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Natural Ventilation Review and Plan for Design and Analysis Tools

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ABSTRACT

Natural ventilation has the potential to reduce first costs and operating costs for some commercial buildings while maintaining ventilation rates consistent with acceptable indoor air quality. While a recent surge of interest in Europe has advanced natural ventilation technology, much work is needed before this potential can be realized in the U.S. This report reviews the application of natural ventilation in commercial buildings, the technology, its potential advantages and related issues that need to be addressed. One area identified as a key to the realization of the potential advantages of natural ventilation is the emergence of hybrid natural and mechanical system strategies. The report also addresses opportunities and issues specific to the application of natural ventilation to commercial buildings in California including analysis of climate suitability via a new ventilative cooling metric, consideration of ambient air quality, and discussion of relevant codes and standards. Finally, current design and analysis processes and tools are reviewed, and a plan for the development of new design and analysis guidance and tools is described.

Keywords: analysis, design, energy efficiency, indoor air quality, modeling, natural ventilation, ventilation

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1. Introduction

Natural ventilation has the potential to significantly reduce the energy cost required for mechanical ventilation of buildings. These natural ventilation systems may reduce both first and operating costs compared to mechanical ventilation systems while maintaining ventilation rates that are consistent with acceptable indoor air quality. Also, some studies have indicated that occupants reported fewer symptoms in buildings with natural ventilation compared to buildings with mechanical ventilation [Mendell et al. 1996]. If natural ventilation can improve indoor environmental conditions, such improvements can also potentially increase occupant productivity by reducing absenteeism, reducing health care costs, and improving worker productivity [Fisk and Rosenfeld 1997].

Because of these potential benefits, natural ventilation is being increasingly proposed as a means of saving energy and improving indoor air quality within commercial buildings, particularly in the "green buildings" community. These proposals are often made without any engineering analysis to support the claimed advantages, e.g., without calculating expected ventilation rates or air distribution patterns. In addition, proven design approaches are not available in this country to incorporate natural ventilation into commercial building system designs. Natural ventilation strategies are less likely to reach the U.S. marketplace until design tools are made available and strategies are investigated and demonstrated for a variety of climates and construction types.

While natural ventilation is becoming more common in Europe, significant questions exist concerning its application in U.S. commercial buildings. These questions include the reliability of the outdoor air ventilation rates, distribution of this outdoor air within the building, control of moisture in naturally ventilated buildings, building pressurization concerns, and the entry of polluted air from outdoors without an opportunity to filter or clean it. Some climates within California may be well suited to natural ventilation, but these questions still must be addressed for these locales. The NIST multi-zone airflow and indoor air quality (IAQ) analysis model, CONTAMW [Dols et al. 2000], is capable of addressing many of these and other issues related to natural ventilation in buildings. In addition, the airflow calculation capabilities of CONTAMW can serve as the basis of a natural ventilation design tool, enabling wider use of natural ventilation in a technically sound manner.

This report presents the results of the first phase of a project intended to investigate the application of current natural ventilation concepts in commercial buildings in California and to develop design methods for natural ventilation in new and retrofit applications. This project will:

- Develop natural ventilation strategies for cooling load reduction in commercial buildings in California.
- Develop natural ventilation design methods, construction techniques, and strategies that address non-energy issues, such as occupant comfort, air filtration, and acoustical isolation.
- Assess indoor air quality impacts of natural ventilation in commercial buildings.
- Develop natural ventilation software tools for design to improve building energy efficiency and lower the cost of building design, construction, and operation.

This report is organized into three main sections – Review of Natural Ventilation Technology, California Opportunities and Issues, and Design and Analysis Tools. The first section contains an overview of natural ventilation in commercial buildings and its potential advantages and a discussion of issues that need to be addressed. It also describes state-of-the-art natural ventilation technologies and strategies available to maximize the performance of natural ventilation systems. The second section discusses opportunities and issues specific to the application of natural ventilation systems to small commercial buildings in California. The third section reviews currently available natural ventilation system design and analysis tools and describes a plan to provide tools to enable the realization of the potential benefits of natural ventilation systems in California. Note that some material in this report is extracted from Axley [2001b] and is not individually referenced.

