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Indoor Air Quality Factors in Designing a Healthy Building

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Abstract

Current guidelines for green buildings are cursory and inadequate for specifying materials and designing ventilation systems to ensure a healthful indoor environment, i.e. a "healthy building," by design. Public perception, cultural preferences, litigation trends, current codes and regulations, rapid introduction of new building materials and commercial products, as well as the prevailing design-build practices, pose challenges to systems integration in the design, construction and operation phases of modern buildings. We are on the verge of a paradigm shift in ventilation design thinking. In the past, thermal properties of air within a zone determined heating, ventilating, and air-conditioning (HVAC) specifications. In the future, occupant-specific and highly responsive systems will become the norm. Natural ventilation, displacement ventilation, microzoning with subfloor plenums, along with the use of point of source heat control and point of use sensors, will evolve to create a "smart" responsive ventilation-building dynamic system. Advanced ventilation design tools such as the modeling of computational fluid dynamics (CFD) will be used routinely. CFD will be integrated into air quality and risk assessment models.

Introduction

At the beginning of the 21st century, "green building design" can be seen as being at the confluence of emerging societal interests, all seeking to use resources wisely in the design of health-promoting environments. The last decade saw the concept of the "global village" emerge through terms such as "sustainable development," "ecotourism," "ecotaxation," "socially responsible investment," and "green architecture," among others. Organizations representing private and public sector interests lay claim to these terms and attempt to establish the consensus to operational definitions, often suited to their perspective and constraints. Others are asking for a civil society that promotes social justice equality, and conservation through the actions of the public and private sectors. Green building concepts are simply a manifestation of these changes in our western society (1).

Are "healthy buildings" a subset of "green buildings?" In the absence of widely accepted definition criteria, the answer is unclear at this time. The concept of a "healthy building" is still polemic, with no consistent guidelines. It is important to recognize that, although indoor air quality (IAQ) is an important determinant of healthy design, it is not the sole determinant, as occupants experience the full sensory world. Other parameters include lighting, acoustics, vibration, aesthetics, comfort, and security, along with safety and ergonomic design factors. Drawing upon contemporary accounts of inner city asthma rates and cases of sick buildings, the building professions need more than cursory and inadequate guidance to incorporate indoor air quality considerations into their "healthy building" design.

Problems with IAQ have traditionally been associated with older and poorly maintained construction (e.g., threats arising from the degradation of asbestos fireproofing or from *Legionella* contamination in cooling towers). Increasingly, however, building-related illnesses caused by poor air quality are being documented in newly constructed or recently renovated buildings. Poor IAQ is being blamed for a host of problems ranging from low worker productivity to increased cancer risk, and the resulting responses have produced action as severe as building demolition. Our building interiors, once thought of as providing safe havens from the pernicious effects of outdoor air pollution and harsh climates, may actually be more polluted than the surrounding ambient environment.

As recently as 1994, the Building Owners and Managers Association (BOMA, Washington, DC) considered concerns with IAQ as "overblown" by activists who "continue to portray IAQ as an epidemic sweeping the nation." OSHA proposed rule on non-industrial workplace air quality was published in the US Federal Register April 5, 1994. BOMA, in response, said that reports of IAQ problems were overplayed in the media, and that current concern for IAQ represents "mass hysteria…fueled by misinformation rather than conclusive scientific evidence (2).[1] Rather than being the product of a newly vocal minority, however, the increased publicity regarding IAQ at *this* time is representative of the convergence of many factors. These multifaceted attributes include a heightened public perception, litigation trends, and the current regulatory status, as well as long-term changes in construction systems, coupled with a shift in building occupancy and functional types.

Rising expectations of occupants for healthy work environments are forcing building owners, operators, and managers to reconsider the importance of IAQ. In a more recent survey conducted by the International Facility Managers Association, IAQ and thermal comfort were the top operational issues in all types of buildings (3). According to a recent telephone survey of building tenants commissioned by BOMA, "control and quality of air" was the fourth most important criteria for attracting and retaining tenants. The study also showed that quality heating, ventilating, and air-conditioning (HVAC) is extremely important for retaining tenants (4).

The problems with defining good IAQ are both multimodal and unprecedented, requiring a multidisciplinary approach for their investigation and resolution. This article

[1] BOMA seemed to reflect concerns from building owners and construction professionals, who pointed to the need for source control by manufacturers. At the time BOMA urged federal efforts looking at causes, such as carpets, paints and coatings, and emissions from office equipment. Fundamentally their argument emphasized prevention at the manufacturing level, not management, once the sources were in the building.

begins with a description of several factors that lead to the wide acceptance that buildings and their IAQ can adversely impact occupants' health. It continues with an offering of design guidance and evaluation tools to advance the state of practice. The article concludes with practical advice for evaluating the healthfulness of IAQ.

IAQ Health Factors

Trends in Public Perception

The general public has become much more aware of their own risk, the risks they are willing to accept for their children[2], and the risks they expect to encounter in public buildings such as schools and hospitals. Much of this increased awareness is an offshoot from the widespread "fiberphobia" that swept through this country at the height of the asbestos debacle. The original concerns were justified in that asbestos materials in many school buildings were degrading and producing an exposure hazard, but many nonhazardous installations were also summarily replaced at great expense. Although in the subsequent fifteen years, asbestos policy has been refined to more reasonably address actual risk, the public fear of fiber contamination from construction materials has not abated.

Recognition of hazardous waste sites in our communities heightened by the widely celebrated Love Canal and Times Beach cases have added "chemophobia" to our lexicon. Now "sporophobia," or the fear of microbial agents and their infectious, allergenic, and toxigenic effects, is emerging. One example is that of *Stachybotrys chartarum* (also referred to as *S. atra*), a fungal spore associated with the widely publicized infant mortality cases in Cleveland, which evokes fear regardless of how much is present or the potential for exposure (5). The popular press is featuring the "toxic mold" phenomenon with stories such as the one that appeared in USA Weekend December 3-5, 1999, reaching millions of households. Radon and formaldehyde are but a few of the chemical substances that were little known not too many years ago and are now part of the vocabulary of the average homeowner who is increasingly wary of widespread "silent" contamination.

One of the great medical achievements of the twentieth century was the extension of life expectancy, but this has resulted in an overall increase in the age of the population, particularly in North America, Japan, and northern Europe. An aging population brings with it all of the diseases of the elderly (cancer, immunological disorders, cardiovascular problems, bone frailty, and skeletal and muscular structure degeneration). As such, the people who are generally least aware of the risks posed to their health are also the ones most susceptible to hazards. This situation is further exacerbated by the increased amount of time elders spend indoors. To the extent that the workforce is also aging, indoor environmental quality and safety will continue to become more important in the design and construction of facilities.

Representative of another general change in the health of the populace is the dramatic rise in allergic diseases. The first documented case of hay fever was recorded 150 years ago by a British physician, who had to collect data for another ten years before he could find seven additional cases[3]. By 1990, it was estimated that 20 per cent of the population suffers from some form of allergic disease (6). Estimates now appear even higher (7). This tremendous increase in adverse health effects is a relatively new

[2] Concern for children's health has become the shield against Congressional budget cutting or interference with promulgating clean air standards for particles and ozone. The EPA now has an office on children's health. NIEHS is sponsoring several centers focusing on children. The recently passed Food Quality Protection Act requires pesticide manufacturers to assess multi-pathway, multi-contaminant impacts on children.

[3] Reported at NIH Conference, Washington, DC.

phenomenon, and it is implicated as a risk factor associated with the reported symptoms that occur in buildings.

Fundamentally, however, occupants still trust their eyes and nose to sense what is in the surrounding environment. The presence of displaced odors (e.g., a smell normally associated with a chemical process, but noticed in an occupied space) is increasingly observed, questioned, and reported. Many unrecognizable odors may produce a chemical input to the fifth cranial nerve, thereby resulting in a protective gag reflex. The connection between the sensory awareness and the body's protective responses mandate that the simple sensory awareness of the presence of an atypical chemical in the surroundings will initiate other symptomatic responses. Stress adds a further complication when the urge to flee a perceived environment is overridden by social conditioning, and often, by economic need.

Basically, the concept of health is no longer thought of as simply the absence of disease. The World Health Organization (WHO) has done much to advance a definition of health that encompasses mental and physical well being, access to clean and safe environments, and health care (8).

Trends in Ventilation Design Philosophy

Changes in construction, materials, energy cost, and health concerns are shifting ventilation philosophy once again. Buildings are now a source of contamination. Health, economics, and aesthetics are becoming more important than comfort in determining the specification for ventilation. Figure 1 is an extension of the concept originally presented by Fanger in 1996. The debate over ventilation is very contentious, as exemplified by American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. (ASHRAE) conceding Standard 62-1999 to a status of "continued maintenance," rather than an accepted standard by consensus. We expect to be in a transition period over the next five to ten years as the design industry struggles to incorporate qualitative attributes into prescriptive standards. Performance criteria based on developing indices for quantifying the health hazard of air comprised of a mixture of contaminants or subjective rating schemes are likely to emerge.

Insert Figure 1

Interestingly, these tenets are beginning to shift the paradigm for ventilation design. As described by Fanger (9), in the nineteenth century poisonous vapors were attributed to foul air. Bensuade-Vincent & Stengers (10) retell the pre-germ theory beliefs that putrid emanations were expelled from the body. In 1869 Lewis Leeds (11) addressed at the Franklin Institute that "We are thus to conclude that our own breath is our greatest enemy."

In the earliest part of the twentieth century , the concern for contagious airborne infection prevailed. Tuberculosis and influenza epidemics fueled the debate between mechanical and natural ventilation requirements. Still, the concern was health, and the source was people. Only when heating, ventilating, and air-conditioning became widely available, and Yaglou published his work on acceptable ventilation to control body odors, did the focus shift to comfort and productivity (12). By the middle of the twentieth century, vaccines were available and many communicable diseases were better understood. Health concerns were no longer motivating ventilation requirements while people remained the primary source.[4]

In the future, advancements in sensor technology, micro-engineered machines, and computerized simulation will position ventilation to be more customized to personal desires. This will lead to further shifts in ventilation philosophy because the bulk properties of building air will not be managed for the mean preference among occupants. Some will enjoy an "indoor spring day" while others acclimatize for their tropical vacation.

