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Simplified Models For Particle Dispersion In Buildings

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SIMPLIFIED MODELS FOR PARTICLE DISPERSION IN BUILDINGS

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Preface

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Simplified Models of Dispersion in Buildings is the interim report for the Simplified Models of Dispersion in Buildings project (contract number XXX-XX-XXX, work authorization number [insert #] or grant number [insert #]) conducted by the University of California San Diego. The information from this project contributes to PIER's [insert RD&D program area from bulleted list above] Program.

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Abstract

Many modern low-energy ventilation schemes, such as displacement or natural ventilation, require the use of temperature stratification in a space. The ability to extract air at elevated temperatures is necessary for energy-efficiency and free cooling. The adoption of these energy-efficient ventilation systems still requires that they provide an acceptable level of indoor air quality and comfort. It is widely believed, although not comprehensively studied and validated, that such low energy ventilation systems will be more effective at removing contaminants. In this work, the focus is on the transport of passive and particulate contaminants in a displacement-ventilated space. By representing heat sources as ideal sources of buoyancy, simple analytical models have been developed that allow us to compare the average efficiency of contaminant removal between traditional and modern low-energy systems. These models are then extended and solved numerically to study and compare the spatial distribution of contaminants within the space of interest. In order to validate the models, small and large scale laboratory experiments were conducted. The results of the models and the experiments are ultimately extended to understand the fate of particulate contaminants, which suffer the additional effect of gravitational settling.

Keywords: **Contaminants, Low Energy Ventilation, Experiments, Analytical, Particles**

Nomencalture

Symbol	Meaning
A_d	Area of downward facing walls
A_u	Area of upward facing walls
A_v	Area of vertical walls
A_v^l	Area of vertical walls in lower layer
A_v^u	Area of vertical walls in upper layer
F	Buoyancy flux in the plume
F_o	Source buoyancy flux of the plume
h	Height of interface
H	Height of Room
K	Concentration of contaminant in room outside plume
K_{in}	Concentration of contaminant entering room
K_l	Concentration in lower layer of two-layer system
K_{ref}	A reference concentration
K_u	Concentration in upper layer of two-layer system
K_{wm}	Concentration in well-mixed space
M	Momentum flux in plume
P	Concentration of contaminant in plume
Q	Volume flux rate in Plume
Q_{df}	Deposition Volume flux from upper to lower layer
Q_{dl}	Deposition Volume flux in lower layer
Q_{dr}	Deposition Volume flux from lower to upper layer
Q_{du}	Deposition Volume flux in upper layer
Q_{dw}	Deposition Volume flux in a well mixed space
Q_{in}	Flow rate into the Room
Q_f	Settling flow rate of particles
Q_p	Flow rate of plume at interface height
S	Cross Sectional Area of Room
t	Time
y_{old}	Vertical location of Geremeles interface before advection
y_{new}	Vertical location of Geremeles interface after advection
v_f	Stokes settling velocity of a particle
v_d	Deposition velocity on to downward facing walls
v_u	Deposition velocity on to upward facing walls
v_v	Deposition velocity on to vertical walls
w	Background velocity field
w_c	Contaminant velocity field
z	Vertical spatial coordinate

Greek Symbols

α	Dimensionless settling rate
α_{df}	Deposition Volume flux from upper to lower layer
α_{dl}	Deposition Volume flux in lower layer
α_{dr}	Deposition Volume flux from lower to upper layer
α_{du}	Deposition Volume flux in upper layer
α_{dw}	Deposition Volume flux in a well mixed space
ε	Plume entrainment constant
κ	Dimensionless concentrations
ρ	Density
τ	Dimensionless time
ζ	Dimensionless interface height

Executive Summary

Introduction

The adoption of energy-efficient ventilation systems requires that they also provide an acceptable level of indoor air quality (IAQ) and comfort. In order to reduce energy consumption, various low-energy systems such as displacement ventilation, both natural and mechanical, underfloor air distribution, operable windows, night cooling, and radiant and evaporative cooling are under consideration. Underlying all these systems is the idea that free cooling is possible. That is, under certain conditions, outside air is used to cool the building and reduce the load. The introduction of outside air, either through filters or simply by opening a window introduces outside pollutants. Additionally, internal pollutants are generated and need to be extracted from the building.

The success of these alternative ventilation strategies depends on the ability to predict the internal environment and to assess the IAQ and comfort, as well as determining the potential energy savings. The purpose of this project is to expand the capabilities to model particulate distributions and transport within energy-efficient buildings, so that designers and engineers can have confidence that the buildings will perform appropriately. The goal is to conduct research that will provide the underpinning of a model that can be used for design guidance, and that will increase confidence in the use of these ventilation strategies in California.

Purpose

The goal of this project is to study the effectiveness of low-energy ventilation strategies for providing comfortable indoor environment conditions, with a particular emphasis on the dispersion of particulate contaminants. Currently, buildings consume 40% of global energy and are responsible for close to 50% of the global anthropogenic CO_2 production. A significant fraction of this energy is used by ventilation. Therefore, development of low-energy ventilation strategies is critical in minimizing the amount of global energy consumption.

At the same time, there is concern that these lower energy systems may not be as effective at providing healthy and acceptable levels of indoor air quality. Recent studies have shown that people spend substantial amounts of time indoors, in many cases close to 90% of the time. For this reason, it is very important to understand the details of the indoor environment, in particular regarding indoor air quality, human comfort, health, and energy consumption. The focus of this project was to study low-energy ventilation strategies in order to determine their effectiveness at reducing energy consumption while still providing healthy indoor conditions. The information gained from this study can then be used to promote and develop future ventilation strategies that maximize indoor environment quality and minimize electricity consumption.

Project Objectives

The overall goal of this project was to develop understanding of IAQ issues in unmixed spaces in buildings. This will ultimately lead to improved IAQ in energy-efficient buildings and increased confidence in the performance of these buildings. Further, this understanding will lead eventually to improved tools that will enable designers and engineers to adopt low-energy alternatives to conventional heating, ventilation, and air conditioning (HVAC) systems in buildings, with consequent energy savings for California.

The specific objectives of this study were the following:

1. To study the dispersion of particulates in a space with thermal stratification, using laboratory experiments and a numerical model.

2. To conduct full-scale experiments of particulate dispersion in a room to compare with the numerical model.

3. To develop a simplified model, based on plume theory, that will provide a basis for the development of a design tool.

Project Outcomes

1. A validated model to predict contaminant distribution in a space with a heat source and temperature stratification for passive and particulate contaminants.

2. Data sets from small-scale experiments of the dispersion of a gaseous (passive scalar) and
settling particles.

3. Data sets from full-scale room experiments.

4. A simplified model that can be used as a basis for design guidance.

Conclusions

1. Caution must be taken when choosing the optimum ventilation strategies. Depending on the size of contaminants and the location of the sources, certain low-energy systems can outperform traditional systems in removing contaminants. However, there are also many scenarios where the traditional system exposes occupants to lower levels.

2. Studying only the average amount of contaminant in a space can be very misleading as displacement ventilation can lead to non-trivial vertical gradients in the contaminant field. Thus, while the average concentration in a space may be below acceptable standards, specific locations may be well above these standards and thus expose occupants to undesirable levels of contaminants.

3. Low-energy ventilation systems can expose occupants to higher levels of contaminants, because the contaminant transport mechanisms do not exploit the same features that are used for heat removal. The energy efficiency of many low energy systems comes from the extraction of the warmest air. However, there is no physical reason why the location of the warmest air must coincide with the highest levels of contaminant.

Recommendations

Displacement ventilation systems are very promising from an energy perspective and should be adopted for this reason. However, one must carefully consider the purpose of the room being ventilated as well as the typical contaminant types and size distributions that may exist in this room. For example, if the primary source of contamination comes from the occupants in the space, then displacement systems minimize exposure compared to traditional mixing ventilation systems. However, if the source of contamination is external, then exposure is typically worse for the low-energy systems.

While this study sets some important groundwork for the study of passive and particulate contaminants in low-energy ventilation systems, it is by no means complete. There are many possible directions for future work, which are not restricted to, but include transient effects, further full-scale studies, case studies, extensions to other low-energy ventilation systems, further physics, health effects studies, uncertainty analysis, and socio-economic studies.

Benefits to California

In California, a large portion of all electricity generated is used in the heating, cooling and ventilation of domestic, commercial and industrial buildings, with a significant portion of this being consumed by expensive and energy inefficient air-conditioning systems. In fact, according to Senate Bill 1790, 2002 ***'Air-conditioning load constitutes 28 percent of California's peak electricity demand, the largest single component of electricity demand.'*** Therefore, the development of low-energy ventilation strategies is critical to minimizing the amount of electricity consumed in the state of California and dealing with periods of peak demand.

This study presents and studies two forms of low-energy ventilation that may aid in reducing this demand. These are natural ventilation, which could be implemented in regions of California with a more temperate climate (e.g., coastal areas), and displacement ventilation, which can be used in areas with very high summer temperatures (e.g., desert areas). The information gained from this study provides a basis for the efficient design of ventilation strategies that maximize indoor environment quality and minimize electricity consumption.

Additionally, California can benefit in the following manner:

1. This study can offer guidance to the California Indoor Air Quality Program run by the Department of Health Services.
2. The models can be used as an additional guideline for estimating the minimum required ventilation rate beyond standards such as ASHRAE 62-2001.
3. This study could be used to estimate values of the EPA's Excess Lifetime Cancer Risk (ELCR), which correlates exposure to certain contaminants to risk of developing cancer. Additionally, it could be combined with the NIH's Hazardous Substances Data Bank and the EPA's Integrated Risk Information System (IRIS).
4. The models presented here can act as an additional guideline for the assessment of California Labor Code 6300 on IAQ, which states that it is "the policy of the Division of Occupational Safety and Health to investigate all complaints or referrals alleging that workplace indoor air quality (IAQ) is injurious to the health of building occupant-employees, or a report of a fatality, serious injury or illness, or serious exposure involving workplace IAQ". Costs associated with employee health problems are estimated to be between $30-150 billion p.a.
5. The work presented here could be used to assess current California ventilation standards from an analytical perspective.
6. The models can be integrated with other studies such as the CBR (Chemical, Biological and Radiological Protection/Planning) at Lawrence Berkeley National Lab.
7. This study can be used to estimate the optimal location of contaminant sensors, so as to detect a contaminant as early as possible.
8. The approaches presented here can be used to estimate the viability of certain ventilation strategies for buildings that are very sensitive to contamination such as hospitals (e.g. by the California Hospital Association) or museums (e.g. by the California Association for Museums).

9. Agriculture is an important part of California's economy. Low-energy ventilation, typically natural ventilation, of life stock housings and greenhouses helps maintain low costs. However, many animals and plants produce large quantities of contaminants that can affect final product quality and reduce output. Therefore, the information from this study can be used to implement effective ventilation that can lower costs, while maintaining high air quality.