2. Review of Natural Ventilation Technology

This section gives an overview of natural ventilation in commercial buildings and its potential advantages and issues to overcome. It also describes state-of-the-art natural ventilation technologies and strategies available to maximize the performance of natural ventilation systems.

2.1 Introduction to Natural Ventilation

Ventilation, whether mechanical or natural, may be used for:

- *Air Quality Control:* to control building air quality, by diluting internally-generated air contaminants with cleaner outdoor air,
- *Direct Advective Cooling:* to directly cool building interiors by replacing or diluting warm indoor air with cooler outdoor air when conditions are favorable,
- *Direct Personal Cooling:* to directly cool building occupants by directing cool outdoor air over building occupants at sufficient velocity to enhance convective transport of heat and moisture from the occupants, and
- *Indirect Night Cooling:* to indirectly cool building interiors by pre-cooling thermally massive components of the building fabric or a thermal storage system with cool nighttime outdoor air.

While these four distinct purposes must be kept in mind when designing a natural ventilation system, direct advective and personal cooling are reasonably achieved in an integrated manner by a properly designed *direct cooling* strategy. Consequently, just three purposes are most often noted in the literature – air quality control, direct cooling, and indirect cooling.

Natural ventilation may be defined as ventilation provided by thermal, wind or diffusion effects through doors, windows, or other intentional openings in the building as opposed to mechanical ventilation that is ventilation provided by mechanically powered equipment such as motor-driven fans and blowers. Although some in the U.S. may think of natural ventilation as simply meaning operable windows, natural ventilation technology has been advanced in recent years in Europe and elsewhere.

The variety and diversity of purpose-provided natural ventilations systems that have been proposed in recent years is staggering [Allard 1998, BRE 1999, CIBSE 1997, Martin 1995]. Hybrid variations of many of these systems, wherein mechanical devices are added to enhance system performance and control, add yet another level of complication. Nevertheless, these systems are invariably conceived as variants of three fundamental approaches to natural ventilation:

- Wind-driven cross ventilation
- Buoyancy-driven stack ventilation, and
- Single-sided ventilation.

Wind-Driven Cross Ventilation

Wind-driven cross ventilation occurs via ventilation openings on opposite sides of an enclosed space. Figure 1 shows a schematic of cross ventilation serving a multi-room building, referred to here as global cross ventilation. The building floorplan depth in the direction of the ventilation flow must be limited to effectively remove heat and pollutants from the space by typical driving forces. A significant difference in wind pressure between the inlet and outlet openings and a minimal internal resistance to flow are needed to ensure sufficient ventilation flow. The ventilation openings are typically windows.

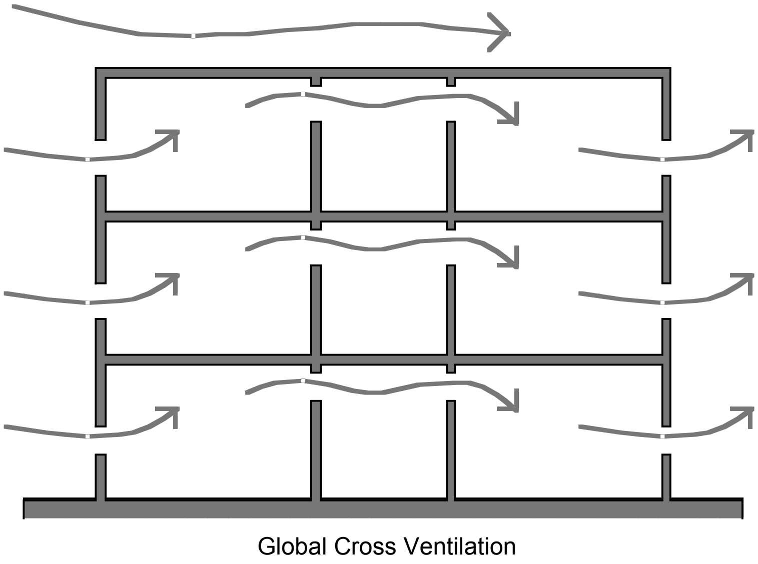


Figure 1 Schematic of wind-driven cross ventilation

Buoyancy-Driven Stack Ventilation

Buoyancy-driven stack ventilation relies on density differences to draw cool, outdoor air in at low ventilation openings and exhaust warm, indoor air at higher ventilation openings. Figure 2 shows a schematic of stack ventilation for a multi-room building. A chimney or atrium is frequently used to generate sufficient buoyancy forces to achieve the needed flow. However, even the smallest wind will induce pressure distributions on the building envelope that will also act to drive airflow. Indeed, wind effects may well be more important than buoyancy effects in stack ventilation schemes, thus the successful design will seek ways to make full advantage of both.