Litigation Trends

In general, we are in an increasingly litigious society, i.e., more aggressive action by lawyers, individuals, and small groups. Fueled in part by the constant media exposure of IAQ problems, occupants are no longer taking a "wait and see" attitude toward suspect reactions.

Several multimillion dollar settlements or awards have been won by plaintiffs. Several U.S. Environmental Protection Agency (EPA) employees working in the Washington, DC, headquarters claimed chronic exposures to air toxins released from furnishings, including carpeting during renovation (*Buhura vs. SSW Investors, Inc., 1993*). Similar claims of exposure to off-gassing materials from recent construction or renovation, along with inadequate ventilation, have been the basis for IAQ lawsuits in courthouses, homes, schools, hospitals, ice skating rinks, and office buildings. Other claims have included pesticides in carpets, molds from water-damaged materials, chlorine from swimming pools, and faulty combustion systems. Contractors, building owners, manufacturers, and designers have been named as defendants in lawsuits, together whose awards have ranged in excess of $25 million.

A new wave of class action suits has appeared since the numerous asbestos suits filed in the 1980s and early 1990s. These include lawsuits filed against manufacturers of paint containing lead, as well as manufacturers of latex gloves. In both cases, the route of exposure asserted is contaminated dust indoors. In the lead case, direct ingestion as well as inhalation of lead paint dust in homes placed children at risk. The cases involving latex exposure followed a marked increase in the use of latex gloves in the health care professions as well as in other service jobs. This increase was a direct result of requirements for universal protection against bloodborne pathogens (HIV, hepatitis B, and others. The first clinical case of latex allergy was documented in 1970. To date, it is estimated that upwards of 7 per cent of medical-related personnel are allergic to latex. (13, 14).

The concerns about potential labor unrest and workforce troubles have prompted many pretrial awards with respect to sick buildings, and for those cases that do go to trial, juries have been generous with both blame and awards. Large settlements have been awarded to occupants complaining about multiple chemical reactions resulting from exposure to commonplace materials, such as carpets, paints, and even computer workstations. In addition, there is an increased willingness to link nonspecific causes with indirect effects. For instance, indoor air pollution is even being blamed for a host of

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[4] M. Addington presents the history of ventilation in a fascinating chapter to be published in Indoor Air Quality Handbook, eds. Spengler, Samet, and McCarthy, McGraw-Hill, 2000.

nonphysical complaints, including poor school performance, for which no direct epidemiological relationship has yet been established.[5]

Current Regulations

The rise of IAQ-driven litigation has yet to result in any substantial change in the U.S. government's involvement in developing and enforcing regulations. Federal standards are limited to those under the jurisdiction of the EPA, the Department of Housing and Urban Development (HUD), the Consumer Product Safety Commission, and the Occupational Safety and Health Administration (OSHA), most of which focus on specific situations or particular materials. Given the wide scope of these agencies' health and safety activities, it may seem surprising that their regulations significantly penetrate the building industry in only three areas: asbestos, lead, and formaldehyde.

EPA's efforts have been on building surveys, product testing, model development, and education. HUD has the PATH program to advance technologies into housing. With appropriations from Congress, HUD has a Healthy Homes Initiative run out of their lead safety office. Public education and survey demonstration projects will form the basis of HUD's efforts.[6] The one attempt at comprehensive regulations for IAQ was unsuccessful. In 1994, OSHA proposed rules governing ventilation, maintenance, IAQ reporting, and restrictions on tobacco smoke in office buildings. The Federal Register (April 5, 1994) proposed rulemaking elicited voluminous responses from tobacco, HVAC, and real estate industries. Changes in the U.S. Congress at that time made it inopportune to expand the regulatory reach of government, and OSHA never pursued final IAQ rules.

While the federal government's activities have mostly been directed at education and research, some states have pursued IAQ through codes and regulations. The California Proposition 65, enacted in the early 1990s, bans the use of carcinogenic substances in building materials, and through labels and warnings, accelerated the growth of smoke-free workplaces. Minnesota had the first IAQ standards for ice skating arenas, followed by Rhode Island and Massachusetts. Washington state, following an initiative to specify low emission office furnishings for a new state office building, proposed new statewide requirements for ventilation, inspection, and maintenance to improve IAQ. Quite recently, New York City's Department of Design and Construction has issued guidelines for the design and construction of high performance buildings that include many IAQ-enhancing features (14).

From within the industry there are numerous activities addressing various aspects of IAQ. Industrial associations, like the North American Insulation Manufacturers Association, the National Association of Home Builders, BOMA , Sheet Metal and Air Conditioning Contractors National Association, among others, are also becoming increasingly involved in the IAQ aspects of building design[7]. ASHRAE has recently revised its Standard 62-1999, *Ventilation for Acceptable Indoor Air Quality*. This latest

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[5] Personal observation following extensive remediation of IAQ problems in a local high school. Legal aftermath included workman's compensation cases and lawsuits brought by parents, claiming disruption of schooling during a critical time hindered children's performance, thus depriving them of competitive college applications to some schools.

[6] www.hud.gov

[7] www.naima.net; www.nahb.org ; www.boma.org www.smacna.org; www.aia.org; www.paint.org; www.acgih.org

version of "model" ventilation standards distinguishes between human-generated contaminants and non-human sources. ASHRAE is struggling to accommodate the conflicting objectives of reducing energy use (lower ventilation), while simultaneously maintaining an acceptable IAQ (increasing ventilation). Prescriptive codes requiring the calculation of source strength and dilution to achieve target concentrations will never work to the satisfaction of heterogeneous occupants, particularly given the scientific uncertainties about the effects of mixtures and mechanisms leading to sensitization, hormonal disruption, or carcinogenicity. Performance-based concepts for ventilation standards that acknowledge the primacy of healthy indoor air will prevail in the 21st century, especially as linkages between healthy building design and business profitability become increasingly apparent (15, 16, 17, 18).

Guidance for Building Systems

Among the first to explore the relationship between occupant complaints and building conditions was the work of Black & Milroy on air-conditioned offices in 1966. Concern about IAQ grew throughout the 1970s with the emergence of sealed buildings and pressures to reduce energy. By the early 1980s, the prevalence of building-related problems had most researchers agreeing there was a phenomenon that is now called "sick building syndrome," or SBS. A working group of experts for the WHO in 1982 provided a definition describing SBS. By the mid-1980s, Akimenko et al (1986), reporting on another WHO international expert group, estimated that "up to 30 per cent of new or re-modeled buildings may have an unusually high rate of complaints." (19) The report acknowledges between-country variability and the somewhat arbitrary definition of what constitutes building-related complaints. By this time, investigators in the U.K., Denmark, and Sweden had begun systematic studies on the prevalence of symptoms among office workers and the possible relationship between design, mechanical, managerial, and environmental factors. Mendell reviewed these and other studies in an attempt to identify common identifying factors (20). Brightman & Moss summarize the findings of these early studies involving multiple buildings and extends the review to the important European and U.S. studies of the late 1990s (21).

One tautology is that IAQ problems are a consequence of the energy crisis and the subsequent tightening of buildings to reduce infiltration. Although it is true that ASHRAE revised ventilation guidelines suggesting that 5 cubic feet per minute (cfm)/person did contribute to poor IAQ in some instances, the more significant influences have occurred over the last forty years as basic envelope systems transitioned from heavy site-built construction to lightweight pre-manufactured systems. Many of the materials and systems used in older construction were more forgiving of variations in temperature and humidity, and they often acted as filters or sponges for absorbing contaminants. Today's lightweight systems with their gaskets, seals, and tight tolerances are intended to function as a barrier to both indoor and outdoor conditions rather than as a floating filter permeable to moisture and gaseous compounds. As a result, not only have these systems tended to exacerbate the precursor conditions for poor air quality, but they have also resulted in a reduction of the sink area for contaminant absorption. These impervious surfaces are then covered with a wide array of non-natural finish products (synthetic fiber carpets, vinyl wall coverings, and plastic moldings) that are glued in place rather than mechanically fastened. The unforgiving envelope is now sealing in complex chemical formulations, many of which we have little experience with. The chemical composition of our modern interior environment is substantially different than that of the first half of this century.

As a different mix of pollutants is accumulating in our interiors, the quality and quantity of the supply air has also been degrading (22). The proliferation of information technology into even the smallest businesses has resulted in the ceding of infrastructure space to electronic communication. Ceiling plenums are quickly being filled with cables, adding outgassing sources while reducing the airflow area. Duct liners, which are steadily replacing external duct insulation, result in supply air exposure to large surface areas of synthetic and occasionally friable materials. These changes are coupled with the general shift in HVAC systems from constant air volume (CAV) to variable air volume (VAV), which was spawned by the energy crisis of the 1970s. VAV systems are more energy efficient precisely because of an overall reduction in supply air. Less dilution and absorption of contaminants is taking place, while contaminant generation is increasing.

This unforgiving combination of materials and systems has then been increasingly deployed in speculative construction for which the interiors must be more flexible to accommodate a greater range of possible functions. Unprecedented, and often irreconcilable, many contemporary building systems combine activities that have historically been separate. For instance, shopping malls may have ice-skating rinks as features, and the routine of cleaning ice with gasoline- or propane-powered machines introduces high levels of nitrogen dioxide and carbon monoxide into the air. Small dental clinics may be located inside high-rise office towers, introducing a variety of controlled chemicals with rigorous ventilation requirements into a building that is ill-equipped to support such specific needs. The trend toward light manufacturing and small biotech laboratories has resulted in these functions being distributed into office-like environments. More widespread, however, is the reconfiguration of today's standard office environment arising from the proliferation of information technology. With its computers, copiers, and printers, the typical office resembles a traditional manufacturing facility in terms of thermal and environmental conditions. The heat generated from personal computers alone is estimated to contribute more than half of a building's total heat gain.[8] HVAC systems designed for generic office spaces can no longer meet the varying and complex demands posed by new occupancy types.