1.0 Introduction

We live in a world where “energy consumption defines the quality of urban life” (Santamouris (2005)). Developed countries consume massive amounts of energy while only accounting for a small fraction of the global population. According to the U.S. Department of Energy’s Energy Information Administration (http://www.eia.doe.gov/), the United States alone produces 25% of the world’s total anthropogenic CO_2 , while accounting for less than 5% of the world’s population. A major fraction of this is produced by modern buildings, which consume approximately 40% of the world’s energy and are responsible for 50% of global anthropogenic CO_2 emissions (U.S. Energy Information Administration statistics, e.g. Hawthorne 2003). A significant fraction of this energy is spent on the ventilation of buildings with summer time cooling accounting for almost 10% of the total energy budget of the U.S.

In order to reduce energy consumption, various low-energy systems such as displacement ventilation, natural and mechanical, underfloor air distribution, operable windows, night cooling, and radiant and evaporative cooling are under consideration (see Santamouris 2005 for a more detailed discussion). Underlying all these systems is the idea that free cooling is possible. Traditional ventilation, such as that provided by a conventional overhead HVAC system, is mixing ventilation, where incoming air is mixed with the air in the room and diluted. This typically results in a relatively uniform interior temperature distribution. In contrast, many modern low-energy ventilation schemes require the use of temperature stratification in a space, with a bottom layer of cooler comfortable air where occupants are located, and an upper layer that is comparatively warm and uncomfortable (Linden (1999)). The ability to extract air at elevated temperatures is necessary for energy efficiency. This can be achieved, for example, by displacement ventilation, underfloor air distribution or natural ventilation. Hence, stratification is an important feature in modern ventilation design. This is particularly true for tall spaces, where temperature differences can be quite significant.

People spend substantial amounts of time indoors, in many cases up to as much as 90 % (Jenkins et al. (1992)). Therefore, effective ventilation systems need to provide a thermally comfortable environment in an energy-efficient manner. It is also important to understand the details of the indoor environment regarding indoor air quality (IAQ). It is widely believed, although not comprehensively studied and validated, that such displacement ventilation systems will be more effective at removing contaminants since they will be transported to the hot upper layer, where they will be extracted (e.g. Nielsen 1993).

There are different types of airborne contaminants in buildings - gaseous and particulate. Gaseous contaminants are usually considered passive contaminants, because it is assumed that they follow exactly the dominant air currents in a space. Some of the more common gaseous contaminants that cause concern in buildings are carbon monoxide, carbon dioxide, nitrogen oxides, ozone, sulfur dioxide, moisture, formaldehyde, and radon gas and its progeny. Many of these contaminants are combustion byproducts; given the proliferation of transportation and industrial sources, there is increasing concern about the levels of these contaminants in outdoor air and, consequently, in indoor air. Many gas-phase contaminants have obvious adverse effects on a person's health, comfort and ability to work above threshold concentrations.

Particulate contaminants can be categorized as bioaerosols (such as pollen, airborne fungi, viruses and animal dandruff), minerals, combustion products, home-care product emissions, or radioactive particulates. Particulate contaminants come in various sizes, shapes, and types. These physical characteristics are particularly important when studying particulate contaminants, as these properties determine particle behavior in suspension. Particulate contaminants generally do not follow the flow exactly, and the departure from the bulk fluid motion depends on the particle mass and drag, as parameterized by the Stokes number of the particle. However, in concentrations that are typical of buildings, it is assumed, correctly, that their presence does not influence the flow. Large particles usually only remain suspended in air for short periods, whereas smaller particles can remain airborne for significant amounts of time. Health effects that may result from inhalation of indoor aerosols are directly related to particle diameters (Owen *et al.* 1992), independent of particular chemical or biological properties of the aerosol, which may add to exposure risks. Recent meta-analyses have shown conclusive associations between lung cancer, cardiopulmonary mortality and long-term exposure to fine particulate air pollution, with increased morbidity and mortality for urban dwellers, who typically have higher exposures to fine and ultra-fine particles (e.g. Stieb *et al*. 2002). It is also important to understand particle size distributions for the efficient design of filters and other removal mechanisms.

The study of particulate contaminants is significantly more complicated than the study of gaseous contaminants. For example, gravitational settling, surface deposition, thermophoresis, and fluid flows may each cause stratification and/or particle concentration gradients. Depending on the situation, the health-related consequences of these effects may be either positive or negative. Obviously, if the particles are deposited on a surface, for example, the risk of human exposure by inhalation is significantly reduced, but subsequent dermal contact and possible exposure through ingestion become possibilities. An accumulation of particulates can also lead to damage of valuable items and equipment. Analytical models of particle deposition date back from an early model developed by Corner & Pendlebury (1951), which has subsequently been developed and improved by several groups of researchers (Crump & Seinfeld 1981, McMurry & Rader 1985, Nazaroff & Cass 1989, Shimada *et al.* 1989 and Benes & Holub 1996). Experimental studies have been conducted to measure the amount of deposition within a space (Cheng 1997, Offerman *et al.* 1985, Okuyuma *et al.* 1986, Thatcher *et al.* 2002). Results for particle fluxes to surfaces span several orders of magnitude (see Lai 2002), and the variation is often explained by the fact that these different studies involve flows with different mixing mechanisms, as well as the fact that parameters such as temperature differences, external forces, levels of surface roughness, particle morphology and other properties can significantly affect the deposition flux.

Particles that have been deposited on a surface may subsequently be resuspended. Indoor activities causing resuspension can generate high concentration events that can result in indoor concentrations that are several orders of magnitude above the background levels. Thatcher & Layton (1995), studying particulate matter in a California residence, found that, even normal activities, such as walking and sitting, dramatically increased local indoor concentrations of particles.

Tracking of particles is another important issue. Particulate matter can be transported by people or objects moving from one area to another. Particles can adhere to shoes and clothing, or can be transported in the wake behind moving people. Thatcher & Layton (1995) tracked particles in buildings. The amount of transport measured in these indoor environments attributable to human motions ranged over several orders of magnitude, depending on the function of the space in question (i.e., whether it was a laboratory, post office, living room, bedroom etc.). They both also found that, for rainy conditions, the amount of tracked-in material could be as much as 100 times higher than corresponding tracked-in material under dry conditions. All these effects should eventually be included in a model that aims to describe contaminant dispersion in buildings.

While there has been significant research in the field of contaminant modeling, most of it is based on single-zone and multi-zone models. In a single-zone model, it is assumed that the entire space (building) of interest is well mixed. This type of model is typically used for a single-story building with no partitions, although it is often been used, inappropriately, for large, complex buildings, where it is clearly not valid (Feustal 1999). With multi-zone models, the building is broken into several zones, which interact with one another. Each of the zones is assumed to be well mixed. This approximation of uniform and instantaneous mixing is very convenient and can often be justified for cases with strong internal air motion. However, this assumption may not always be appropriate, for example, if pollutant emissions are from a localized source and air movement is weak, or in a stratified space. In such cases, exposure to the contaminants may depend heavily on a person's location with a space. Various researchers, including Ozkaynak *et al.* (1982), Rodes *et al.* (1991), Baughman *et al.* (1994) and Drescher *et al.* (1995), have discussed cases where this assumption may not be valid.

Traditional ventilation, such as that provided by a conventional overhead HVAC system, is mixing ventilation, where incoming air is mixed with the air in the room and diluted. This typically results in a relatively uniform interior temperature distribution. In contrast, many modern low-energy ventilation schemes require the use of temperature stratification in a space, with a bottom layer of cooler comfortable air where occupants are located, and an upper layer that is comparatively warm and uncomfortable (Linden, 1999). The ability to extract air at elevated temperatures is necessary for energy efficiency and free cooling. This can be achieved, for example, by displacement ventilation or underfloor air distribution.

Hence, stratification is an important feature in modern ventilation design. This is particularly true for tall spaces, where temperature differences can be quite significant. It is widely believed (although not comprehensively studied and validated) that such displacement ventilation systems will be more effective at removing passive contaminants since it is assumed that they will be transported to the hot upper layer, where they will be extracted. However, this raises the concern that, while the passive contaminants may be flushed out of the room with the warmer air, particulate contaminants, since they do not follow the flow exactly, may in fact not be exhausted or eliminated as quickly. For example, particles with an appreciable settling velocity could potentially remain in the lower regions of the room for a longer period of time under a displacement strategy than with a mixing strategy.

Because the purpose of displacement strategies is to create a non-uniform environment, the instantaneous mixing assumption discussed above will not be valid and should not be used for the whole space. Displacement ventilation methods have been successfully modeled analytically and experimentally by representing heat sources as turbulent buoyant plumes (Linden *et al.* 1990, Caulfield *et al.* 2002, Kaye & Hunt 2004). The fundamental model for such studies is that of the turbulent plume due to Morton *et al.* (1956), which addresses the problem of turbulence closure by making the very simple, but powerful 'entrainment' assumption, which assumes that horizontal entrainment velocities into the plume can be related linearly to a characteristic vertical velocity. Baines & Turner (1969) studied the interaction of such a plume with a space of finite volume with the so called 'filling box' model. They demonstrated that a buoyant plume will rise to the top of a room, spread out across the ceiling, and then drive a descending front into the air surrounding the plume. In 1975, Germeles developed a simple, but powerful, numerical method for determining the evolution of the background density by assuming a separation of time scales between the quickly progressing plume and the slower evolution of the background. These models have been successfully used to study various forms of ventilation – natural ventilation (Linden *et al.* 1990), mechanical ventilation (Caulfield & Woods 2002), hybrid ventilation (Woods *et al.* 2003), and underfloor air distribution (Liu & Linden 2005). These studies have only considered the background density evolution and have not included the study of any contaminants. Also, most prior work is based on steady state models, while the strength of typical heat sources vary in time, causing the ventilation flow to vary in time also . In real buildings, sources of heat and contaminants tend to be time varying and, hence, transient effects (such as people entering and leaving a space and equipment being turned on and off) may be important to model.

Computational fluid dynamics (CFD) can prove a useful tool in the study of contaminant dispersion, and it has been successfully used to model the transport of contaminants within buildings (Holmberg & Li (1998)). Most of the buildings considered in previous modeling efforts have been relatively small with relatively simple geometries, which is often not the case for actual buildings. Also, even when using simplified models such as drift flux models (Holmberg & Li 1998) that provide simplified descriptions of contaminant transport, with current computer speeds the expense and time associated with CFD may be prohibitive for some applications, but in general CFD is enjoying increasing use. It is often used to model specific sections of buildings. Zhao *et al.* (2004) proposed using CFD as a stepping stone in multi-zone modeling. Using the results from a specific CFD simulation they break the building into well-mixed zones, as determined by the model and an age-of-air concept that is determined from trajectories of air as it flows through the building. Then, using these zones in a multi-zone model, they run a full year simulation on the building. However, it is reasonable to expect that zones that might be well mixed for one situation should not be treated as well mixed for a simulation lasting a whole year. For example, Baughman *et al.* (1994) noted that a given space had a characteristic mixing time that varied from 7-100 minutes depending on the boundary conditions imposed on the velocity and contaminant fields at the internal surfaces of the building . Another major limitation of CFD for ventilation modeling is that it can often take considerably longer to get the numerical convergence in stratified flows (Versteeg & Malalasekra 1996).