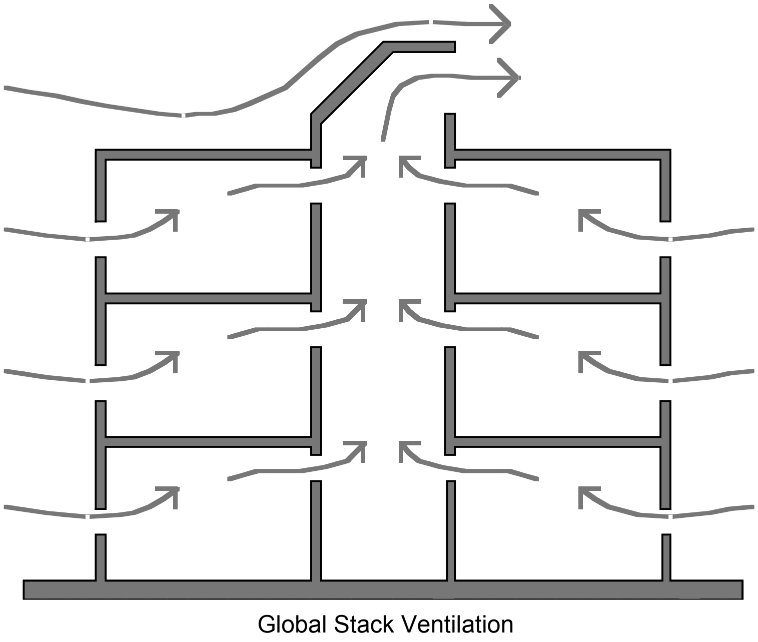


Figure 2 Buoyancy-driven stack ventilation

Single-Sided Ventilation

Single-sided ventilation typically serves single rooms and thus provides a local ventilation solution. Figure 3 shows a schematic of single-sided ventilation in a multi-room building. Ventilation airflow in this case is driven by room-scale buoyancy effects, small differences in envelope wind pressures, and/or turbulence. Consequently, driving forces for single-sided ventilation tend to be relatively small and highly variable. Compared to the other alternatives, single-sided ventilation offers the least attractive natural ventilation solution but, nevertheless, a solution that can serve individual offices.

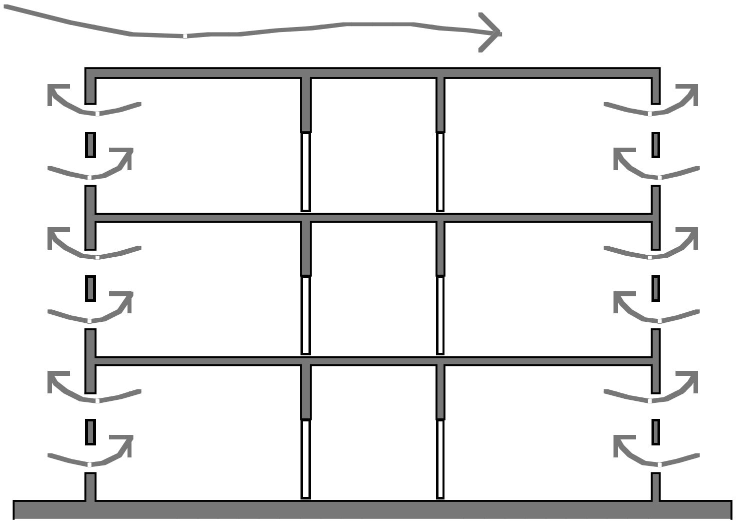


Figure 3 Schematic of single-sided ventilation

Elaborations of the Basic Strategies

Many built examples employ elaborations of these basic schemes. In some instances these three schemes have been used in a mixed manner in single buildings to handle a variety of ventilation needs. The most notable example of such an approach is the Queens Building of De Montfort University in Leichester, England that has proven, perhaps, to be the most influential of the *first generation* of the newer naturally-ventilated buildings. See Figure 4 for a schematic of mixed local/global and stack/wind ventilation strategy.