Interior fit-outs in speculative construction, particularly to support the trend toward smaller tenants with high turnover, have capitalized on finish materials to provide the visible amenities desired by these new occupants. Rapidly entering the market are a wide variety of composite surface materials and wall systems, as well as the new trend for integrated office furniture, that attempt to meet several different criteria within a single unit. Surface texture and finish for the client's amenity will often be coupled with insulation for thermal and acoustic purposes and then further stiffened to allow installation as a stand-alone partition. These combinations of materials often introduce new problems; for example, a common combination mates impervious surface materials with cellulose backing, creating ideal breeding grounds for molds and fungi. Of even greater concern is the chemical interactivity between these sandwiches of foams, adhesives, plastics, and fabric. Fleeced and porous surfaces in offices have most certainly

[8] Personal computer power wattage has increased with computational capacity, where 100-400 watts might be typical of office PCs today.

increased over the last two decades, with fabric-covered partitions and acoustical ceiling tiles. Levin states that large amounts of surfaces in office buildings never get cleaned. Freestanding partitions are more than three times the floor area (23).

Unducted air supply often uses the ceiling space as a plenum. The surface area in contact with air can be twice the floor area. These surfaces may include unfinished wallboard, fire proofing, fiberglass, acoustical insulation, power and communication cables, and the top sides of ceiling tiles. While there is some experience with the individual materials, there is limited knowledge of emissions from many materials may interact with each other in our interior environments.

The American Institute of Architects provides a reference, the *Environmental Resource Guide*, to assist designers and specify various building materials[9]. This guide, while useful, does not provide specific recommendations, nor does it propose a methodology for selecting among a variety of manufactured products. Other schema are under development. The National Paint and Coating Association[10] offers a Hazard Material Identification System (HMIS) developed for shipping, fire fighting, and emergency spill response, modified for IAQ application. The American Conference of Governmental Industrial Hygienists [11] has a formula for assigning a threshold limit value for chemical mixtures. With modification to reflect product formulation from material safety data sheets (MSDSs)[12], a hazard index for a specific product is obtained.

Currently, there is no widely applicable procedure for evaluating the IAQ potential of products, or the combination of materials and systems in operation. The physical/chemical complexities of emissions from composite materials, sinks, and re-emission from furnishings, floor, wall, and ceiling components, as well as in plenums and ducts challenge the formulation of a simple discriminating selection scheme. The typical construction practices in the U.S. almost ensure that these complex issues will not be addressed beyond the simplistic specification to use low-emission paints. Although substantial progress has been made to characterize emissions from building products, paints, and equipment, predictive models reflecting complexity of interactions, variability, and human response lag behind (24, 25, 26).

The Building Construction Process

The process by which buildings are actually constructed can contribute to the indoor air quality problems, arising in part by the separation of responsibility among professions participating in the design and build teams. Financing and bidding constraints can also contribute to lack of construction quality resulting in buildings that simply do not perform well. In 1995, the American Thoracic Society, Medical Section of the American Lung Association, assembled an interdisciplinary group to assess the underlying causes of poor IAQ (27). Participating in the Santa Fe Workshop were architects, HVAC engineers, contractors, physicians, and industrial hygienists, among others. The process of designing, bidding, and building structures, and the role this played in the etiology of SBS was evaluated. It was concluded that the common

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[9] www.aia.org
[10] www.paint.org
[11] www.acgih.org
[12] Occupational Safety and Health Administration, Hazard Communication Standard (29CFR1910.1200), *OSHA Regulations (Standards - 29 CFR).*

design/bid/build system and its variants in the U.S. had a high likelihood of contributing to the problem.

The design/construction teams are not necessarily interactive. They have distinct responsibilities, do not participate throughout the project, and have different financial arrangements. Prime architects and general contractors rely on subcontractors hired usually based on the low bid. Further, contractors make most of their profits on *change orders*. Change orders occur under several circumstances, including improper or inadequate plan-specifications. With the *design/build* approach, the architectural and design professionals usually work for the construction firm. The construction company has an interest in containing costs by reducing the customization. Components such as HVAC systems have been standardized and repeatedly used for buildings constructed in different climate zones. To operate properly, the emerging, more sophisticated HVAC systems and control systems require more competence in design and construction. Large firms do not innovate quickly in part because it requires more expensive professional staff in building component design. On-site construction work is generally managed by the lead firm, but performed by subcontractors. Here again, the incentives are misplaced and deficiencies in some aspects of the building jeopardize performance in other areas. Even when high performance systems are designed, they may operate sub-optimally because of poor quality construction.

The preceding discussion, although lengthy, was necessary to convey that improved IAQ cannot be achieved by directing attention only on sources or ventilation. In some sense, SBS is symptomatic of a complex system involving manufactured materials, construction practices, legal and financial constraints, as well as human susceptibility, perceptions, and behaviors. This article alone cannot address all these aspects. Instead, we discuss one class of indoor contaminants, volatile organic compounds (VOCs), and various strategies to deal with them. We assert that there are tools (models) available to assess the consequences of sources and various ventilation designs. Further, these models can be used to predict thermal, moisture, as well as contaminant conditions inside buildings. The implication of architectural features (e.g. atria, windows, parking garages, loading docks, etc.), material specifications, and ventilation design on air quality can be known long before occupancy. With the tools described, along with others addressing moisture, air and thermal transfer through building envelopes, as well as lighting and acoustics, it is now possible to predict various IAQ-related aspects of building performance.

Designing high-performance buildings that provide healthful indoor environmental conditions will come to rely more on sophisticated source-ventilation models. So too, product “ecolabeling” and “building green” certification protocols will eventually appreciate the predictive aspects of these models.

Healthy Building Design

There have been many attempts recently to describe the attributes and process for achieving green buildings. The design, construction and use stages as well as the functional components of buildings, from the envelope to furnishings, have been addressed quite comprehensively in books and guidelines (15, 28). Table 1 reflects the standard list of design issues encountered in most building developments. Here, we annotated the relationship of these decisions to potential IAQ issues. The list serves the

point to instruct the designer that a myriad of choices will potentially contribute to IAQ through either the location and strength of sources or the ventilation component that influences exposure pathways and dilution.
Insert Table 1

Contaminant Sources

Table 2 is a partial list of chemical sources found indoors. Specification of coatings, adhesives, surface finishing, and furnishings are among a few actions used by architects determining the mixture of compounds and the frequency and rates of their emissions. However, for many other building materials, finishings, furnishings, and cleaners, information about chemical composition and emissions is less well known and beyond the architect's reasonable ability to specify acceptable alternatives. Phthalates and PCBs, for instance, are a class of compounds implicated as mammary carcinogens and/or endocrine disruptors. Rudel (29) summarizes the literature on these compounds indicating substantial indoor exposures. Pesticides are widely used indoor or around the outside of homes. In either circumstance elevated levels are reported indoors in a review by Lewis (30). The use of pesticides is made by the homeowner or facility manager and is not subject to design review.

Similarly, decisions about cleaning services and specific cleaning materials determine chemical loading indoors. Cleaning compounds introduced indoors are becoming more recognized for potential contribution to occupant symptoms. Adverse outcomes include adult onset asthma and acute irritation of the eyes and the respiratory tract (31, 32, 33). Suspected is acquired sensitization to the various ingredients and the reaction products formed when citric based solvents react with the ozone (34, 35, 36). The reactions of ozone with unsaturated hydrocarbons common in citrus-based cleaners, or added for scent to many consumer products, is just a recent example of how complex indoor air chemistry is, and unanticipated changes to IAQ from new formulations, new products or equipment.
Insert Table 2

The next section discusses modeling indoor VOC emission sources. These models will eventually be improved and coupled to ventilation models to predict indoor concentrations. Until then, "green building" recommendations suggest avoiding VOC emitting sources or substituting materials with lower VOC emissions. We cannot expect architects, unfamiliar with the health literature and product testing protocols, to understand the subtle nuances behind product claims. When chamber tests are used to evaluate off-gassing emission rates, usually the values are expressed as total VOC or are compound-specific (e.g. formaldehyde). Interpreting results requires knowledge about test protocols (42, 43).

Manufacturers reformulating products to test "environmentally friendly" may lower the total VOC emissions in the short-term test by substituting longer-chained hydrocarbons. Cometto-Muniz & Cain (44) and Cometto-Muniz et al (45) show that, within families of organic compounds (i.e., acetates, ketones, alkylbenzenes, aldehydes), more carbon atoms usually translates to an increased odor and irritation potential. These larger molecules generally have lower vapor pressures, but continue to off-gas over long periods of time. Hence, focusing only on the short-term total volatility may have a perverse effect by making indoor environments worse.

Modeling Indoor VOC Emission Sources

Quantifying the VOC emissions from the building materials and furnishings is both challenging and important, because the emissions account for a major part of the indoor pollutants (46). To design a healthy indoor environment, one requires accurate VOC emission models.

At present, most models for building materials assume that emissions are exclusively dominated by internal diffusion. These models, called diffusion models, use Fick's law to solve VOC diffusions in a solid under simple initial and boundary conditions. For example, Dunn (37) calculated diffusion-controlled compound emissions from a semi-infinite source. Little et al (38) simulated the VOC emissions from new carpets using the assumption that the VOCs originate predominately in a uniform slab of polymer backing material. These models, though based on the sound mass transfer mechanisms of the VOC species, still have limitations. They presume that the only mass transfer mechanism is the diffusion through the source material. The models neglect the mass transfer resistance through the air phase boundary layer, and also the air phase concentration on emissions. Although this may be true for some building materials, the assumption as a general one has not been well justified. The models also tend to solve the VOC diffusion problem analytically, assuming a one-dimensional diffusion process with a simple boundary and initial conditions. In practice, emissions can be three-dimensional with complicated initial and boundary conditions.