This project aimed to address the fundamental gaps in knowledge in contaminant dispersion for flows where stratification plays a role. The goal was to take previously developed models, build on them and develop analytical and numerical methods, which will aid in the developing of simple rules that will result in better design of low-energy ventilation strategies. The approach in this study is based on the following methodology in which small and large scale model laboratory experiments were carried out that examined the physics of passive and particulate contaminant dispersion in a stratified space. These experiments were modeled using a numerical model based on plume theory and the results compared with the experiments. Simplified, semi-analytical models were also developed for incorporation into a design tool. The methodology is described in the following section.

2.0 Methods

In this section, the two approaches used to study contaminant dispersion in building are described. These approaches are mathematical and experimental.

2.1 Mathematical Models

In order to understand the fate of particles in a ventilated space, it is necessary to understand the flow within the space. As mentioned previously, many modern low-energy ventilation schemes, such as displacement or natural ventilation, exploit vertical temperature stratification in a space. So, it is critical to understand how heat sources within a ventilated enclosed space stratify that space. Many heat sources within a building can be regarded as localized and can often be modeled as pure sources of buoyancy. Using the plume equations developed by Morton *et al.* (1956) along with the 'filling' (Baines & Turner 1969) and 'emptying-filling' box models (Linden *et al.* 1990), the flow in such low energy buildings can be modeled, and the transport of particulate contaminants within the interior space can be calculated.

2.1.1 The Fluid Dynamics of Displacement Ventilation

A conceptual model of a displacement ventilated space is depicted in figure 1. A space with an ideal heat source and inlet and extraction vents at the top and bottom of the room is considered. The flow rate into the space, Q_{in}, can be specified as desired either as a fixed ventilation flow supplied by a fan in a mechanical system (Sandberg & Etheridge (1996)) or as determined by the strength of plume and size of openings in a naturally ventilated enclosure (Linden, Lane-Serff & Smeed (1990)). The resulting stratification has two layers of uniform temperature with cool air in the lower layer (corresponding to the temperature of the air introduced through the lower vent) and warm buoyant air in the upper layer. The interface that divides the upper and lower layer corresponds to the height where the flow rate in the plume is the same as the flow rate into the space. From conservation of volume $Q_{in}=Q_{out}=Q_p$.

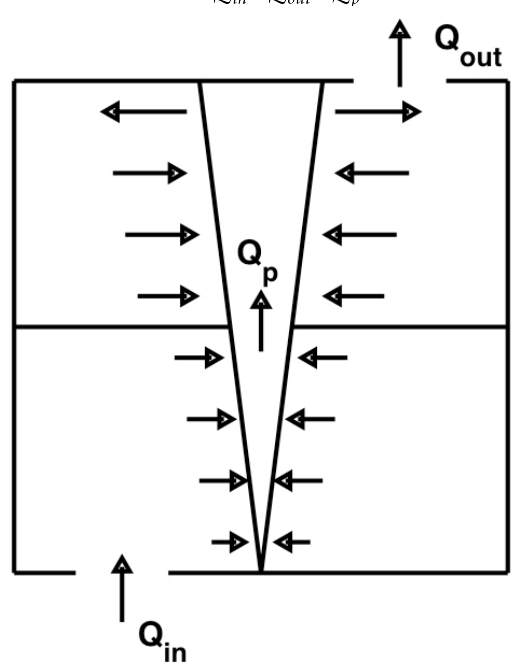


Figure 1: Conceptual Schematic of Displacement Ventilation. The arrows represent the entrainment and detrainment from the thermal plume

The flow within the space is determined by coupling the plume flow with the environment outside the plume. For a Boussinesq plume with assumed top-hat profiles, in which the density differences are sufficiently small that they only affect the buoyancy force and are assumed to be uniformly distributed across the plume, the equations for mass, momentum and buoyancy conservation in the plume are

$$\frac{dQ}{dz} = 2\epsilon M^{\frac{1}{2}} \qquad \frac{dM}{dz} = \frac{FQ}{M} \qquad \frac{dF}{dz} = \frac{g}{\rho_0}\frac{d\rho}{dz}Q \tag{1}$$

where πQ is the volume flux, πM is the specific momentum flux and πF is the specific buoyancy flux in the plume, g is gravitational acceleration, z is the vertical coordinate, ρ is the density outside the plume and ρ_0 is a reference characteristic density (Morton, Taylor & Turner (1956) – referred to as MTT). The entrainment constant, ε, defined in MTT relates the vertical velocity scale in the plume to the entrainment velocity on the edge of the plume.

In order to couple the plume to the environment it is assumed that the cross sectional area of the room, S, is sufficiently large such that at all heights the plume occupies a negligible fraction of the area, i.e. $b << S$. Therefore, the entrainment into the plume should essentially be horizontal and the MTT plume equations written above can still be applied (Baines & Turner 1969). When the plume impinges on the ceiling it spreads horizontally to the sidewalls, which then cause the resulting warm air to descend into the space. Volume conservation in the region outside the plume is

$$wS = -\pi Q - Q_{out} \tag{2}$$

where w is the vertical velocity outside the plume and Q_{out} is the volume flow rate out of the space through the upper vent. Provided that heat conduction is negligible (i.e. the Peclet number is sufficiently high), the conservation of mass equation is

$$\frac{\partial \rho_a}{\partial t} + w\frac{\partial \rho_a}{\partial z} = 0, \tag{3}$$

where ρ_a is the density in the ambient fluid outside the plume and t is time. It is necessary to assume that the background density in the room varies on a much slower time-scale than that associated with the evolution of the plume, which requires

$$\left(\frac{5}{6\epsilon}\right)^2 \frac{S}{\pi H^2} \gg 1 \tag{4}$$

(Baines & Turner (1969)). H is the height of room. The restriction requires the room to have a small aspect ratio. The interface that divides the upper and lower layer corresponds to the height where the plume flow rate is the same as the flow rate through the vents (i.e. when $Q = Q_{in}$, which is the height where w= 0).

2.1.2 Average Contaminant Models

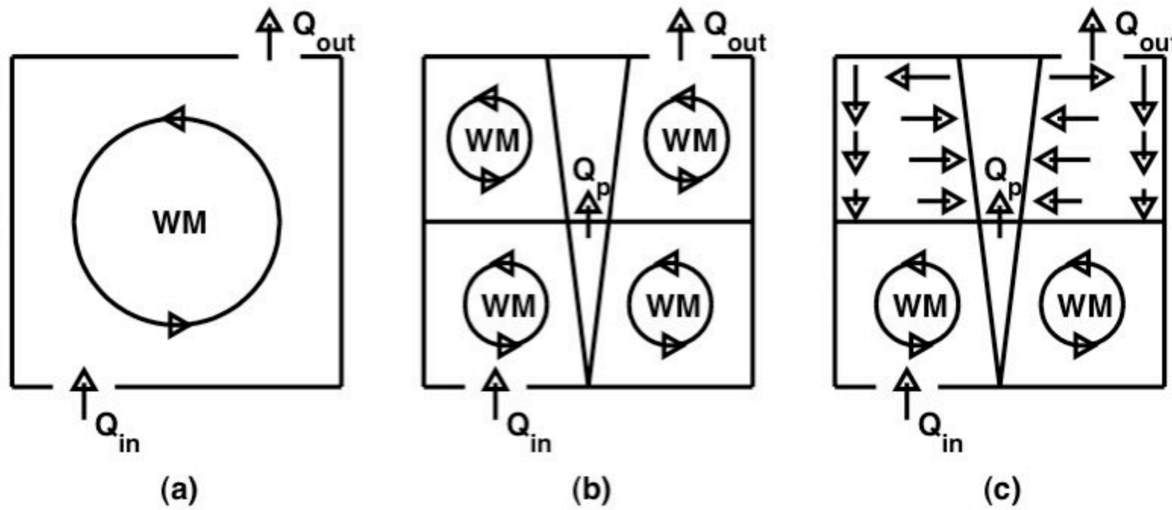


Figure 2 Three models of ventilation. (a) Traditional Mixing System, (b) and (c) Low Energy Displacement Ventilation. WM means well mixed. The arrows in (c) depict the general direction of flow

Figure 2 shows a schematic of the three models for contaminant that were considered. Two low-energy ventilation models ((b) and (c)) and one traditional mixing model (a) were analyzed. In the low-energy models, the space was considered to be either mechanically or naturally ventilated with fresh air entering through a low level vent and hot buoyant air leaving via a vent at high level. Heat sources in the space are represented by an ideal plume.

For each of the models depicted in Figure 2, three types of contamination situations were considered:

1. Step-Down (Natural Attenuation): where a space is initially uniformly filled with a contaminant and fresh, uncontaminated air is introduced into the space.

2. Step-Up (External Contaminant): where a space is initially uncontaminated, and then a contaminant is introduced through the ventilation system

3. Isolated Source in Plume: where a space is initially uncontaminated, and a contaminant is introduced as a point source. The location of the point source is within the plume. This location was chosen because people are often the source of heat as well as the source of contaminants in buildings. Additionally, it was also the only type of point source that could be currently adequately described in the model.

<u>Model (a) - Entirely Well Mixed Space</u>

In this model, the entire room is treated as well mixed (figure 2(a)). The reason for this is twofold. First, it allows the comparison of low-energy ventilation systems to traditional mixing systems, which destroy stratification by mixing the space. Second, many building software packages treat buildings as networks of spaces, each of which are assumed to be well mixed. As many researchers have previously pointed out (e.g. Baughman *et al.* (1994), Klepeis (1999)), this assumption is questionable and is tested here. Conservation of contaminant in a well-mixed single space can is written as

$$\frac{dK_{wm}}{dt} = -\frac{Q_{in} + Q_f}{SH} K_{wm} + \frac{Q_{in}}{SH} K_{in} + \frac{Q_{in} K_s}{SH}, \tag{5}$$

where K_{wm} is the concentration of contaminant in the well mixed space, Q_f is the deposition flow rate, S is the cross sectional area of the space, K_{in} is the concentration of contaminant entering the room, K_s is the concentration of contaminant from an internal source and t is time.