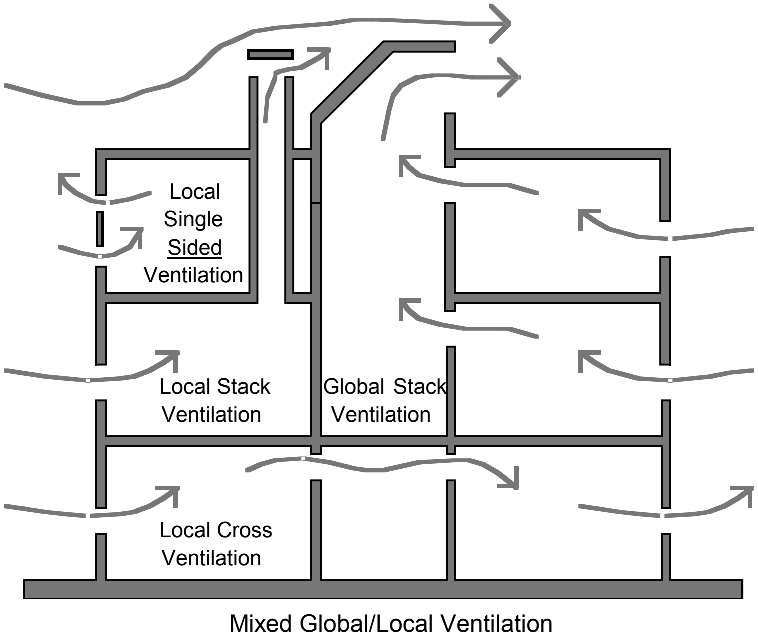


Figure 4 Schematic of mixed natural ventilation strategies

In other instances, the elaboration resides in the details of inlet, exhaust, and distribution tactics. One common approach involves the use of in-slab or access-floor distribution of fresh air to provide greater control of air distribution across the building section. Figure 5 shows a schematic of stack ventilation with a sub-slab distribution system.

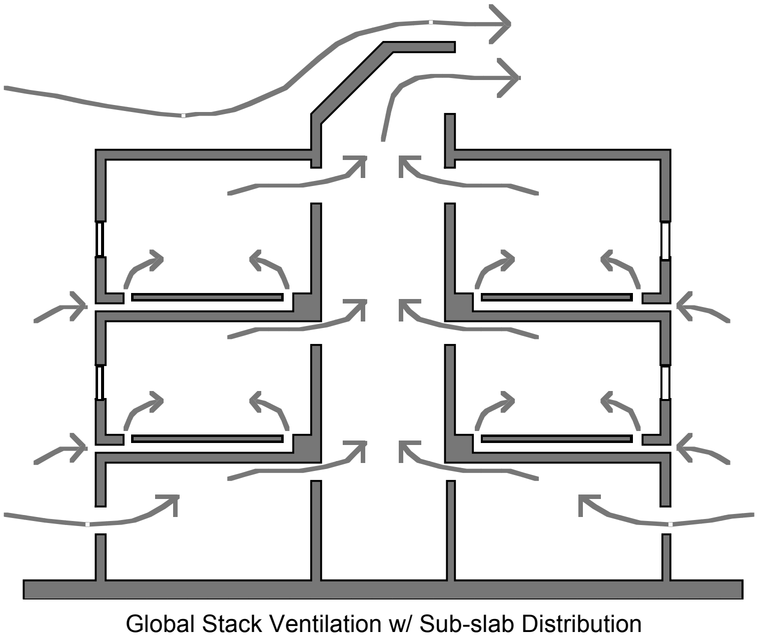


Figure 5 Schematic of stack ventilation with sub-slab distribution

The CIBSE Applications Manual [CIBSE 1997] and Martin [1995] describe dozens of natural ventilation cases (seven in detail) applying modern natural ventilation technology incorporating advanced windows, trickle ventilators, window and vent actuators, thermal chimneys, wind chimneys, dampers, thermal mass, and atria. The case study buildings are typically six stories or fewer and are used for office, education, retail, and industrial purposes.