Recently, Yang et al (47) developed a numerical model with the following four parameters: initial VOC concentrations in the material, a solid-phase diffusion coefficient, a material-air partition coefficient, and the age of the material, to predict both short and long-term emissions. The model can predict the VOC emissions, if those four parameters are known. Since there are thousands of products on the market, it is not easy to obtain the four parameters for most of the products.

In addition to being primary sources of emissions, building materials can also affect the transport and removal of indoor VOCs by sorption (adsorption and desorption) on the interior surface. The re-emission of adsorbed VOCs from building materials can elevate VOC concentrations in the indoor environment (48, 49). Materials capable of depositing, adsorbing, and/or accumulating pollutants can influence the IAQ during the entire service life of a building (50). A low-emitting material at the beginning does not necessarily mean a clean one, because the material may emit a large amount of VOC over its useful life. Therefore, prediction of IAQ must take sorption into account.

All sorption models can be generally classified into two classes (51): statistical models and theoretical models. The classification is based on different understandings and assumptions regarding sorption. Statistical models view sorption as a two-way process in which the adsorption and desorption processes occur simultaneously and the interface between the air and the material is not always at equilibrium. In contrast, theoretical models always assume sorption as an instantaneous process and the interface between the air and the material is always at equilibrium. Hence, statistical models focus on the kinetics of the sorption process, whereas theoretical models focus on the overall effect, ignoring the kinetics of the sorption process.

A major shortcoming of statistical models lies in the fact that they have to obtain multiple model parameters by curve-fitting (nonlinear regression) with measured data often from a small test chamber. Though the principles of the models are reasonable, the model parameters that are obtained from curve-fitting may not represent what is intended. Furthermore, they may not be generalizable. The other problem with this kind of curve-fitting method is that it is difficult to validate the model. For example, the sorption-diffusion hybrid model (52) has some problems with the boundary condition; however, the model can still fit the experimental data well.

In contrast, theoretical models are more reliable, in that they can be validated. The model parameters have solid physical significance and can be measured *directly* from experiments, thereby eliminating the problem of curve-fitting. The numerical model proposed by Yang et al (47) can consider both the transport of VOCs in the room and the diffusion of VOCs inside the materials. It can predict the VOC concentration reasonably well basing solely on the material and compound properties, without resorting to expensive sorption measurements. Therefore, the numerical model has predictive capabilities. The disadvantage of this model is that it can only be used for homogeneous materials.

Given the complexity of indoor sources and the modeling limitations, quantifying the source strength for many indoor contaminants is not a straightforward task. There are still uncertainties in obtaining reliable data from contaminant sources, and more research in this area is needed.

Source Elimination

Even without the quantitative source information, it is still possible to design a healthy building through proper control of the indoor contaminants. The control strategies are to reduce the concentration of the contaminant in an indoor space below the threshold defined by standards and codes. Unfortunately, there are very few recognized indoor air quality standards. Applying ambient air standards from the US, WHO, or elsewhere covers very few chemical compounds (<50).[13] There is no guidance form recognized authorities for hundreds of chemicals. Even for those known or suspected to be human carcinogens, an “acceptable” level of indoor risk has not been established. Often occupants or parents of school children invoke the “precautionary principle” on a compound-specific basis, requiring levels to be below detection limits, or essentially removed from indoor environments.

Professional microbiologists have resisted sanctioning guidelines for airborne fungal counts (47). Short of identifying and removing specific organisms (e.g. *Aspergillus*, *Stachybotrys*, *Penicillium*, and others), the absence of hard evidence associating exposure to health risk precludes setting guidelines. The same limitation extends to glucans and endotoxin. In the biological context, only cat and mite allergens have guidelines for comparing measurements.

The lack of IAQ standards for microbiological components limits assessing the degree of hazard for occupants. Even if such standards existed, however, they could not be used in predictive models. Emission rates for spores, bacteria, allergens, and endotoxin are completely unknown. By comparison, VOC modeling in relatively advanced.

Essentially, there are three control strategies used to improve the IAQ in a building (53): source elimination, local source control, and dilution of the indoor

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[13] WHO European Air Quality Guidelines from Copenhagen have been recently reviewed and updated. (8). USEPA National Ambient Air Quality Standards cover SO_2, NO_2, CO, O_3, Pb, and particulate matter.

contaminants by ventilation. Hadlich & Grimsrud (54, 55) also recommend the three control strategies for residential buildings.

Source elimination is the most effective and often the least expensive method to improve IAQ. For example, prohibition and isolation of smoking can greatly reduce indoor pollution (56). Source elimination may also be achieved through environmental parameter control, such as temperature and relative humidity. For instance, VOC emissions and sorption are related to temperature and relative humidity. Similarly, conditions that regulate fungal growth depend on temperature and moisture conditions of materials and nutrients. Source elimination can also be achieved by using an alternative product. Products treated with sealants and/or antimicrobial coatings (e.g. silver) can also lower or eliminate sources. This approach is especially effective for building materials, because building materials are major indoor pollutant sources. Modifying Levin's suggestions (57), building material characteristics ideal for better IAQ include durability, hard smooth surfaces, long service life with clean non-toxic materials, low VOC emissions, low moisture content, low moisture absorptivity, and low toxic chemical and fiber content.

Local Source Control

In addition to source elimination control, local source control is also very effective. This technique limits pollutant transport within a building. In chemical and biological laboratories, the use of fume hoods to exhaust toxic and hazardous gases, after filtration, to the outdoors is essential. Even office spaces can benefit from local exhaust. For example, local exhaust systems can be installed in spaces with copiers and printers. This would reduce the risk of the pollutant transport and dispersion from the sources to the other part of the building. In residential buildings, the use of exhaust systems in kitchens and bathrooms are also preferred design features to improve IAQ.

Dilution of Indoor Contaminants by Ventilation

Another commonly used control strategy is dilution of the indoor contaminants by ventilation, defined by ASHRAE as "the process of supplying or removing air by natural or mechanical means to or from any space." Ventilation systems are used to maintain a good thermal comfort level and acceptable IAQ in an indoor environment, at a reasonable cost. Today, although IAQ attracts more and more attention, thermal comfort is still the major concern of the HVAC industry.

The major parameters that have an impact on thermal comfort are air temperature, relative humidity, air velocity, and environment temperature. Other parameters, such as turbulence intensity and radiant temperature asymmetry, are also important to thermal comfort. To design a thermally comfortable indoor environment, the comfort parameters should fall within a tolerable range. The most commonly used standard for thermal comfort design is ASHRAE Standard 55-1992 (58). The standard stipulates an operative air temperature between 20 and 27^{o} C and a relative humidity between 30% and 60%. The temperature varies with different seasons, the clothing level, and the metabolism of occupants.

By design, the ventilation should be sufficient to dilute the contaminant sources so that the concentrations of the contaminants will be below the thresholds. There are two ways to achieve ventilation in a building: Natural ventilation, or mechanical ventilation.

Natural ventilation has two components: daytime ventilation and nighttime cooling. Daytime ventilation is the most common natural ventilation system. The system uses outdoor air during daytime to remove the heat gains and contaminants indoors in a way shown in Figure 2(a). The system increases the occupant's thermal comfort by increasing convective and evaporative heat transfer between the occupants and the room air. The maximum indoor air velocity is approximately 2 m/s (59). If the outside temperature is high, the indoor air temperature will then be too high to be acceptable for the occupants. This system works better in climates with a mild summer.

Insert Figure 2

Nighttime cooling uses cooler outdoor air during the night to cool the building thermal mass (building internal partitions and structure) and to flush out indoor contaminants. The thermal mass functions as a heat sink during the day, absorbing the internal heat gains. Figures 2(b) and 2(c) show the operation principles of night cooling. In order to reduce the heat gains due to ventilation during the day, the windows should be kept closed. In this period, infiltration should provide sufficient fresh air for an acceptable IAQ. The lower the outdoor air temperature during the night, the more effective the night cooling system. This system works better for a climate with a minimum temperature of below 22° C during the night.

Compared to mechanical ventilation systems, natural ventilation systems consume little energy, require little maintenance, have low first costs, and are environmentally friendly. Occupants can expect a high air temperature in naturally ventilated buildings in summer, compared with that in the mechanical ventilated buildings. Busch (60) conducted thermal comfort surveys in Bangkok offices. He divided the more than 1,100 Bangkok office workers into two groups: one acclimatized to air-conditioned offices and the other to a naturally ventilated office. The study found that, based on 80% satisfied workers, the acceptable effective temperature is 28^{o}C in the air-conditioned buildings, and 31^{o}C in the naturally ventilated buildings. Comparing the responses from the naturally ventilated buildings with those from the air-conditioned buildings provides convincing evidence of acclimatization. If a building is designed to use natural ventilation, the period of air conditioning use can be significantly reduced because of the high acceptable temperature. This has a major impact on the building energy consumption and first costs.

Because natural ventilation generally provides a larger amount of fresh air than mechanical ventilation, the increased air supply would improve IAQ, provided the outside air was clean. The U.S. has a great potential to use natural ventilation. This is shown in Table 3, in which the U.S. climate is divided into 17 regions (61). In many regions, no air-conditioning system is needed during the summer with proper natural ventilation.

It should be noted that natural ventilation could be used where outdoor air quality would be acceptable as indoor air. It is almost impossible to filter outdoor air in naturally ventilated buildings. However, passive diffusion of gases and particles, along with ultraviolet catalytic irradiation, could clean outdoor air substantially without imposing a significant pressure drop.