Initially, the deposition of particles to the ceiling and sidewalls was excluded because it was assumed that particles settle out of the lower and upper layers due to gravitational effects only. This a reasonable assumption for larger particles (>O (0.1-1μm)), where the predominant mechanism of deposition is gravitational settling and Brownian effects are small (Lai and Nazaroff 2000). For ultrafine particles (< O(0.1-1μm)), deposition is also driven by Brownian effects. Deposition due to Brownian effects is strongly dependent on the turbulent friction velocity at the boundaries of the room. Since for displacement ventilation, characteristic velocities are typically an order of magnitude smaller than for traditional mixing systems (Jiang *et al.* 1992), it is reasonable to assume that deposition effects driven by Brownian settling will also be much smaller.

While the main focus of this work was on larger particles, we discuss in section 3.3 the models that include additional settling effects, typically experienced by smaller particles. It is shown that the qualitative observations made for larger particles also hold for smaller particles.

Model (b) - Well Mixed Two Layer Model

Model (b) from Figure 2 is similar to that of Hunt & Kaye (2006) and assumes that the upper and lower layers are always well mixed. The justification for this assumption is that the plume will cause some mixing in the upper layer. This assumption does not describe the complete dynamics of the system. Nonetheless, at least for passive contaminants, it has been shown to be an adequate model (Hunt & Kaye 2006) that is very appealing due to its simplicity. It is also assumed that the lower layer is well mixed. Since the incoming flow will have a certain amount of momentum, a certain amount of mixing will be inevitable, and in experimental work on passive contaminants (Bolster & Linden 2007) this was shown to be a reasonable assumption. Thus the governing equations for conservation of contaminant in each of the layers are

$$\begin{aligned} \frac{dK_l}{dt} &= -\left(\frac{Q_p + Q_f}{Sh}\right) K_l + \frac{Q_f}{Sh} K_u + \frac{Q_{in}}{Sh} K_{in} \\ \frac{dK_u}{dt} &= \frac{Q_p}{S(H-h)} K_l - \left(\frac{Q_f + Q_p}{S(H-h)}\right) K_u + \frac{Q_p K_s}{S(H-h)} \end{aligned} \tag{6}$$

where S is the cross sectional area of the room, h is the height of interface dividing the upper and lower layers and K_l and K_u are the concentrations of contaminant in the lower and upper layers, respectively

Model (c) - Mixed Lower Layer, Unmixed Upper Layer

In model (c) from Figure 2, for a well-mixed lower layer and unmixed upper layer, the conservation equations for the upper and lower layer are slightly modified from the previous section. Instead of removing the fluid of the average concentration of contaminant, the model now accounts for the fact that the upper layer can have concentration gradients within it, thus leading to the following conservation equations:

$$\frac{dK_l}{dt} = -\left(\frac{Q_p + Q_f}{Sh}\right)K_l + \frac{Q_f}{Sh}K_u(z=h) + \frac{Q_{in}}{Sh}K_{in},$$

$$\frac{d\bar{K}_u}{dt} = \frac{Q_p}{S(H-h)}\Big(K_l - K_u(z=H)\Big) - \left(\frac{Q_f}{S(H-h)}\right)K_u(z=h) + \frac{Q_p K_s}{S(H-h)}. \tag{7}$$

In order to understand the dynamics of the upper layer, it is important to understand the flow within the space, which is determined by coupling the plume flow with the environment outside the plume as described in section 2.1.1 (see Linden, Lane-Serff & Smeed 1990 for more details). Contaminant with concentration *K(z)* in the room is entrained into the plume, which has contaminant concentration *P(z)*. Since the vertical velocities in the plume are typically much larger than those in the background, the effect of gravitational settling within the plume is neglected and only considered in the ambient. The conservation of contaminant volume flux in the plume can be expressed as (Bolster & Linden 2007)

$$\frac{dP}{dz} = \frac{5}{3z}(K-P), \qquad 0 < z < h$$

$$\frac{dP}{dz} = \frac{1}{z - \frac{2}{5}h}(K-P) \qquad h < z < H \tag{8}$$

where *K* is the concentration of the contaminant in the background and *P* is the concentration of contaminant in the plume.

In addition, neglecting diffusion due to typically high Peclet numbers, the room contaminant conservation equation is

$$\frac{\partial K}{\partial t} + w\frac{\partial K}{\partial z} = 0. \tag{9}$$

where *w* is the velocity of the contaminant field, which includes the effect of gravitational settling. In the upper layer, this can be shown to be (Baines & Turner 1969)

$$w_c = \frac{\pi}{S}\left(2\epsilon\left(\frac{9\epsilon}{10}\right)^{\frac{1}{3}} F_0^{\frac{1}{3}} h^{\frac{2}{3}}\right)(h-z) - v_f, \tag{10}$$

where F_0 is the source buoyancy flux of the heat source, ε is the entrainment coefficient for a turbulent plume (Morton Taylor & Tuner 1956) and v_f is the settling velocity, assumed to be the Stokes settling velocity of a spherical particle.

Nondimensionalisation

The equations are nondimensionalized as follows:

$$t = \tau \frac{SH}{Q_p}, \qquad K = K_{ref}\kappa, \qquad h = H\zeta, \tag{11}$$

where K_{ref} is a reference concentrations, which will be different for each of the three situations considered. For the step down method, it will be the initial concentration of contaminant in the space ($K_{ref} = K_0$). For the step up system, it will be the concentration of contaminant entering the spaces ($K_{ref} = K_{in}$). For the point source case ,it will be the concentration of the source ($K_{ref} = K_s$).

There are two important dimensionless parameters that govern the behavior of this transport problem. These are

$$\zeta = \frac{h}{H} \qquad \alpha = \frac{Q_f}{Q_{in}} \tag{12}$$

where ζ is the dimensionless height of the interface in the room and α represents a dimensionless form of the particle settling velocity. When α is small, the settling velocity of the particles is small compared with the mean upward flow in the space. When α is large, particle settling is dominant.

2.1.3 Germeles scheme

A solution to the conservation equations presented so far provides sufficient information to calculate the total amount of contaminant within the upper and lower layers and provides only an approximate description of the contaminant distribution within the space. However, the detailed structure of the upper layer above the descending front is not resolved, and in order to determine the vertical concentration profile, the system of equations (8)-(10) is solved using a modification of a numerical scheme originally developed by Germeles (1975).

Although this algorithm is well-known and commonly-applied (Cardoso & Woods 1993, Caulfield & Woods 2002, Worster & Huppert 1988), a review of the the algorithm is presented here, as it is typically only applied to density and not contaminant fields. The numerical method relies on the discretization of the ambient into a finite number of layers, n. Each layer is assigned an initial concentration K_0 corresponding to the initial concentration in the space. As mentioned before, it is assumed that the plume evolves far more rapidly than the ambient field, and so, at every time step, the plume equations (8) are solved assuming a steady background contaminant field using a fourth-order Runge-Kutta algorithm. The concentration layers in the background are then advected downwards with a velocity calculated using the discretized version of (10), i.e.

$$w(i) = \frac{\pi}{S}\left(2\epsilon\left(\frac{9\epsilon}{10}\right)^{\frac{1}{3}} F_0^{\frac{1}{3}} h^{\frac{2}{3}}\right)(h - z(i)) - v_{fall}, \tag{13}$$

where i represents each different layer ($1 < i < n$). Each layer is then advected downwards as follows

$$y_{new}(i) = y_{old}(i) - \Delta\tau w(i) \tag{14}$$

where y_{old} is the height of each layer before being advected, y_{new} is the new height and $\Delta\tau$ is the chosen numerical time-step.

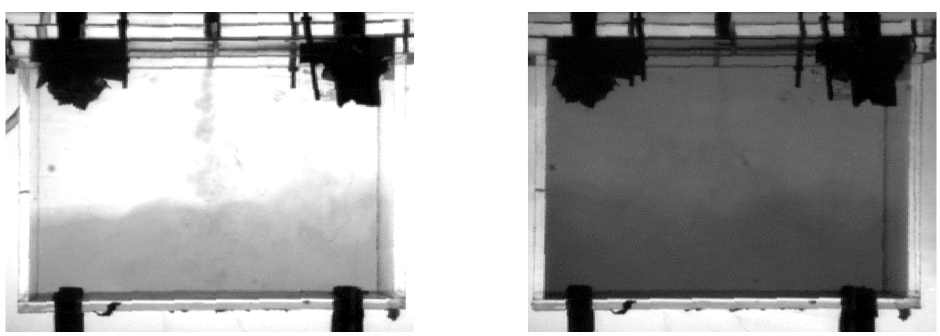
This process captures the entrainment of fluid from each layer by the rising plume since the layers decrease in thickness as they descend. During each time-step a new layer is added at the top of the room. The thickness and concentration of this new layer are calculated as

$$ynew(i) = 1 - \Delta\tau(Q_P(z = H) - Q_{out})$$
$$Knew(i) = P(z = H) \tag{15}$$

2.2 Experiments

2.2.1 Small-Scale Experiments

A series of analogue laboratory experiments, based on the salt bath technique (Linden 1999), was conducted to compare to the results of the theoretical models. The space is represented by a plexiglass tank (30x30x40 cm) within which there is a low-momentum plume source (Hunt, Cooper & Linden 2000). There are openings on the lower and upper surfaces through which water is pumped and extracted. The plume source is located at the top centre of the tank and injects negatively buoyant (heavier) salt water. The geometry is inverted compared to the model described in the previous sections. Due to the Boussinesq behavior (since density differences in the system are small) of the system, this inversion has no effect on the dynamics. Freshwater is pumped in through the upper openings using an aquarium pump connected to a reservoir of freshwater. The saltier water (equivalent to the warmer air in the model) is extracted from the lower vents. By adjusting the flow rate into the tank, the interface height for a given value of source buoyancy flux can be adjusted.



(a) (b)

Figure 3: Snapshots from the experiments. (a) A point source contaminant and (b) A step down case

In order to achieve ideal displacement, it is desirable to have fluid with the least possible momentum entering the space in order to minimize mixing in the upper (lower in model) layer. However, due to space restrictions, which also occur in real buildings, there is a limit to how much area can be dedicated to inlet vents. In the experiments, there are twelve 2.5 cm diameter holes spread across the top of the plexiglass tank, which act as inlet vents. Further, in order to reduce the momentum of the incoming fluid, horizontal struts, 5 cm wide, are placed 2.5 cm above the inlet holes. These reduce the momentum and deflect the incoming flow horizontally.

Two reservoirs of freshwater supply the tank. One is 'contaminated' with food dye, while the other is uncontaminated. Initially the system is fed with contaminated fluid and the plume is turned on until the system reaches steady state and is uniformly contaminated. Then the source of ambient fluid is switched to the uncontaminated reservoir. Concentration measurements were obtained by dye concentration. The plexiglass tank was backlit with a fluorescent light source, and the experiments were recorded and analyzed with the image processing package DigImage. The light intensity at each point in the tank is recorded and correlated to the concentration of contaminant present. Using pre-determined calibration curves of light intensity against concentration, the local concentration of contaminant within the box can be inferred (see Cenedese & Dalziel 1998 for details). The vertical concentration profiles are then horizontally averaged across the entire width of the tank, excluding the zone with the plume in order to reduce random noise. The standard deviation associated with this averaging process is small (typically less than 5 % of the average value), suggesting good accuracy.