2.2 Pros and Cons of Natural versus Mechanical Ventilation

A number of issues should reasonably be considered when comparing natural ventilation strategies to mechanical alternatives. Here, sets of these issues that are inextricably linked will be considered including a) cooling energy savings and limits of applicability, b) fan power savings and heat recovery, c) control and reliability, d) occupant health, comfort and productivity, e) HVAC equipment costs and space requirements, f) duct cleanliness and filtration, and g) other issues such as acoustical isolation, privacy, security, etc.

Cooling Energy Savings and Limits of Applicability

When applicable, natural ventilation can offset cooling energy consumption and the associated energy costs and carbon dioxide emissions thought to be related to global climate changes. In direct comparisons of naturally ventilated and air-conditioned offices in the United Kingdom, naturally ventilated buildings offset from 14 kWh/m^2 to 41 kWh/m^2 of cooling energy annually, for *good practice standard* office buildings to *typical prestige* office buildings respectively, saving from 0.77 £/m^2 to 2.05 £/m^2 (approximately 1.30 \$/m^2 (0.12 \$/ft^2) to 3.60 \$/m^2 (0.33 \$/ft^2)) annually in energy costs [BRECSU 2000]. These savings account for approximately 10 % of total energy costs in a climate where outdoor air temperatures seldom exceed thermal comfort limits in the summer and thus, one well-suited for ventilative cooling of office buildings.

The potential cooling energy that may be saved depends, of course, on both the climate in which a building is located and the relative level of internal and other gains that impact the building's thermal performance. Clearly, when natural ventilation is not applicable due either to outdoor temperatures or, in some instances, outdoor humidities that are too high, then these energy savings cannot be realized. The general question of climatic suitability will be addressed in a subsequent section of this report and methods presented to evaluate the limits of applicability of ventilative cooling strategies.

Fan Power & Heat Recovery

Of course, ventilative cooling may be accomplished by either natural means or mechanical means (e.g., using so-called *economizer cycle* operation). When resorting to mechanical means to cool buildings, however, fans will consume a significant amount of the energy. In all-air systems – the most common mechanical system cooling strategy in the U.S. – fans consume at least two-thirds of the total energy consumed for cooling in office buildings in the United Kingdom [BRECSU 2000]. While a directly comparable number is not readily available for the U.S., there is a growing awareness that fans consume a large portion of the energy used to cool buildings [Brodrick and Westphalen 2001]. When compared to all-air mechanical cooling systems, naturally ventilated buildings in the U.K. offset from 20 kWh/m^2 to 60 kWh/m^2 of fan energy consumption annually for cooling purposes, saving from 1.0 £/m^2 to 3.0 £/m^2 (approximately 1.70 \$/m^2 (0.16 \$/ft^2) to 5.20 \$/m^2 (0.48 \$/ft^2)) annually in energy costs (i.e., again for *good practice standard* to *typical prestige* office buildings). By implication, these savings account for approximately 15 % of total energy consumption in U.K. office buildings.

These statistics from the U.K. establish the potential that natural ventilation offers when climatic and operational conditions prove particularly suitable. Roughly, natural ventilation may be expected to provide cooling energy savings on the order of 10 % and fan power savings (i.e., for all-air systems) on the order of 15 % of annual energy consumption when climatic and operational conditions are suitable.

U.S. statistics to support these U.K. observations are a bit sparse but are available. Kavanaugh [2000] reports that as mechanical cooling systems have become increasingly complex in the U.S. the relative importance of fan power energy consumption has increased:

> "The good news is that chillers, furnaces, compressors, and other HVAC components are becoming increasingly efficient. The bad news is that air system friction losses, high ventilation rates, filter efficiency requirements, part-load air distribution methods, and the lack of space for ductwork can combine to make fan demand and energy the largest component in HVAC systems. ..."

Kavanaugh investigated three systems – two centralized air handling systems with variable air volume (VAV) air distribution systems and a distributed system with multiple fan coil units (FCU). Full-load energy consumption was estimated for each of these three options indicating fans accounted for 53 % of energy consumption in the more common relatively high pressure VAV system, 36 % for a low-pressure VAV system, and 24 % for the very-low-pressure distributed FCU system. The reduced fan power consumption realized by the lower pressure systems, however, was offset in part by increased chilled water pumping costs resulting in the combined fan and pump energy costs ranging from 40 % to 62 %. For part-load demand an additional significant penalty is paid in losses of fan efficiency [Kavanaugh 2000]. Combined together, then, Kavanaugh's analysis supports the U.K. findings that in conventional all-air systems, fans account for approximately two-thirds of the total energy consumed for cooling. The less common low-pressure mechanical systems, however, mitigate the impact of these *parasitic losses*.