However, it is not easy to design and control natural ventilation. Natural ventilation is related to wind speed and direction, building shape and density, surrounding landscape and buildings, thermal conditions in and around buildings, window size and location, and the internal spatial arrangement in a building. Outdoor noise can easily be transferred into the indoors with natural ventilation. In a hot and cold climate, natural ventilation alone cannot provide an acceptable thermal comfort level indoors. Therefore, the use of mechanical ventilation is inevitable.

Mechanical ventilation can be classified into mixing, displacement, and localized ventilation systems.

Mixing ventilation is the most popular system in the U.S. In mixing systems, conditioned air is normally supplied from air diffusers at a high velocity with a suitable temperature for heating or cooling. The diffuser jet mixes the conditioned air with the ambient room air through entrainment. Thus, the air velocity is reduced and the temperature will become close to the room air temperature. In the same time, the conditioned air dilutes the contaminant concentrations in the indoor space.

ASHRAE (62) has classified the mixing ventilation system into four groups:

- Conditioned air is discharged horizontally at or near the ceiling (Figures 3a and 3b)
- Conditioned air is discharged vertically at or near the floor (Figure 3c)
- Conditioned air is discharged horizontally at or near the floor
- Conditioned air is discharged vertically at or near the ceiling (Figure 3d)

Figure 3 shows the airflow pattern in a typical section in an office. These patterns do not reflect the presence or movement of persons or objects within the workspace, and the turbulent flow they generate. Thousands of air diffusers can be used to achieve the airflow pattern. However, in the most effective scenario, mixing ventilation creates relatively uniform contaminant concentrations in the occupied zone. Ventilation effectiveness, defined as the ratio of exhaust concentration to concentration in the occupied zone, can only reach a maximum value of 1.0, one that is not very high. Other forms of ventilation (e.g. displacement) can have ratios of 1.3 or higher.

Insert Figure 3

Displacement ventilation has been used quite commonly in Scandinavia during the past twenty years. It has been increasingly used in Scandinavia as a means of ventilation in industrial facilities to provide good IAQ while saving energy. More recently, its use has been extended to ventilation in offices and other commercial spaces where, in addition to IAQ, comfort is an important consideration. In the Nordic countries in 1989, it was estimated that displacement ventilation accounted for a 50% market share in industrial applications, and a 25% market share in office applications (63).

A typical displacement ventilation system, as shown in Figure 4, supplies conditioned air from a low side wall diffuser. The supply air temperature is slightly lower than the desired room air temperature and the supply air velocity is low (lower than 0.5 m/s). Through the diffuser, the conditioned air is introduced directly 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 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 the air from the surrounding occupied zone. When properly designed, displacement ventilation can take advantage of the contaminants carried by the thermal plumes, and thus, can increase the ventilation efficiency. If the indoor space needs heating, a separate heating system, such as baseboard heaters, can be used.

Insert Figure 4

Traditionally, the amount of supply air in a displacement ventilation system has been less than that of the mixing-type systems. This necessitates a careful design of the system configuration and operation to adequately handle the space cooling loads. The supply air temperature, velocity, and vertical temperature gradient in the occupied zone are all very important, comfort-related design parameters. However, one must comply with the specification of ASHRAE Standard 55-1992 (58) for an acceptable vertical temperature difference in the occupied zone. This places limitations on the magnitudes of the supply-room air temperature difference. It also places limitations on the space cooling loads for a given supply airflow rate. This is especially important when the system is applied to a building in the U.S., in which the cooling load can be high and the weather can be hot. Yuan et al (64) have developed a design guide for displacement ventilation systems in U.S. buildings.

The third type of ventilation system is localized ventilation. A localized ventilation system supplies conditioned air to areas close to the building occupants. The system creates a microclimate (local area) within a macroclimate (entire indoor space). The building occupants can regulate the air supply device to achieve a desired thermal comfort and IAQ level. Localized ventilation systems have a higher air supply volume, higher supply velocity, and smaller diffusers than the displacement ventilation systems (62). An attractive localized ventilation system is a task-conditioning system (65).

Ventilation Rate and Energy Efficiency

In addition to ventilation system, ventilation rate is very crucial to IAQ. Before the energy crisis in the 1970s, the ventilation rate was generally large and the IAQ problems were not as severe as today. Fisk (66) found that, with a doubling of minimum ventilation rates, building energy use would increase modestly (e.g., 5%) in most buildings except in schools (e.g. 10-20%) because of a high occupant density. In general, energy used to heat or cool ventilation air is a small portion of total building energy consumption. Fisk (66) suggested increasing the ventilation rate because of a strong correlation between ventilation rate and productivity. In most non-industrial workplaces, the costs of salaries and benefits exceed energy costs, maintenance costs, and annualized construction costs or rent, by a large factor, e.g. 100 (67).

Tools for Designing Ventilation

Increased awareness of the potential health risks associated with indoor air pollutants (68, 69, 70) has stimulated interest in improving our understanding of how ventilation air is distributed and how pollutants are transported in buildings. Pollutant transportation and distribution depend in general upon the ventilation system, building geometry, pollutant source characteristics, and thermal/fluid boundary conditions, such as the flow rate, locations of supply outlets and return inlets, and diffuser characteristics. The task of predicting the pollutant transport by ventilation systems is not a simple one. For a certain kind of building geometry and pollutant source, IAQ may be improved by increasing the ventilation rate. However, the increase of ventilation results in higher energy consumption and sometimes increases equipment cost. Although re-circulated air and air treatment devices can be used, they may not be economically feasible.

In addition to energy consumption and the first costs, a good ventilation system can be evaluated by the indoor environmental parameters, such as the distributions of contaminant concentrations, air velocity, air temperature, relative humidity, and turbulence intensity. Another important parameter for evaluating the performance of a ventilation system is the mean age of air. The mean age of air is defined as the averaged time for all air molecules to travel from the supply device to that certain point. The younger the mean age of air, the fresher the air. Ventilation effectiveness is also widely used to evaluate the ventilation system performance. Many definitions have been used to describe how effectively the ventilation system removes the contaminant from the space. The most original definition was from Sandberg & Sjoberg (71).

The air distribution by ventilation in building interiors is complicated by the geometry of the interiors. Partitions, furniture, and passageways between indoor spaces all distort the airflow. The air motion in the building may be a strong function of the air velocity (kinetic energy) as it enters. This, in turn, may be a function of the wind flow pattern around the outside of the building or the variability of the fan controls for the mechanical ventilation system. In many building interiors, the airflow may be strongly influenced by buoyancy effects: light hotter air moving up and cooler air moving down. The temperature pattern of the air will change with the temperature of the air delivered by mechanical systems. Equally important may be solar energy entering through windows and temperature patterns on walls due to external weather conditions.

IAQ problems may involve the multiple areas in a building, where the problems can be attributed to the transfer of ventilation air carrying pollutants from one indoor space to another. This inter-space transfer may be set up by the ventilation system, but most likely, it also involves the exchange of air between different rooms and public spaces in the building. At this level of understanding, a first approximation to the air and pollutant flows may be gained by assuming the gases in each room are well mixed. The flow between rooms is represented as a simple flow resistance between two elements at different pressures. The pressures and driving flows may be set up by the mechanical ventilation systems, the wind-driven flows from the outside, and the buoyancy-driven flows, or a combination of all three.

In many cases, this level of understanding is insufficient to deal with the building design or to solve an existing IAQ problem. The air circulation pattern within an individual space must be understood. The circulation pattern within one space may influence the exchange between neighboring spaces as well as the overall flow for the building.

Two approaches are available for the study of IAQ problems - experimental investigation and computer simulation. In principle, direct measurements of the building interior give the most realistic information concerning the IAQ. Due to the non-uniform distributions of the flow and pollutant, measurements must be made at many locations. Taking direct measurements of the air velocity, flow direction, contaminant concentrations, and the air temperature at many locations is very expensive and time consuming. Furthermore, to obtain conclusive results, the airflow and temperature from the ventilation systems and the temperatures of room enclosures should be maintained unchanged during the experiment. This is especially difficult because as outdoor conditions change, it causes the temperatures of the room enclosures and the airflow and air temperature from the ventilation systems to vary with time. For proposed building designs, direct measurements from previous buildings can be misleading. Some information can be gained by experiments carried out on scaled down models.

An environmental chamber may be used to simulate IAQ; for it completely isolates the measured system from the external world. Such an environmental chamber, with necessary equipment for measuring air velocity, temperature, relative humidity, and contaminant concentrations, costs more than $300,000. Also, complete measurements are tedious, time consuming, and costly. This technique is not an efficient way to examine a variety of designs or conditions. Furthermore, it may not be easy to change from one spatial configuration to another in such an environmental chamber. The experimental approach is still used since it is considered most reliable. In many cases, the parameters are normally measured at only a few points in a space.

Computational Tools

The computational approach, using computational fluid dynamics (CFD), is used most often than the experimental approach to study IAQ problems. This involves the taking numerical solution of the flow behavior using a computer. CFD involves the solutions of the equations that govern the physics of the flow. Due to the limitations of the experimental approach and the increase in the performance and affordability of computers, CFD provides a practical option for computing the airflow and pollutant distributions in buildings. The next section will describe how the problem is formulated for a numerical solution. The succeeding sections will present typical CFD results and describe the future of this technique. Although CFD has become the most popular method of predicting airflow associated with IAQ, it is essential to validate the model results with a few experiments carefully carried out over the range of conditions that are under consideration. Results from CFD techniques that have not been validated should be used with caution.

The flow transport of air and contaminants is governed by the geometry of the space and the forces present to move the material through the space. To deal with this numerically, there are two points of view that could be followed. In the first view, one could follow each packet of gas or particles as they move around the space, like following billiard balls as they collide and move around a table. This turns out to be impractical for airflows in a room, since the packets divide, mix, and are constantly changing their location, velocity and mixture concentration.