2.2.2 Full-Scale Experiments

In order to validate the models and gain some further insight into the dynamics of particles in low-energy ventilation systems, a series of full-scale laboratory experiments were conducted. A chamber (of cross sectional area 1.3 × 2.6 m and height 1.8 m) is ventilated by a displacement system as depicted in figure 4 below. Although the experimental chamber is not as tall as a typical interior space, it is large enough to ensure that the main physical processes are represented accurately. The temperature in the background was measured at various heights (30, 60, 90, 120 and 150 cm) using type K thermocouples. A heat source of 65 Watts is placed in the center of the room. The heat source consists of a light bulb that is encased in a specially constructed wooden enclosure (0.2x0.2x0.22m) to minimize radiative losses. Radiative losses from the wooden enclosure were assumed to be negligible, because wrapping the box in materials of lower emissivity (e.g. aluminum foil) did not affect the background temperature in the room. The 65 Watt heat source was chosen, because for the flow rates achievable through this system, it was possible to place the interface dividing the upper and lower thermal layers around the mid height of the room.

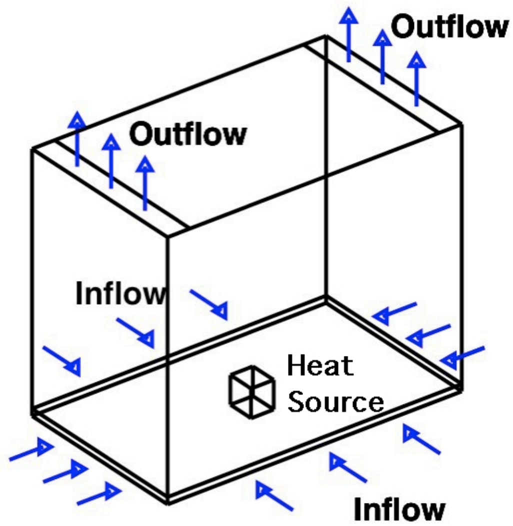


Figure 4: A schematic of the large scale experiment setup

Because of the difficulties involved in generating step-up or step-down scenarios with particles, the only situation considered was the point source in the plume, which still demonstrates all of the interesting dynamics associated with this flow.

The temperature interface dividing the upper and lower layers is located at a height corresponding to half the height of the room (i.e., $\zeta = 0.5$). This was done by matching the flow rate into the space with the thermal plume flow rate at this height (see section 2.1.1 for details). Three values of α=0.1, 0.625 and 2.5 were considered. Once the temperature in the room had reached steady state, particles were injected vertically into the plume with a medical nebulizer (see Hahn *et al.* 2001). The particles used were polystyrene 'Microbead NIST Traceable Particle Size Standard' manufactured by Polysciences Inc., and they were manufactured to within a ±2.5%size standard (i.e. the standard deviation of particle diameter is less than 2.5% of the average particle diameter). The flow rate of injection was very small compared to the flow rate in the plume, and so its effect was considered to be negligible. Running the nebulizer did not affect the temperature field.

The contaminant source was turned on for 5 minutes and then switched off. A Model 237A/B Met One Particle Counter was used to detect and count particles. It was placed at various heights within the room, and particle concentrations were measured periodically every 30 seconds. The particle concentrations were tracked until they returned to the background noise levels, so that both the increase and drop in concentrations were captured.

3.0 Results

3.1 Mathematical Models

Figure 5 displays sample solutions for the average contaminant concentration for each of the models at interface height, $\zeta = 0.5$, and three values of $\alpha = 0, 1, 10$, corresponding to passive contaminants and two sizes of particulate, respectively. For the 'step down' case, the average amounts of contaminant are similar for all cases, suggesting that each system exhibits comparable efficiency vis-à-vis overall contaminant removal. Although the average concentrations for the other two cases are approximately the same, this does not imply that the vertical concentration profiles are also the same, merely that the concentration being extracted is similar. This point will be further illustrated in the next section.

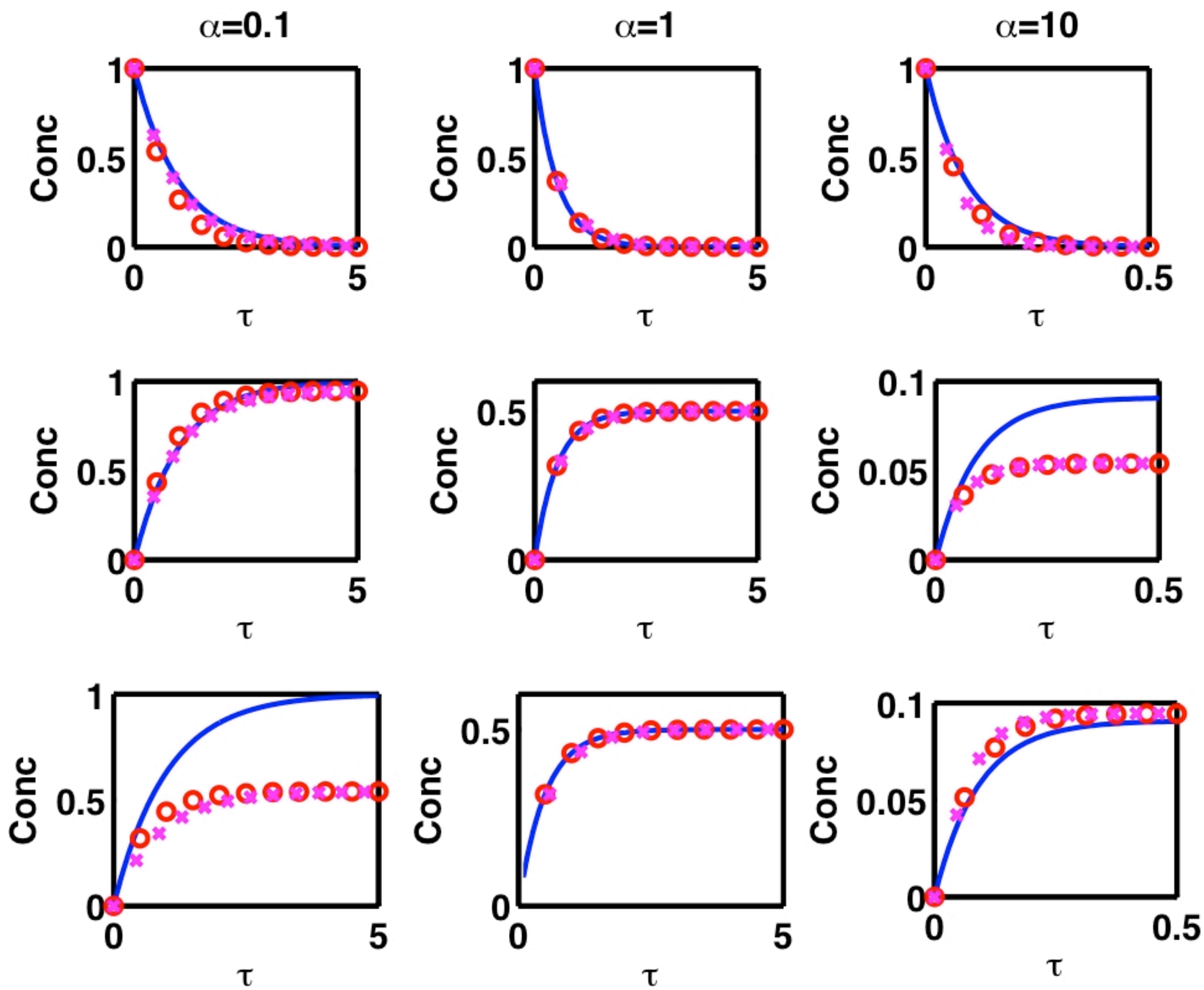


Figure 5: Average Concentration for 'step down' (top row), 'step up' (middle row) and 'point source' (bottom row) models with various 〈 =0.1(left column), 1(middle column) and 19 (right column) and $\zeta = 0.5$. Entirely well mixed (solid line blue –), Two Layer Model (b) (open circles red o) and Two Layer Model (c) (purple x)

Step-Up Steady State

Unlike the step-down scenario, the step-up case has some interesting steady state characteristics. For passive contaminants, this steady state corresponds to a uniformly distributed concentration of contaminant equal to that of the source. However, the influence of gravitational settling leads to non trivial steady state distributions. Therefore, the steady state solutions are presented first and then the transient approach to these steady states.

For the one and two layer cases, both systems tended to different steady states. It can be shown for these systems that

$$\kappa^{(a)} = \frac{1}{1+\alpha}, \qquad \kappa_u^{(b,c)} = \frac{1}{(\alpha+1)^2-\alpha}, \qquad \kappa_l^{(b,c)} = \frac{(1+\alpha)}{(\alpha+1)^2-\alpha}. \tag{16}$$

The superscripts (a) and (b,c) relate to the well mixed and two layer models, respectively. Therefore, for the two layer systems (i.e. (b) and (c)) at steady state, the concentration in the lower layer was always greater than that in the upper layer and occupants were exposed to the highest concentrations in the space. Interestingly, this steady state was also independent of ζ, the interface height.

A comparison of the overall average concentration at steady state of Model (a) vs. Models (b) and (c) showed that there were ranges of α and / where the concentration is higher in one case than another. More importantly the steady state value of the concentration of lower layer for models (b) and (c) to the well mixed case was compared – see equation (17) below. Interestingly, regardless of the value of α or ζ , the lower layer always had a higher level of contaminant than the well mixed case. Thus people would always be exposed to a higher concentration in the low-energy ventilation system, regardless of whether mechanism (b) or (c) captures the true behavior of the system. Additionally it should be noted that there were maximum values for the ratio of concentrations equal to 1.33 at α = 1, which means that this corresponded to the worst case scenario regarding a comparison between traditional and low energy ventilation systems.

$$\frac{\bar{\kappa}^{(b,c)}}{\bar{\kappa}^{(a)}} = \frac{\zeta\kappa_l + (1-\zeta)\kappa_u}{\frac{1}{1+\alpha}} = \frac{(1+\zeta\alpha)(1+\alpha)}{\alpha^2+\alpha+1} \tag{17}$$

Point Source Steady State

In the same fashion as for the step up case, the ultimate steady state that the system reaches will differ for the traditional and low-energy systems. Systems (b) and (c) will reach the same steady state by different mechanisms. However (a) will tend to a different state. The well mixed space in model (a) tends to a uniform contaminant concentration shown in (18). For the two layer cases, both systems tended to the same steady state where both layers were well mixed. For this situation the upper and lower layer concentration fields were also shown in (18).

$$\kappa^{(a)} = \frac{1}{1+\alpha} \qquad \kappa_u^{(b,c)} = \frac{1+\alpha}{(\alpha+1)^2-\alpha}, \qquad \kappa_l^{(b,c)} = \frac{\alpha}{(\alpha+1)^2-\alpha}. \tag{18}$$

At steady state, the concentration in the upper layer was always greater than that in the lower layer and people, who only occupy the lower layer, would only be exposed to the lowest concentrations in the space. Again, these steady state values were independent of α. Comparing the concentration of the lower layer in the well mixed models to that of the entirely well mixed model, the following relationship was obtained:

$$\frac{\kappa_l^{(b),(c)}}{\kappa^{(a)}} = \frac{\alpha^2 + \alpha}{\alpha^2 + \alpha + 1} < 1 \qquad (19)$$

which indicates that for this type of point source the low energy system always did a better job at removing contaminants than the traditional system, regardless of the interface location or particle size. This ratio was zero for $\alpha = 0$, which corresponds to a passive contaminant, and approaches 1 as $\alpha \rightarrow \infty$. This makes sense because the source was effectively in the upper layer and for $\alpha = 0$ no contaminant can fall back into the lower layer. However, as α increases, more and more contaminant can fall through, thus increasing the concentration of the lower layer.

