition to air quality, comfort is an important consideration. In 1989 in Nordic countries, it was estimated that displacement ventilation accounted for a 50% market share in industrial applications and 25% in office applications (Svensson 1989).

Displacement ventilation system can be divided into the following three types:

- Traditional displacement ventilation, as shown in Figure 1.1
- Displacement ventilation with a chilled ceiling panel
- Displacement ventilation with a raised floor

This book focuses on the first type: traditional displacement ventilation.

A typical displacement ventilation system for cooling, as shown in Figure 1.1, supplies conditioned air from a low sidewall diffuser. The supply air temperature is slightly lower than the desired room air temperature, and the supply air velocity is low (lower than 100 fpm or 0.5 m/s). Through the diffuser, the conditioned air is directly introduced to the occupied zone, where the occupants stay. Exhausts are located at or close to the ceiling through which the warm room air is exhausted from the room. Because it is cooler than the room air, the supply air is spread over the floor and then rises as it is heated by the heat sources in the occupied zone. These heat

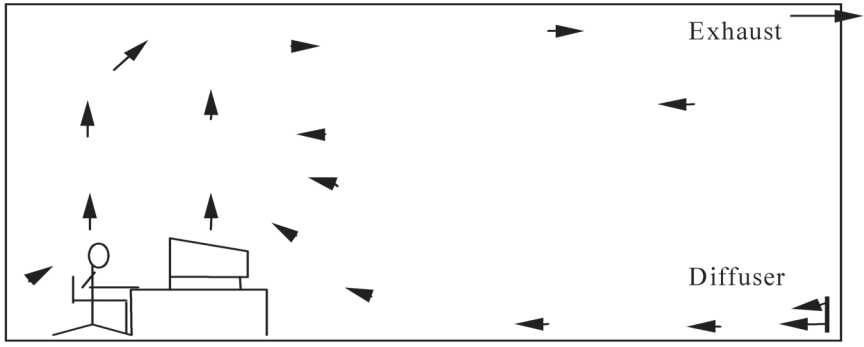


Figure 1.1 Sketch of displacement ventilation.

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sources (e.g., persons and computers) create upward convective flows in the form of thermal plumes. These plumes remove heat and contaminants that are less dense than air from the surrounding occupied zone.

Traditionally, the amount of supply air in a displacement ventilation system has been less than that of mixing-type systems. This necessitates careful design of the system configuration and operation to adequately handle the space cooling loads. The supply temperature, velocity, and vertical temperature gradient in the occupied zone are all very important comfort-related design parameters. Compliance with the specification of ASHRAE Standard 55-1992 (ASHRAE 1992) for acceptable vertical temperature difference in the occupied zone places limitations on the magnitude of supply-room temperature difference and/or space cooling loads for a given supply airflow rate. This is especially important when the system is applied to a U.S. building in which the cooling load can be high and weather can be hot.

Previous research (Svensson 1989; Sandberg and Blomqvist 1989; Wyon and Sandberg 1990) has indicated that in office environments with normal room heights of around 9 ft (2.7 m), displacement ventilation cannot maintain acceptable comfort for cooling loads above 8 to 10 Btu/(h·ft^2) (25 to 30 W/m^2) unless the air supply volume is increased or additional heat removal capacity is provided through the use of cooled ceiling panels. With higher ceiling heights, displacement ventilation systems are capable of removing larger heat loads.

A stable, vertically stratified temperature field is essential for this type of system to function properly. Numerous studies show that, when properly designed, displacement ventilation can take advantage of the naturally occurring thermal stratification in the room and, thus, can increase the ventilation efficiency.

1.2 SPECIAL FEATURES IN U.S. BUILDINGS

Research on displacement ventilation has been mainly conducted in Scandinavian countries. Recently, REHVA (2002) published a guidebook on designing displacement ventilation in non-industrial premises. Many U.S. cities have higher temperatures in summer than those in Scandinavian cities, and U.S. offices may have more lighting and equipment that produces more heat. Therefore, the cooling load could be higher in the U.S. than in Scandinavian countries (Chen et al. 1999). In many U.S. offices, there are large core spaces that are completely isolated from the external climate. Cooling is always needed in the core spaces, and there is great potential for the use of displacement ventilation in such spaces.

On the other hand, heating and cooling are required in the perimeter spaces. In Scandinavian countries, a radiator is often used to offset heating load in winter and fresh air is supplied by the displacement ventilation system. This implies that the supply air temperature in winter can still be somewhat lower than the room air temperature, and a stratified flow can be maintained. However, in many U.S. office buildings, air-conditioning systems are often used for both heating and cooling and there is no radiator available. If a displacement ventilation system is used in the

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perimeter spaces, a separate heating system is needed to maintain the flow pattern. Convectors, baseboard heaters, radiant panels, or resistance wires can be used. However, the first costs and operating costs with two systems would be different. Displacement diffusers can be used for heating as well, but the airflow pattern will be of the mixing type.

In addition, many U.S. offices and restaurants are large spaces with many partitions to form individual work stations or dinning areas, while most European offices and restaurants are small spaces. Therefore, direct application of the Scandinavian results for U.S. design is not feasible.

1.3 OBJECTIVE OF THIS BOOK

Displacement ventilation may improve indoor air quality and has the potential to save energy. However, the performance of displacement ventilation is still not totally understandable, and the special features of U.S. buildings have not been considered in previous research. The objective of this book is to answer the following two questions:

- Is displacement ventilation suitable for U.S. buildings?
- How should displacement ventilation systems be designed?

To evaluate whether a ventilation system is suitable for U.S. buildings, we need to consider, simultaneously, its impact on indoor air quality, comfort, energy consumption, and costs. In order to design such a ventilation system, it is necessary to provide a design guide. This book tries to answer the above questions by providing the following information for displacement ventilation systems:

1. Literature review to identify the existing results and problems
2. Experimental study to get reliable data, including the distribution of velocity, turbulence intensity, temperature, tracer-gas concentration, etc.
3. Validation of a computational fluid dynamics (CFD) program by the experimental data to determine the accuracy of the program
4. Numerical simulation of a large number of cases by the CFD program to establish a database on the performance of displacement ventilation
5. Model development to develop models needed for design guidelines
6. Energy and cost analysis to assess the impact of energy and first costs
7. Guidelines to help designers in the U.S. to design displacement ventilation

Chapter 2 of this book presents a state-of-the-art review on displacement ventilation. Chapter 3 describes the experimental study in a full-size test room simulating a small office, a large office with partitions, and a classroom. The experimental results are used to validate a CFD program. Chapter 4 describes a database of displacement ventilation by CFD computations of numerous cases for different thermal and flow conditions for different types of U.S. buildings. Based on the computed

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results, two models are developed for prediction of the air temperature difference between head and foot level and the ventilation effectiveness at head level. Chapter 4 also introduces a simplified CFD program for calculating indoor airflow. Chapter 5 discusses the performance of displacement ventilation. Chapter 6 describes energy and cost analysis. Chapter 7 outlines a ten-step design guideline for displacement ventilation. Chapter 8 offers important conclusions about displacement ventilation.