A more practical approach is to subdivide the space inside the room into a number of imaginary sub-volumes, or elements. These sub-volumes usually do not have solid boundaries; rather, they are open to allow gases to flow through their bounding surfaces. Each of the sub-volumes has a single temperature associated with it; this is the average temperature of all of its contents. It also has a single concentration of air and other components. Finally, it has a single average velocity, although in this case the velocity components in the two vertical and horizontal directions must be included (to account for the velocity magnitude and its orientation in a three dimensional room). In the beginning of the CFD problem, the temperature, concentrations of contaminants, and velocity are unknown for most of the sub-volumes. The values at the boundaries of the room, let's say at the outlet of a duct or a window, may be known. Similarly, the wall temperatures and the concentration of a pollutant source at its origin may be known. The goal of the CFD program is to find the temperature, concentrations of contaminants, and the velocity throughout the room, for each of the sub-volumes. This will reveal the flow patterns and the pollution migration throughout the room.

To produce a solution, the CFD program solves the equations describing the process in the room. Each of the sub-volumes involve the conservation of

- mass
- energy
- momentum
- chemical/biological species

Since each of the equations for the conservation of mass, energy, momentum, and chemical/biological species involve the pressure, temperature, velocity, and chemical/biological concentration of an element and its neighbors, the equations for all of the elements must be solved simultaneously. The smaller the sub-volumes, the larger the number of equations that must be solved. For a three dimensional problem, halving the size of an element's width, length and height, increases the total number of elements by a factor of eight. For a fast speed of calculation, the element size should not be too small. On the other hand, the use of a few large elements, each with a single average velocity, temperature, and concentration, may not capture the true pattern of conditions within the space. In fact, it may sometimes lead to a very erroneous overall flow prediction with air moving in a direction opposite of its true value.

The presence of a turbulent flow complicates matters, and improper handling of this is one of the prime causes of inaccurate CFD predictions. A turbulent flow, which exists in most room flow situations, involves a mixture of eddies of widely different sizes. To accurately capture the behavior of the smallest eddies would require a very fine subdivision of the space. The computational resources to solve for the flow this way, known as direct numerical simulation, are stupendous. It is not practical with today's computers. Rather, investigators have adopted a number of ways to approximate the turbulent behavior without using very fine subdivisions. The problem with this approach is the absence of a single approximation for turbulent flow that works well in all situations. Techniques developed for predicting high-speed turbulent flow over airplane wings do not necessary yield good results in large rooms where the buoyancy effect may be important. Although most commercial CFD codes will yield a solution to an IAQ problem, there is no guarantee it is the right solution.

The most common CFD techniques are Direct Numerical Simulation (DNS), Large-Eddy Simulation (LES), and the Reynolds Averaged Navier-Stokes (RANS) equations with turbulence models. Each technique handles turbulence in a different manner.

Simulation Techniques

Direct Numerical Simulation (DNS) solves the Navier-Stokes equations without approximations. DNS requires a very fine grid resolution to catch the smallest eddies in the flow. An eddy, a small element of flow in an indoor space, is typically 0.1 to 1 mm in size. In order to include the smallest eddies in the flow in the computations, the total grid number for a three-dimensional indoor airflow is around 10^{11} to 10^{12}. Current super computers can have a grid resolution as fine as 512^3, that is around 10^8. The computer capacity is still far too small to solve such a flow. In addition, the DNS method solves the time-dependent flow with very small time steps to account for eddy breakup and reforming which occurs in a flow that on average is “steady”. This makes the calculation extremely time consuming. DNS for indoor environment simulation is not realistic in the near future.

Large-Eddy Simulation (LES) was developed in the early 1970s by Deardorff (72) for meteorological applications. He separated turbulent motion into large-eddies and small-eddies. The theory assumes that the separation between the two does not have a significant effect on the evolution of large-eddies. LES accurately solves the large-eddy motion for a three-dimensional, time dependent flow. Turbulent transport approximations are used for small eddies. The small eddies are modeled independently from the flow geometry, eliminating the need for a very fine spatial grid and short time steps. LES is successful because the main contribution to the turbulent transport comes from the large-eddy motion. LES is also a more practical technique than DNS. LES can be performed on a large, fast workstation. Figures 5a and 5b show an instantaneous flow field around a simple building with single-side natural ventilation, calculated by using LES. Thousands of the instantaneous flow images can be averaged to obtain a mean flow as shown in Figures 5c and 5d. For a single-side natural ventilation system design, LES produces the most realistic results. Nevertheless, LES is still too time consuming because it calculates a time-dependent flow. In addition, such a large, fast workstation is not available in most designers' offices.

Insert Figure 5

The Reynolds Averaged Navier-Stokes method (RANS) is the fastest but may be the least accurate method. RANS solves the time-averaged Navier-Stokes equations by using approximations to simplify the calculation of the turbulent flow. The approximations can sometimes generate serious problems that will be discussed later. The grid number used for the simulation with RANS (1.0E5) is normally much less than that for LES (1.0E6). Most importantly, a steady flow can be solved as time-independent. Therefore, the computing costs are the cheapest compared to those for LES and DNS. The latest generation of PCs has the speed and capacity to utilize this CFD technique. The CFD method with RANS is a very promising and popular tool for IAQ prediction. The most popular RANS model is the standard k-ε model developed by Launder & Spalding (73). Recently, the RNG k-ε model (74) is the most widely used. The computational method can provide informative results inexpensively. Most CFD computations of a three-dimensional indoor airflow and pollutant transport can be done on a PC with 64 MB of memory and a Pentium processor.

Figure 6 shows CFD results for a section of an ice rink arena, although the results are available three-dimensionally in the entire space. The results were obtained with the RNG k-ε turbulence model. Although this model is not universal, the model gives stable and reasonable results for many indoor airflows in buildings, such as offices, classrooms, etc. (75). In CFD simulations, it is necessary to provide boundary conditions as inputs, such as wall surface temperature and flow characteristics from diffusers. In many cases, experimental measurements or numerical computations with a heat transfer program are necessary to obtain these boundary conditions. In the present study, the fresh, heated outdoor air is supplied from an air diffuser on the upper part of the left wall, as shown in Figure 6(a). The warm air can reach to the opposite wall because of its high momentum.

Figure 6(b) illustrates a strong thermal stratification in the arena because of the thermal buoyancy from the warm supply air and the cold ice sheet on the floor. The air velocity and temperature distributions provide important information to evaluating the thermal comfort in the space. This particular study assumes a resurfacer produces a certain amount of carbon monoxide when it resurfaces the ice. Figure 6(c) shows the carbon monoxide concentration distribution in the section through the air supply diffuser. Because of the stratified flow, the ventilation system does not effectively deliver the fresh air into the occupied zone on the ice. This ineffectiveness can also been seen from the distribution of the mean age of air (Figure 6(d)). The mean age of the air is oldest on the ice and is very young at the region close to the air diffuser.

Insert Figure 6

With the CFD tool, it is possible to improve the ventilation system design for better indoor air quality. For example, by changing the return exhausts on the upper right wall to the screen wall near the ice sheet, the CFD results indicate that the ventilation effectiveness can be 50% higher (76).

The two examples indicate that CFD is a powerful tool to study indoor environment (thermal comfort and IAQ). With the tool, different design alternatives can be carefully studied and analyzed with little cost. However, it is very difficult to obtain reliable CFD results since the CFD method uses many approximations and requires good knowledge of fluid dynamics and numerical skill. Due to the development in CFD modeling and computer technology, the CFD tool becomes more and more popular for IAQ and thermal comfort studies.

Conclusion

In the absence of widely accepted definition criteria or consistent guidelines, the concept and definition of a “healthy building” is still evolving. What *is* known is that IAQ is an important determinant of healthy design. There are numerous factors that lead to the wide acceptance that buildings and their IAQ can adversely impact occupants’ health. Several IAQ design guidance and evaluation tools are in development to advance the state of practice. Evaluating the healthfulness is a particular challenge, given the truly multidisciplinary nature of both the problem, and the solution.

Trends in public perception, litigation, current regulations, and new building materials and systems propose new challenges to provide good IAQ. Building ventilation is a good measure being linked to not only health and thermal comfort but also productivity. The trend of ventilation, which considers the people, the building, and the outdoor environment as a whole, would be linked to personal aesthetics in the next few decades.

Due to changes in building materials (including recycled content) and construction technologies, new contaminants are being introduced to workplaces, schools, hospitals, and homes. Even known contaminants, such as volatile organic compounds from building materials, are not easily quantifiable. Our ability to model VOC emissions is further developed than our other simulation capabilities, such as modeling indoor chemical reactions, or determining emission rates for biological contaminants. Many other potentially harmful components, such as endocrine-disrupting chemicals, latex, and ultrafine particles, are just beginning to be assessed.

Three strategies are available to control indoor contaminants: source elimination, local source control, and dilution of the indoor contaminants by ventilation. Since the first two have their limits, ventilation becomes very important for achieving an acceptable level of IAQ. Compared to mechanical ventilation, natural ventilation consumes little energy, requires little maintenance, has low first costs, and is environmentally friendly. Natural ventilation should be used wherever and whenever possible. Among the three mechanical ventilation systems (mixing ventilation, displacement ventilation, and localized ventilation), the displacement ventilation systems seem to be the most promising for creating a better IAQ and an acceptable thermal comfort level indoors.

Although both experimental and computer approaches are available for studying and designing IAQ, a computer-based approach using CFD is a powerful design tool of the future.

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Figure Legends

Figure 1 Paradigm shifts in the philosophy of ventilation since 1800 [extension of Fanger (6)].

Figure 2 Principle of daytime ventilation (a) and nighttime cooling (b and c). (a) Outdoor air removes the heat gained indoors, (b) Outdoor air cools the thermal mass during the night, and (c) The thermal mass absorbs heat during the day.

Figure 3 Airflow pattern in an office with different diffusers.

Figure 4 Sketch of a typical displacement ventilation system.

Figure 5 Airflow in and around a building with single-side ventilation computed by LES. a) instantaneous velocity in a vertical section, b) instantaneous velocity in a horizontal section, c) mean velocity in a vertical section, d) mean velocity in a horizontal section.