The step-up and point-source cases illustrate the importance of considering the three different types of contamination. Here, there are clear differences in concentration between the two mechanisms, particularly for larger particles for the step-up case and passive contaminants for the point source. Once again, merely understanding the average concentration in the room can be deceptive as vertical differences can exist in the two-layer model.

Figure 6 displays the vertical concentration profiles for a passive contaminant computed with the Germeles algorithm described in section 2.1.3, for an interface height corresponding to half the height of the room. The case considered is the step-down case. In the previous discussion, it was shown that the average reduction of contaminant was approximately the same for all cases. Here, however, the vertical distribution of contaminant was very different for each model.

The concentration at the top of the room for all three models was approximately the same at all times. Therefore, the concentration of contaminant being extracted was about the same in all cases, which explains why the reduction in average concentration did not vary significantly between the three systems. On the other hand, the 'occupied' lower layer concentration was always less in both two-layer models than in the entirely well-mixed case, which is clearly desirable. However, the concentration of contaminant in the upper layer was always higher. Further, the peak in contaminant concentration was always located at or just above the height of the temperature interface. This stems from the background velocity field. In the upper layer the flow was all downward, while in the lower layer it was upwards. The interface dividing the upper and lower layers corresponded to the height where the background velocity was zero. Therefore, the high initial concentration in the upper layer was continuously being pushed down towards the interface, causing the peak level to occur there. A similar peak, although it decreased in magnitude with time due to the settling out of the upper layer, was observed.

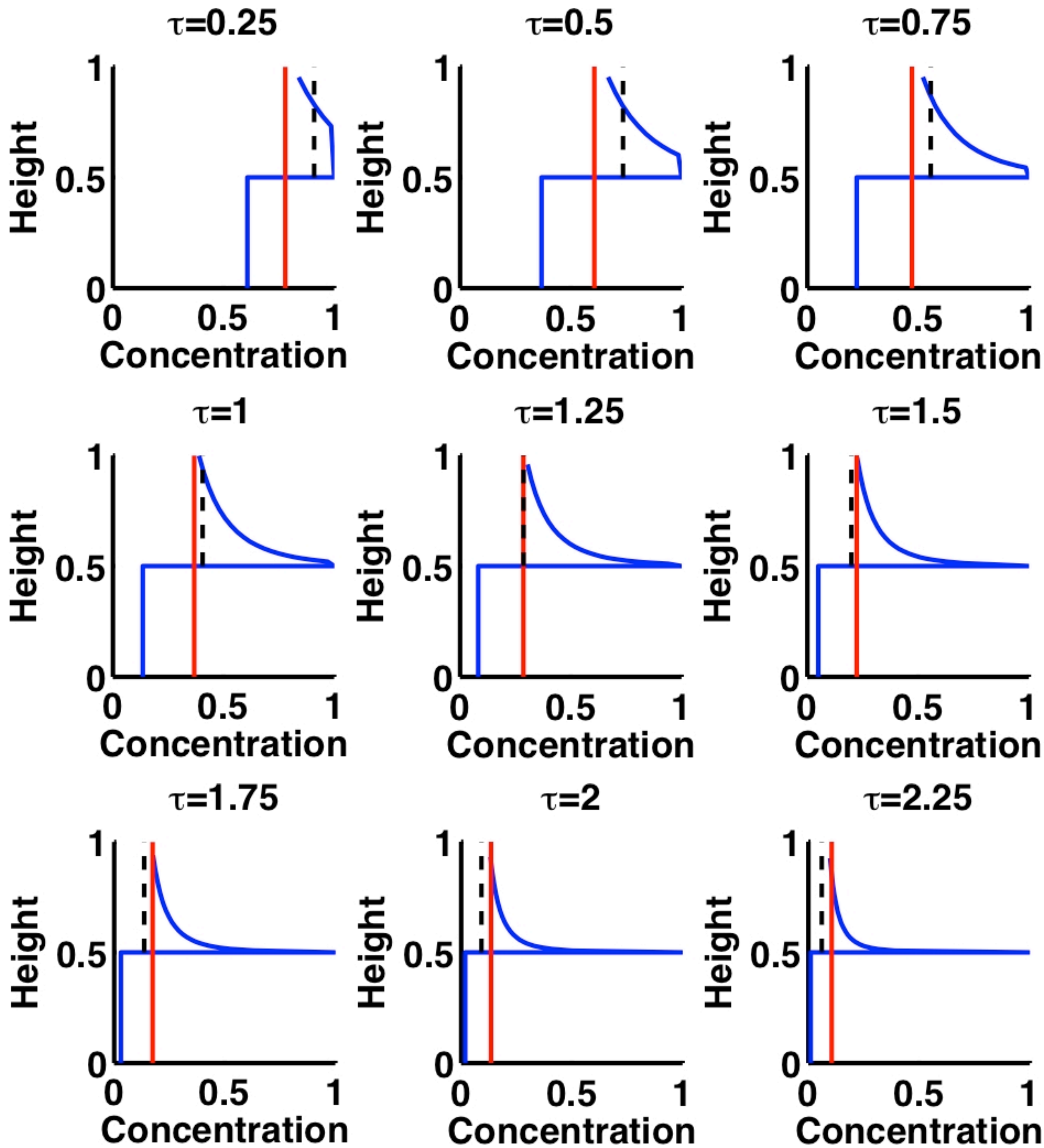


Figure 6. Comparison of concentration profiles at intervals of 0.25 | for (= 0.5 for an entirely well mixed space (red -), two layer model (b)(black --) and a model (c) (blue-)

3.2 Small Scale Experiments

Figure 7 displays the results from a series of experiments for an interface at $0.25H$ and $0.5H$. The measured levels of contaminant over time were compared to those predicted by the theoretical models. As can be seen, the qualitative comparison was good. The lower layer seemed to be better described by the well-mixed model for the two lower interface heights, although some displacement behavior was definitely visible, particularly at early times. The quantitative disagreement can probably be attributed to the fact that it was virtually impossible to create ideal displacement ventilation. The finite area and momentum of the fluid entering through the vents inevitably caused some level of mixing, which, as mentioned above, was attempted to be minimized by placing the deflecting plates above the inlets. The location of the inlets also played an important role, because certain parts of the lower layer were contaminated faster than others and so the plume was not necessarily exposed to an average amount of contaminant instantly. This is very much an issue for real displacement ventilation systems where such considerations are important. However, despite these shortcomings of the experiments, reasonable quantitative agreement was obtained.

One of the most important features present was the peak in concentration of contaminant at the thermal interface level. Quantitatively, the agreement was not all that good here and this was probably due to the finite thickness of the interface, which can exchange fluid with the surrounding space, thus losing high concentration contaminant by entrainment into the plume and replenishing it with lower concentration fluid from the lower and upper layers. However, this concentration peak was clearly observed to be a robust feature of the experiments and marked a significant difference from well-mixed ventilation.

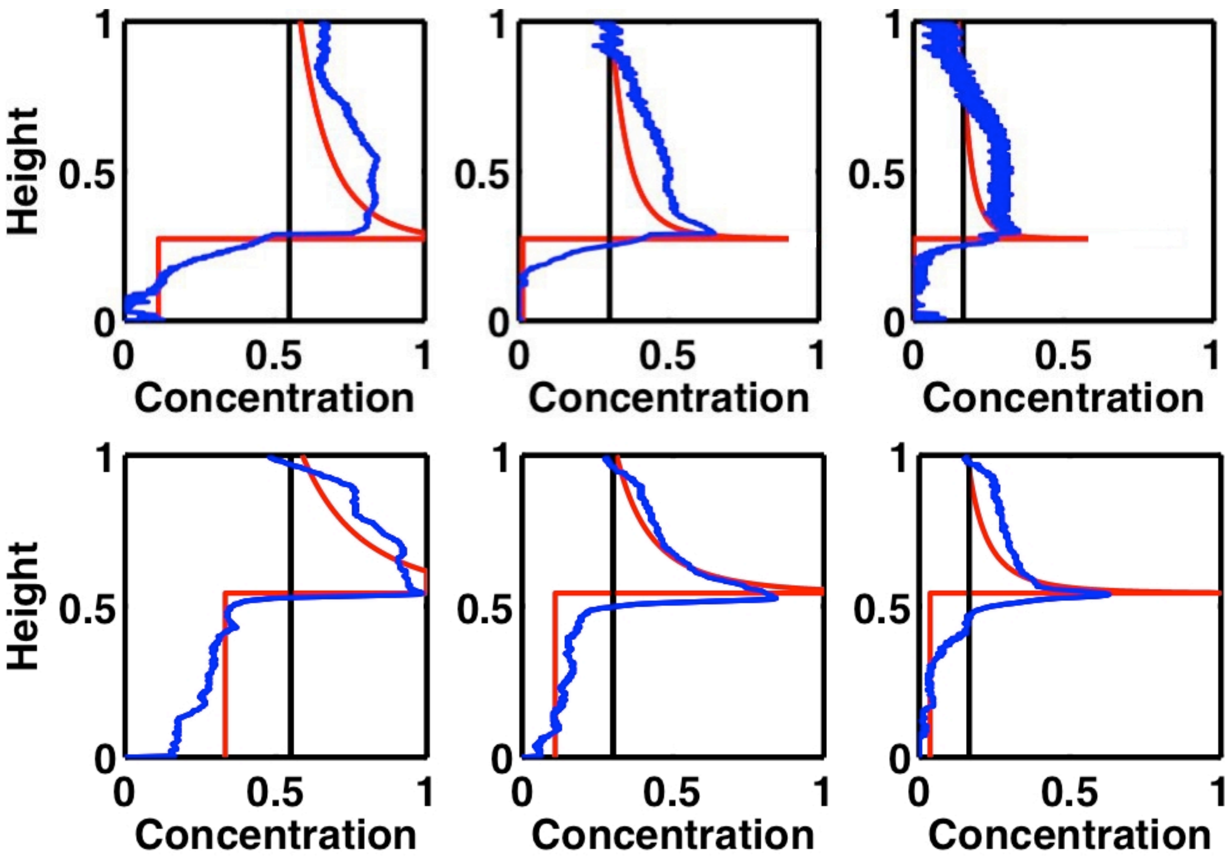


Figure 7. Vertical concentration profiles for (= 0.25 (top row) and for (= 0.5 (bottom row) at time intervals of 0.6 | , 1.2 | and 1.8 | . Experiments (blue -), Well Mixed Lower Layer (red -), Entirely Well Mixed (black -)

3.3 Large Scale Experiments

A sample set of results of the experiments is shown in figure 8. Concentrations at 4 heights within the room were compared to the theoretical predictions. As shown in figure 7, the concentrations within the upper layer differed greatly at different heights, suggesting that perfect mixing in the upper layer did not occur. However, the lower layer appeared to have some degree of mixing. The whole space was definitely not well mixed. Qualitatively, the theory and experiments agreed well with one another, and even quantitatively the disagreement was consistent, suggesting that the model works, but that there may be some uncertainty in the parameters that have not been captured accurately.