Heat recovery, on the other hand, is put forward as the key advantage of mechanical ventilation systems – the demonstrated advantage of a number of mechanical system configurations to recover thermal energy from exhaust air through the use of air-to-air and so-called "run-around" air-to-water-to-air heat exchangers. Indeed in the cold climate of Finland it has been estimated that fan-power accounts for only 13 % of annual energy consumed in ventilating buildings while the remaining 87 % is used to condition, specifically in Finland to heat, the ventilating air [Heikkinen and Heimonen 2000]. Even a modest heat recovery efficiency could, therefore, have a significant impact during the heating season in cold climates.

The potential benefit of heat recovery during the cooling season is likely, however, to be marginal. This is due, in part, to the relatively small temperature difference between outdoor and indoor air during even extreme summer conditions in most of the U.S. and, in part, due to additional parasitic energy consumption required by fans in mechanical heat recovery systems. Indeed, Kavanaugh presents an analysis of one office building equipped with a heat recovery unit (HRU) following manufacturer's recommendations in Birmingham, Alabama and concludes: "Annual energy savings with the HRU were non-existent due to the large amount of fan power energy consumed." However, one may better realize the benefits of HRUs if these units are designed to minimize pressure losses when significant heat recovery may be affected and to bypass them under other operating conditions [Berry 2000].

Nevertheless, if natural ventilation strategies are to be competitive during extreme seasons, when either mechanical heating or cooling must be provided, then they may need to be designed to recover heat. This has become a central goal of the most recent work in the development of natural ventilation systems and thus will be considered below. Conversely, however, it must be emphasized that during the shoulder seasons, when mechanical heating or cooling need not be provided, heat recovery is no longer an issue; thus, the fan power savings offered by natural ventilation systems stands unqualified.

Likewise, as mechanical systems have been devised that more effectively recover heat then the relative importance of the fan-power consumed in these systems becomes more significant. Consequently, recent research on the mechanical side has been directed to the development of low-pressure mechanical systems in an effort to minimize fan-power consumption [Heiselberg 2000]. Depending on the system design, low-pressure mechanical systems may have a building owner cost in building space.

Control and Reliability

In mechanical ventilation systems, fans that are often controlled electronically drive airflow. On the other hand, wind and buoyancy forces that are stochastic in nature drive natural ventilation, making control more difficult. As a result natural ventilation systems may at times *under-ventilate*, resulting in overheating or unacceptable air quality conditions, *over-ventilate*, resulting in unnecessary energy consumption to condition indoor air, or provide *unacceptable air distribution*, resulting in local thermal discomfort due to cold drafts or insufficient cooling or local air quality problems.

At face value, the control and reliability offered by mechanical ventilation systems would appear to be a significant advantage when compared to natural ventilation systems. Indeed, this is often cited as the primary reason mechanical ventilation should be preferred to natural. However, in practice, mechanical ventilation systems are often regulated to control temperature rather than air quality and, thus, may not provide adequate ventilation for air quality control. For example, VAV systems, which are commonly used in commercial buildings, may fail to maintain acceptable air quality for this reason [Leyten and Kurvers 2000]. On the other hand, mechanical ventilation systems that are controlled based on indoor contaminant levels, while not commonly used in practice, have the potential to be both reliable and energy efficient in operation.

The need to maintain ventilation rates reliably and the inherent difficulty of doing so when using natural driving forces must be seen as a major challenge for the development of natural ventilation systems. Consequently recent research efforts have been directed to meet this challenge. System design strategies, including axisymmetric exhaust vents and inlet vents linked via a common plenum space, have been identified that reduce sensitivity to wind direction and thus improve the directional reliability of wind-driven flow. Recently developed automatic, self-regulating vents [Knoll and Kornaat 1991; Anon 1992; Knoll 1992; de Gids 1997; de Gids 1999] and digital control strategies coupled to controlled inlet devices [Knoll and Phaff 1998] may provide the means to control over-ventilation and the associated discomfort due to cold drafts. As promising as these recent developments are, however, purely natural ventilation systems will fail when the natural driving forces are simply not available, consequently recent trends have favored fan-assisted natural ventilation.