Figure 6 The CFD-computed distributions of airflow, temperature, CO concentration, and the mean age of air at the symmetric section of an ice rink (blue – low, green – low moderate, yellow – high moderate, red – high). (a) Air velocity (b) Air temperature (c) CO concentration (d) The mean age of air

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	Paradigm	Pollution Sources
2050	Personal aesthetics	People Buildings Outside Environment
2025	Health, productivity, comfort	
2000	Comfort (+ health)	People + Buildings
1975	Comfort	People
1935	Contagion	
1900	Poison	
1800		

Figure 1 Paradigm shifts in the philosophy of ventilation since 1800 (extension of Fanger (6)).

Table 1 Building components potentially affecting IAQ

Planning and Construction	*Potential Contributors to IAQ*
Siting	• Traffic, parking • Upwind sources or change of air flow • Soil emissions of radon • Moisture / drainage
Building Envelope	• Moisture intrusions • Cooling/heating loads affecting dilution, condensation (if cooling capacity is over-designed) • Unintended infiltration of untreated air
Waste Services Loading Dock Entrances served by vehicles (hotels, emergency rooms, convention/recreational centers, schools)	• Odors from waste and diesel service trucks drawn in through loading dock and/or window vents • Particle intake and possible health risk (e.g. soot)
HVAC System Plumbing System Electrical Systems	• Filters, condensation traps, wet insulation dirty return air ducts as source of odor, microbiologicals • Air intakes, venting , potential of re-entrainment • Operating set points can cause cool surfaces and unwanted condensation • Unintended pathways • Sweaty and leaking pipes, valves, joints, gaskets provide moisture leading to material damage and microbiological growth • Electromagnetic fields causing interference to equipment (e.g. computers), exposures, and noise.
Sanitation Vents, Kitchen Exhausts, Fume Hoods, Cooling Towers	• Potential chemical biological exposures to workers on roof or to pedestrians around building • Entrainment into air intakes of present and neighboring buildings
Communications	• Excessive wiring in ceiling space restricts repairs, offgasses VOCs • Wire, drainage, pipe chase provide unwanted pathways for air flow • Electromagnetic exposures near antennae
Materials used for Internal Finishings,Furnishings, Equipment, and Cleaning	• Sources of VOC, aldehydes, phthalates, and particles • Sources of nutrients for microorganisms

Table 2 Indoor sources of selected VOCs (32,33)

VOC	*Possible Sources*
Acetaldehyde	Perfumes, dyes, tobacco smoke
Benzaldehyde	Fiberboard, particleboard
Benzene	Adhesives, spot cleaners, paint removers, particleboard, tobacco smoke, silicone caulk
Carbon Tetrachloride	Grease cleaners
Chloroform	Chlorinated water
p-Dichlorobenzene	Deodorizers, moth crystals
Ethylbenzene	Floor/wall coverings, insulation foam, chipboard, fiberboard, caulking, adhesives, lacquer, grease cleaners
Formaldehyde	Plywood, particleboard, fiberboard, chipboard, gypsum board, urea foam insulation, carpets, linoleum, upholstery, latex-backed fabric, new clothing, wallpaper, fiberglass, gas-space heaters, range-top gas burners, gas ovens, caulking, floor varnish, floor lacquer, adhesives, tobacco smoke
Methylene Chloride	Paint remover, aerosol finishers
Styrene	Plastics, paints
Tetrachloroethylene	Dry cleaned fabrics/ upholstery
Toluene	Adhesives, edge-sealing, molding tape wallpaper, floor coverings, silicone caulk, paint, chipboard, linoleum, kerosene heaters, tobacco smoke
1,1,1-Trichloroethane	Dry cleaned fabrics/ upholstery
Trichloroethylene	Paints and varnishes, degreasing, dry cleaned materials
Xylenes	Adhesives, wallpaper, caulking, floor coverings, floor lacquer, grease cleaners, tobacco smoke, varnish, kerosene heaters

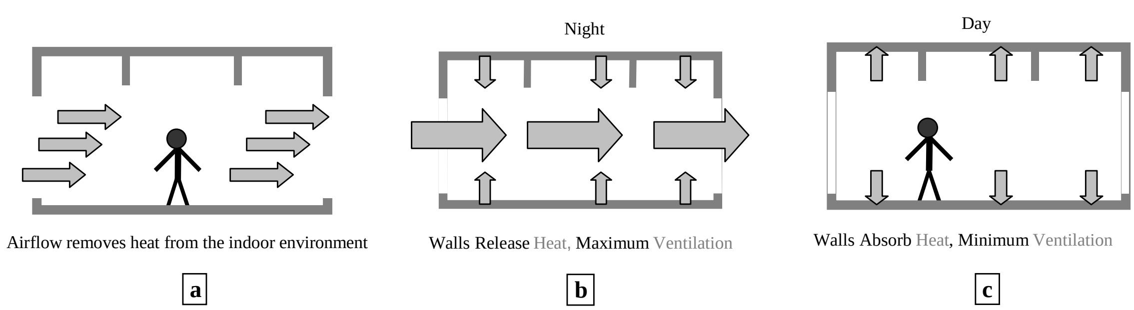


Figure 2 Principle of daytime ventilation (a) and nighttime cooling (b and c). (a) Outdoor air removes the heat gained indoor, (b) Outdoor air cools the thermal mass during the night, and (c) The thermal mass absorbs heat during the day.

Table 3. The potential to use natural ventilation in the U.S.

Climate region and Reference city	Periods suitable for natural ventilation (NV) and when air conditioning (AC) or heating (H) is needed										
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1. Hartfort, CT	H	H	H	H	NV	NV	NV	NV	NV	H	H	H
2. Madison, WI	H	H	H	H	NV	NV	NV	NV	NV	H	H	H
3. Indianapolis, IN	H	H	H	NV	NV	NV	AC	AC	NV	NV	H	H
4. Salt Lake City, UT	H	H	H	H	NV	NV	AC	AC	NV	NV	H	H
5. Ely, NV	H	H	H	H	NV	NV	NV	NV	NV	NV	H	H
6. Medford, OR	H	H	H	NV	NV	NV	NV	NV	NV	NV	H	H
7. Fresno, CA	H	H	NV	NV	NV	NV	NV	NV	NV	NV	H	H
8. Charleston, SC	H	H	NV	NV	NV	AC	AC	AC	AC	NV	NV	H
9. Little Rock, AR	H	H	H	NV	NV	AC	AC	AC	NV	NV	NV	H
10. Knoxville, TN	H	H	H	NV	NV	AC	AC	AC	NV	NV	NV	H
11. Phoenix, AZ	H	NV	NV	NV	AC	AC	AC	AC	AC	NV	NV	H
12. Midland, TX	H	H	NV	NV	NV	AC	AC	AC	AC	NV	NV	H
13. Fort Worth, TX	H	NV	NV	NV	AC	AC	AC	AC	AC	NV	NV	H
14. New Orleans, LA	H	H	NV	NV	NV	AC	AC	AC	AC	NV	NV	H
15. Houston, TX	H	NV	NV	NV	AC	AC	AC	AC	AC	NV	NV	H
16. Miami, FL	NV	NV	NV	NV	AC	AC	AC	AC	AC	AC	NV	NV
17. Los Angeles, CA	H	H	NV	NV	NV	NV	AC	NV	NV	NV	NV	H

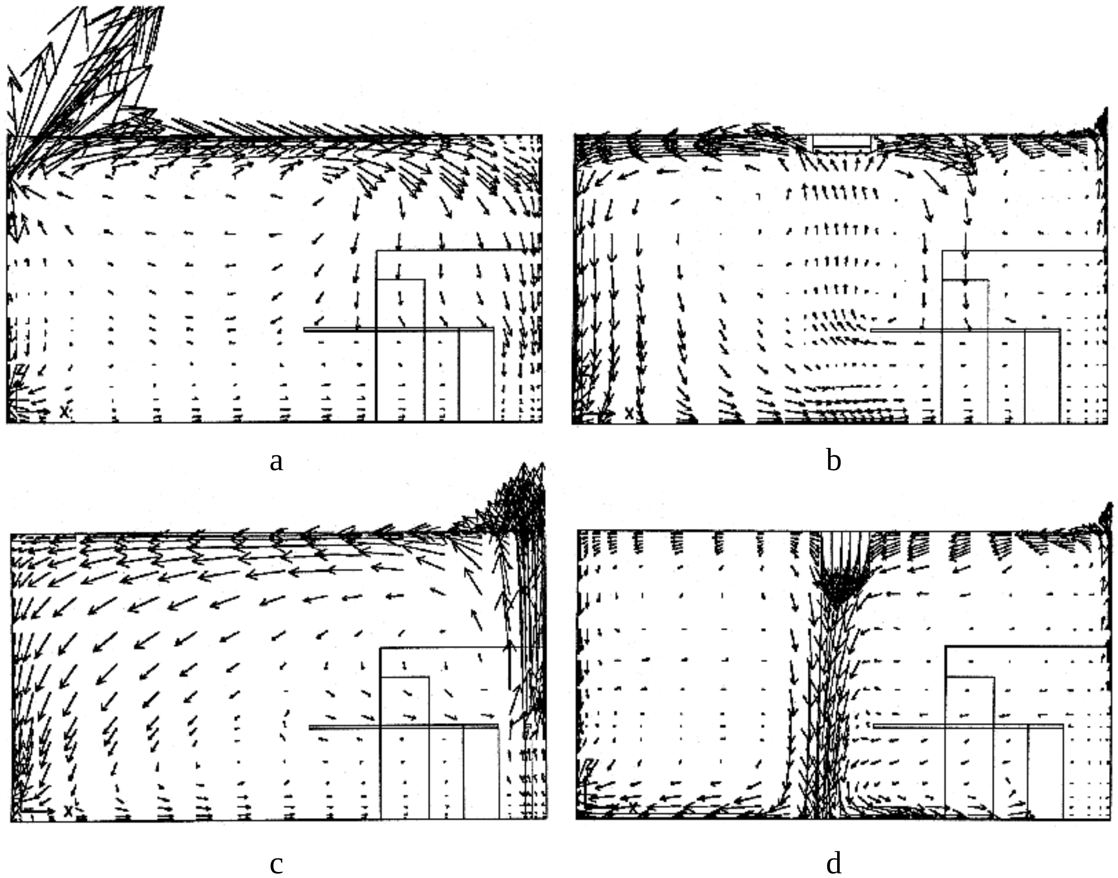


Figure 3 Airflow pattern in an office with different diffusers.