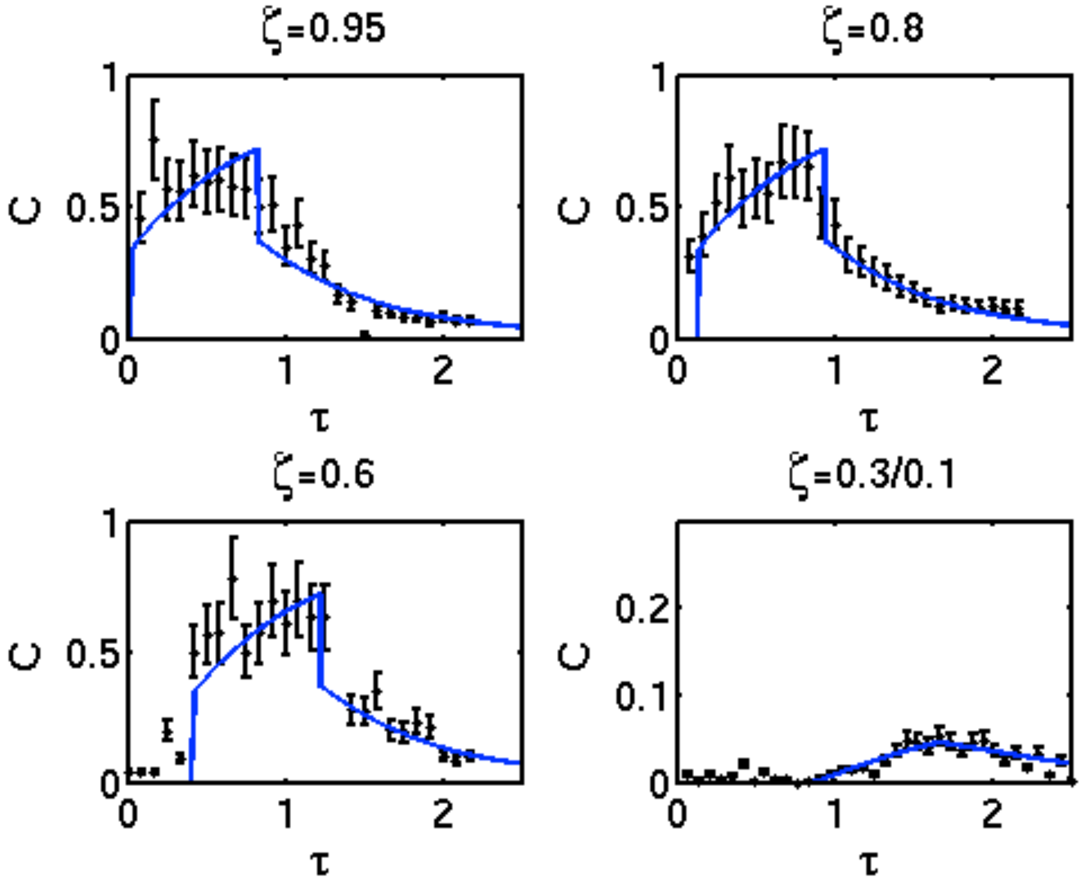


Figure 8: Concentration for particle 'point source' Experiments (black) vs. Theory (blue) at various heights ($\alpha = 0.1$).

3.4 Discussion on Additional Deposition Mechanisms

While gravitational effects dominate the deposition mechanisms for large particles (typically > 1μm, although this is dependent on the friction velocity at a boundary, which for a displacement system should be less than for traditional mixing system), the deposition of particles smaller than this can be strongly driven by Brownian diffusion (Lai & Nazaroff (2000)). Therefore, for such particles the governing equations must be modified to account for this. Since the ultimate steady state for both two-layer models (b) and (c) is the same, the focus is on model (b) here. Accounting for additional settling to all surfaces, the governing equations become

$$\frac{dK_{wm}}{dt} = -\frac{Q_{in}+Q_{dw}}{SH}K_{wm} + \frac{Q_{in}}{SH}K_{in} + \frac{Q_{in}K_s}{SH},$$

$$\frac{dK_l}{dt} = -\left(\frac{Q_p+Q_{dl}}{Sh}\right)K_l + \frac{Q_{df}}{Sh}K_u + \frac{Q_{in}}{Sh}K_{in}$$

$$\frac{dK_u}{dt} = \frac{Q_p+Q_{dr}}{S(H-h)}K_l - \left(\frac{Q_{du}+Q_p}{S(H-h)}\right)K_u + \frac{Q_pK_s}{S(H-h)} \tag{20}$$

where Q_{dw} is the flow rate at which particles settle out of the well mixed space, Q_{dl} is the flow rate at which particles settle out of the lower layer, Q_{df} is the flow rate of particles that flow from the upper to lower layer across the interface, Q_{du} is the flow rate at which particles settle out the upper layer and Q_{dr} is the flow rate at which particles cross the interface from the lower to upper layers. These quantities are evaluated as follows:

$$Q_{dw} = v_vA_v + v_dA_d + v_uA_u \quad Q_{dl} = v_vA_v^l + v_dA_d + v_uA_u \quad Q_{df} = v_uA_u$$

$$Q_{du} = v_vA_v^u + v_dA_d + v_uA_u \quad Q_{dr} = v_dA_d \tag{21}$$

where v_v is the deposition velocity of a particle depositing on to a vertical surface, v_d is the deposition velocity of a particle depositing on to a downward facing horizontal surface, v_u is the deposition velocity of a particle depositing on to an upward facing horizontal surface, A_v is the total area of vertical boundaries in the space, A_{lv} is the area of vertical boundaries in the lower layer, A_{uv} is the area of vertical boundaries in the upper layer, A_u is the area of the an upward facing boundary and A_l is the area of downward facing boundaries. The deposition velocities can be evaluated using equations presented in Table 2 in Lai & Nazaroff (2000). In the two-layer model, the interface is as a 'ficticious' rigid boundary through which fluxes can occur. In dimensionless terms these equations become become:

$$\frac{d\kappa_{wm}}{d\tau} = -(1+\alpha_{dw})\kappa + \kappa_{in} + \kappa_s,$$

$$\frac{d\kappa_l}{d\tau} = \frac{-(1+\alpha_{dl})\kappa_l + \alpha_{df}\kappa_u + \kappa_{in}}{\zeta},$$

$$\frac{d\kappa_u}{d\tau} = \frac{(1+\alpha_{dr})\kappa_l - (1+\alpha_{du})\kappa_u + \kappa_s}{1-\zeta}, \tag{22}$$

where $\zeta_{di} = Q_{di}/Q_{in}$ represents the dimensionless forms of the various deposition flow rates defined in (21). The subscript I can represent the subscripts *w*, *l*, *f* , *u* or *r*. By accounting for these additional mechanisms several new dimensionless parameters are introduced. In the limit of large particles, the deposition velocities to upward facing surfaces reduces to the settling velocity, while the deposition to downward facing and vertical surfaces reduces to zero and the equations presented section 2 are recovered.

Rather than consider the transient evolution to steady state, based on the discussion and observations made earlier, the focus is on the ultimate steady states, which is shown to be

$$\kappa^{(a)} = \frac{\kappa_{in} + \kappa_s}{1 + \alpha_{dw}}$$

$$\kappa_l^{(b,c)} = \frac{(1 + \alpha_{du})\kappa_{in} + \alpha_{df}\kappa_s}{1 + \alpha_{dl} + \alpha_{du}(1 + \alpha_{dl}) - \alpha_{df}(1 + \alpha_{dr})}$$

$$\kappa_u^{(b,c)} = \frac{(1 + \alpha_{dr})\kappa_{in} + (1 + \alpha_{dl})\kappa_s}{1 + \alpha_{dl} + \alpha_{du}(1 + \alpha_{dl}) - \alpha_{df}(1 + \alpha_{dr})}$$

(23)

Step-Up Case

For the step-up situation considered previously (i.e. $\kappa_{in} = 1$ and $\kappa_s = 0$) again the upper to lower layer concentrations in the two-layer system are compared. The lower layer concentration is also compared to the concentration in the traditional well-mixed space.

$$\frac{\kappa_l^{(b,c)}}{\kappa_u^{(b,c)}} = \frac{1 + \alpha_{du}}{1 + \alpha_{dr}}$$

(24)

Because α_{du} includes deposition to vertical and horizontal surfaces, while α_{dr} only involves deposition to a downward facing horizontal surface, it is readily seen that $\alpha_{du} > \alpha_{dr}$ and, therefore, $\kappa^{(b,c)}{}_l > \kappa^{(b,c)}{}_u$??. Once again for the step-up case the concentration in the lower layer is always greater than it is in the upper layer, even with the additional settling mechanisms for fine and ultrafine particles. Now the lower layer concentration in the two-layer system is compared to the concentration in the traditional mixing space

$$\frac{\kappa_l^{(b,c)}}{\kappa^{(a)}} = \frac{(1 + \alpha_{du})(1 + \alpha_{dw})}{1 + \alpha_{dl} + \alpha_{du}(1 + \alpha_{dl}) - \alpha_{df}(1 + \alpha_{dr})}$$

(25)

It is relatively straightforward to show to that the denominator is greater than the numerator. Therefore, as observed previously, occupants are exposed to higher levels of contaminants in the low energy system when a step-up case is considered.

Point-Source Case

In the same manner the point source situation ($\kappa_{in} = 0$ and $\kappa_s = 1$) can be considered, where

$$\frac{\kappa_l^{(b,c)}}{\kappa_u^{(b,c)}} = \frac{\alpha_{df}}{1 + \alpha_{dl}} \tag{26}$$

Now, from (21) it is known that $\kappa_{df} < \kappa_{dl}$. Therefore, the lower layer concentration is always less than that in the upper layer. Similarly

$$\frac{\kappa_l^{(b,c)}}{\kappa^{(a)}} = \frac{\alpha_{df}(1 + \alpha_{dw})}{1 + \alpha_{dl} + \alpha_{du}(1 + \alpha_{dl}) - \alpha_{df}(1 + \alpha_{dr})} \tag{27}$$

Once again, it can be shown that the denominator is less than the numerator. Therefore, as observed previously, occupants are exposed to lower levels of contaminants in the low energy system when a point source is considered.

4.0 Conclusions and Recommendations

4.1 Conclusions

4.1.1 Passive Contaminants

This study investigated the transport of a contaminant in a displacement ventilation system with a single source of buoyancy. In order to study this problem for passive contaminants, the 'step-down' method was used, where the space was initially filled uniformly with contaminant. Then fresh uncontaminated air was introduced into the space through the vent. For a passive contaminant, the results were equivalent and exactly opposite to the 'step-up' method, where contaminant entered an initially uncontaminated space.

The analytical solutions indicated that this problem displayed some interesting, and perhaps unexpected, behavior. It is widely believed that along with its efficiency at removing buoyancy from a space, displacement ventilation is also better at removing a contaminant. However, this study suggests that this may not be true. Displacement ventilation takes advantage of the natural stratification that will arise in a space, extracting air of the warmest temperature that naturally rises to the top of the room. Nevertheless, this extracted air may not be the most contaminated since the velocity field for these low energy systems advects contaminants towards the interface between the lower and upper layers. Thus, the contaminant extraction process does not utilize the mechanism that offers displacement ventilation its improved energy efficiency. Instead, the concentration at the outlet vent is relatively insensitive to the ventilation scheme, giving similar overall flushing rates.

In this study, the peak level of contaminant for this 'step down' analysis occurred at the thermal interface between the upper and lower layers. Therefore, depending on the location of this interface, while people sitting down may be in the clean lower layer, someone who stands up may have their head at the peak concentration height. As such, the height of the interface is not only important from a comfort perspective, but also becomes a critical parameter in the design of a building for indoor air quality (IAQ) since it appears to be imperative to locate it above head height.

Another issue to consider is the following. In this experiment, the room was filled with a contaminant initially and then fresh air was introduced through the lower vents. What if the source of contaminant was the ventilation system? This corresponds to the 'step-up' case discussed above. Now, the exact opposite system to that just described exists, which means that the highest concentration of contaminant will exist in the 'occupied' lower layer. There is a simple explanation as to why displacement ventilation does not exhibit the same benefits for removal of contaminants and it does for heat. The efficiency of displacement ventilation at removing heat stems from the fact that warmest air is always extracted from the top room. In terms of a passive contaminant, this high efficiency mechanism does not take place since the location of maximum contaminant and temperature do not coincide.

Finally, the displacement and mixing systems were compared for the same volume flow rate. In practice, displacement ventilation offers two methods of energy savings. Either the incoming air is introduced at a warmer temperature than with a mixing system, thus saving energy on the cooling system, or the incoming flow rate could be reduced, thus saving on fan power. This study suggests that the first option is the more sensible one in terms of IAQ, since a lower flow rate will yield even lower contaminant removal efficiency. It may often also the most sensible strategy from an energy approach.

It is important to point out that the flow modeled in this work is forced displacement flow. However, there is no reason to expect the behavior to be any different for a buoyancy-driven flow such as displacement natural ventilation. The only difference is that in one case the flow is forced through the space and the plume only provides the resulting stratification, while for natural ventilation the buoyancy provided by the plume leads to a stratification that in turn causes the flow through the system. Once both systems reach steady state they behave in a similar manner and, therefore, all the analysis and observations made should hold for both systems.

For the other common case, an isolated release at a specific location within a space, this model may not be applicable, except for the specific case where the source of contamination is in the plume. While it is widely believed that studying the 'step-up', 'step-down' and isolated-release cases are equivalent (Coffee & Hunt 2005), displacement ventilation does not dilute the space as effectively as mixing ventilation. Therefore, local concentrations of contaminant should be higher, and the efficiency of removal will depend on the location of the source.

4.1.2 Particulate Contaminants

In this report, the transport of particulate contaminants in a displacement ventilated space was considered. Three models were compared, one representing a traditional ventilation system and the other two representing the displacement-ventilated space. Three types of contamination scenarios were considered, namely a step-down, a step-up and a point-source contaminant. Several important differences between the traditional and low energy systems were noted.

It is often argued that studying one of the step-up, step-down and point-source contamination scenarios is equivalent to studying them all. This is not necessarily the case for the low-energy displacement system described here. For a passive contaminant, it is true. However, the effect of gravitational settling for particulate contaminants introduces an 'irreversibility' or 'preferential direction' to the flow, which destroys the symmetry of the step-up, step-down and point-source scenarios. Therefore, it is important to understand the differences between these three scenarios as all three give important information about real contamination distributions. Fortunately, the governing equations presented in this paper are linear, and, therefore, each scenario could be studied separately, and the superposition of solutions could be used to study a more complex situation that combines all three.

It is widely believed that low energy displacement ventilation systems are better than traditional mixing systems at removing contaminants from a space. This is because there is a belief that these systems will use the same mechanism for contaminant removal as they do for heat removal, where there are clearly more efficient. However, the heat extraction problem exploits the natural stratification that develops, extracting the warmest air that naturally sits at the top of the room. However, there is no physical justification as to why this location should also correspond to the location of maximum contaminant concentration. In fact, many times it does not correspond, as shown for a passive contaminant.

In summary, it is important to consider the source of contamination carefully in order to determine the end result. For example, as shown in this study, for an external contaminant entering the building, the traditional mixing system will outperform the modern displacement one. However, if the contaminant is from an internal source, the low-energy system appears to do a better job of keeping the contaminant away from occupants. The reason for this is that very different vertical concentration profiles can evolve depending on the source location.

4.2 Recommendations

While this study sets some important groundwork for the study of passive and particulate contaminants in low energy ventilation systems, it is by no means complete. There are many possible directions for future work, including the following.

1. Point-Source Contaminants: The work done so far can only account for contaminants that are released within the thermal plume of a heat source. Further experimental work on both small scales for passive contaminants and large scales for particulate contaminants should be conducted to understand the transport of contaminants from a point source of arbitrary location. Simple mathematical models and some asymptotic analysis can be developed to account for such sources.
2. Network Models: The model presented here is for a single ventilated space. Most buildings consist of multiply connected spaces. Therefore, it would be useful to incorporate the current model into network models that would allow for the study of full-scale buildings.
3. Case Study: The experimental work presented here, while essential for understanding the fundamental physics of the problem, is for an idealized laboratory case. Case studies of various actual buildings in California need to be conducted in order to incorporate many further "real life" effects into these models.
4. Transient Sources: All the contaminant sources in the models presented here are temporally continuous, while many real sources are intermittent. A study of the influence of transient contaminant sources is needed, particularly related to exposure indices such as the EPA's Excess Lifetime Cancer Risk (ELCR), which are defined based on temporal averages of exposure.
5. Economic Study: The study presented here focuses on the flow and transport physics of displacement ventilation. Using the information obtained, a socio-economic study needs to be conducted of where and why such displacement systems would be viable in terms of health, current costs and future monetary savings.
6. Other Low Energy Systems: The methods presented here should be extended to other low energy ventilation systems, such as Under Floor Air Distribution System (UFAD).
7. Further physics: The models need to be extended to include additional effects that have been neglected so far, such as multiple heat sources, further deposition mechanisms, resuspension of contaminants and coagulation. Additionally, the models in this study are for monodisperse contaminants and should be extended to incorporate the polydisperse nature of real particles.
8. Uncertainty: Flows in real buildings are incredibly complex and due to this complexity certain parameters can never be known with absolute certainty. Therefore, studies need to be conducted to incorporate this uncertainty into models using stochastic modeling techniques.
9. Estimate Health Effects: Understanding the distribution of contaminants in a space in only half the problem when studying the impact of these contaminants on human health. Depending on flow direction, speeds and many other factors occupants inhale varying amounts of surrounding contaminants. Therefore, this study should be coupled with inhalation studies to quantify effective exposure.

4.3 Benefits to California

In California, a large portion of all electricity generated is used in the heating, cooling and ventilation of residential, commercial and industrial buildings, with a significant portion of this being consumed by expensive and energy-inefficient air-conditioning systems. In fact, according to California Senate Bill 1790 (2002), air-conditioning load constitutes 28 percent of

California's peak electricity demand, the largest single component of electricity demand. Therefore, the development of low energy ventilation strategies is critical to minimizing the amount of electricity consumed in the state of California and dealing with periods of peak demand.

This study presents and studies two forms of low energy ventilation that may aid in reducing this demand. These are natural ventilation, which could be implemented in regions of California with a more temperate climate (e.g., coastal California), and displacement ventilation, which can be used in areas with very high summer temperatures (e.g., desert areas). The information gained from this study provides a basis for the efficient design of ventilation strategies that maximize indoor environment quality and minimize electricity consumption.

Additionally California can benefit in the following manners:

1. This study can offer guidance to the California Indoor Air Quality Program run by the Department of Health Services.
2. The models can be used as an additional guideline for estimating the minimum required flow rate beyond standards (such as ASHRAE 62-2001).
3. This study could be used to estimate values of the EPA's Excess Lifetime Cancer Risk (ELCR), which correlates exposure to certain contaminants to risk of developing cancer. Additionally, it could be combined with the NIH's Hazardous Substances Data Bank and the EPA's Integrated Risk Information System (IRIS).
4. The models presented here can act as an additional guideline for the assessment of California Labor Code 6300 on IAQ. Costs associated with employee health problems are estimated to be between $30-150 billion.
5. The work presented here could be used to assess current California ventilation standards from an analytical perspective.
6. The models can be integrated with other studies such as the CBR (Chemical, Biological and Radiological Protection/Planning Center) at Lawrence Berkeley National Laboratory.
7. This study can be used to estimate the optimal location of contaminant sensors, so as to detect a contaminant as early as possible.
8. The approaches presented here can be used to estimate the viability of certain ventilation strategies for buildings that are very sensitive to contamination such as hospitals (e.g. by the California Hospital Association to minimize secondary infection) or museums (e.g. by the California Association for Museums to protect sensitive artifacts).
9. Agriculture is an important part of California's economy. Low energy ventilation, typically natural ventilation, of life stock housings and greenhouses helps maintain low costs. However, many animals and plants produce large quantities of contaminants that can affect the final product's quality and reduce output. Therefore, the information from this study can be used to implement effective ventilation that can lower costs, while maintaining high air quality.

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