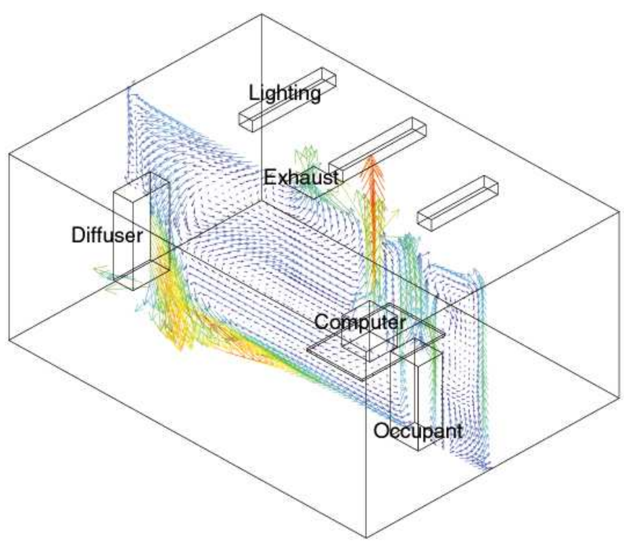


Figure 4 Sketch of a typical displacement ventilation system.

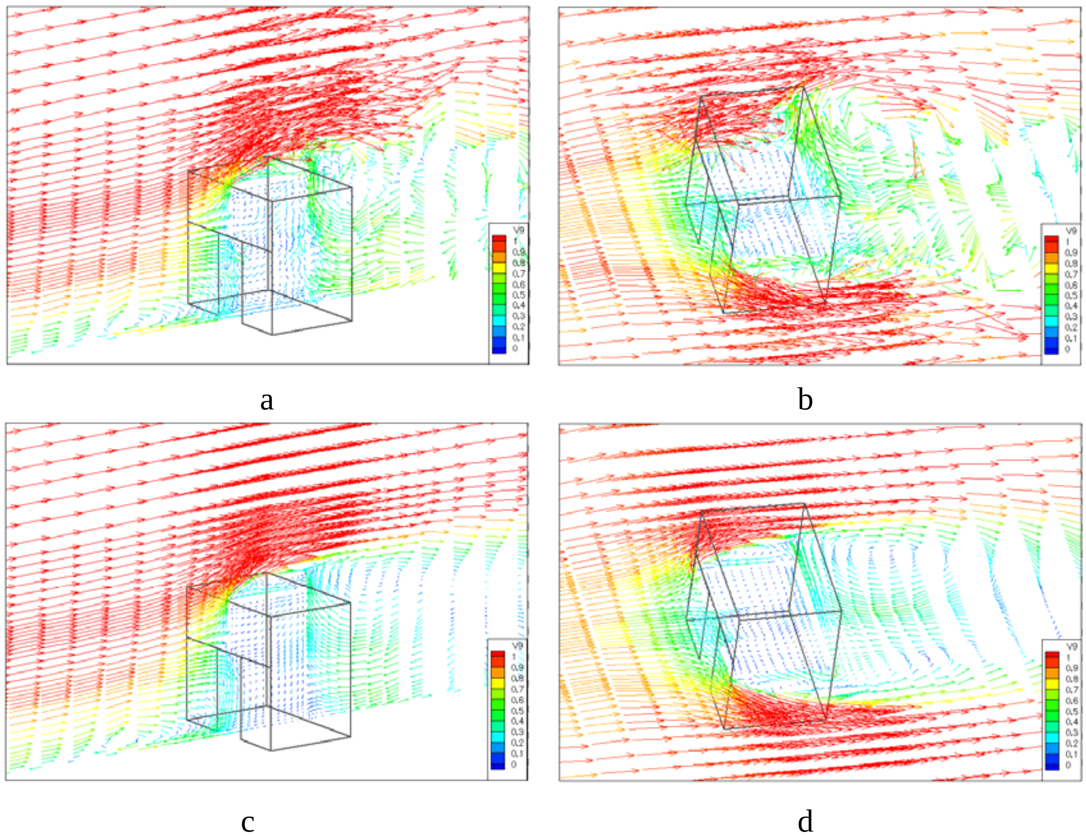
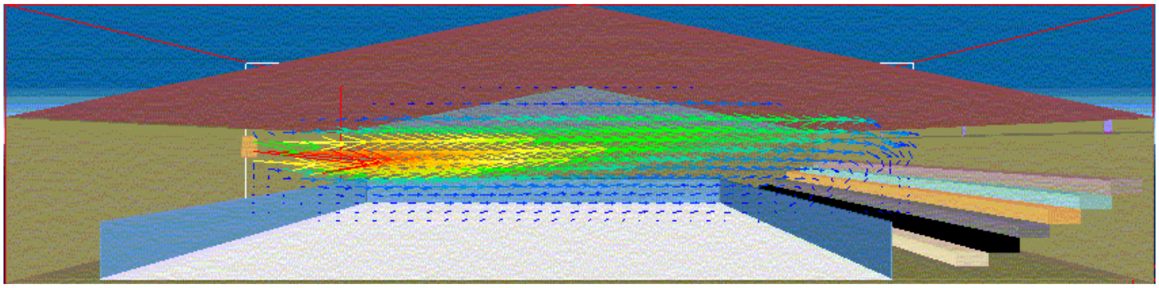
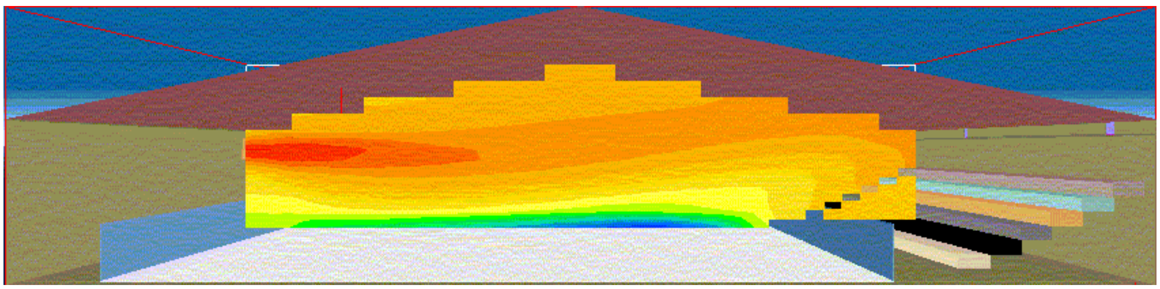


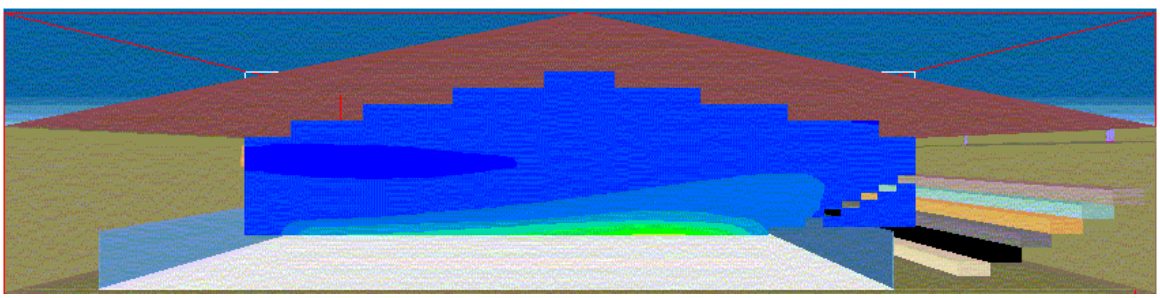
Figure 5 Airflow in and around a building with single-side ventilation computed by LES. a instantaneous velocity in a vertical section, b instantaneous velocity in a horizontal section, c mean velocity in a vertical section, d mean velocity in a horizontal section.



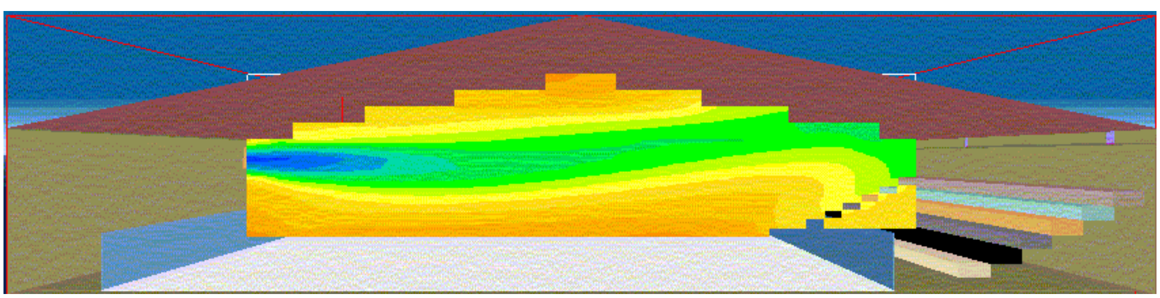
(a) Air velocity



(b) Air temperature



(c) CO concentration



(d) The mean age of air

Figure 6 The CFD-computed distributions of airflow, temperature, CO concentration, and the mean age of air at the symmetric section of an ice rink (blue – low, green – low moderate, yellow – high moderate, red – high).