Occupant Health, Comfort & Productivity

The actual health, comfort, and productivity impacts of mechanical ventilation systems often fall short of expectations [Fisk and Rosenfeld 1997; Fisk 1998]. In comparisons of negative health symptoms of office workers in a limited number of naturally and mechanically ventilated systems, in both the European and North American context, the naturally ventilated buildings reported lower symptom prevalence in comparison to the mechanically ventilated and, especially, air conditioned buildings [Mendell et al. 1996]. Much anecdotal evidence supports these scientific findings, yet the fundamental reasons behind these findings are not self-evident.

A recent Dutch study supports these findings and attempts to explain why they are observed:

> "Epidemiological studies consistently show that occupants' complaints are more prevalent in office buildings with more sophisticated HVAC systems, that is systems with more technological devices to control and regulate the indoor environment. These complaints not only include physical symptoms, but also complaints about indoor air quality and thermal comfort. Since in most cases these more sophisticated systems primarily aim at better compliance with some set of health and comfort standards, the higher complaint levels seem odd. The most frequent explanation of this phenomenon is that more sophisticated HVAC systems contain more potential sources of indoor air pollution, like filter sections, cooling sections and humidifiers. The authors of this paper submit that this, though in itself correct, is only part of the explanation, and that a more comprehensive explanation can be hypothesized." [Leyten and Kurvers 2000]

Leyten and Kurvers go on to introduce the notion of system *robustness* – the ability of a system to perform up to expectations when assumptions and conditions underlying its design are violated. They offer a number of reasons HVAC systems may lack robustness: systems may be particularly sensitive to "aberrations" in their underlying design assumptions, maintenance requirements of systems may not be feasible or simply not addressed, integration of heating (or cooling) and ventilation places conflicting demands on system operation and control, systems sensitive to the regulation of airflow rates (especially recirculation airflow rates) may not be feasible, and difficulty in understanding system operation on the part of both occupants and building operators. In short, they conclude that the more complex, "sophisticated," HVAC systems tend to be less robust than the simpler, more comprehensible systems. Importantly they conclude that natural ventilation systems tend to rank high in terms of robustness [Leyten and Kurvers 2000]. While the concept of robustness may be behind the differing symptom rates in mechanically and naturally ventilated buildings, additional studies are needed to support this explanation.

The growing importance of adaptation in thermal comfort considerations [Nicol and Raja 1997; Olesen 2000] may well be linked to Leyten and Kurvers' identification of system legibility or *transparency* as a prerequisite of robustness. If a system is *transparent* to the occupants of the building the occupants can act directly to identify the causes of problems that compromise health, comfort, and even productivity. If, in addition, occupants are offered control of these systems they will make changes to mitigate these problems. This has led to the conclusion that natural ventilation systems that offer occupant control over ventilation rates (and solar gain) can be effectively designed for slightly larger comfort zones than commonly used in the design of mechanical HVAC systems [Conte and Fato 2000; Martinez, Fiala et al. 2000; Brager and de Gear 2000]. Indeed, a recent study of a school whose mechanical system was replaced by a natural ventilation system offering user control concluded [Gunnarsen 2000]: "The school users were as good, or better, at obtaining comfortable temperature and air quality as the poorly maintained mechanical ventilation system with central automation."

While it is tempting to conclude from these limited studies that natural ventilation systems can provide more healthful, comfortable, and productive environments, it may be more reasonable to conclude that *robust* natural ventilation systems may offer this advantage. There is a trend in the design of natural ventilation systems in recent years towards complexity – these complex natural ventilation systems may well prove to be less robust and thus may suffer shortcomings similar to those of the more complex mechanical ventilation systems.

Beyond quantitative evaluations of health, comfort, and productivity advantages that natural ventilation systems may offer, it is important to recognize that many if not most building occupants may simply prefer natural ventilation systems qualitatively. Largely for these reasons alone, architects have accepted natural ventilation as one of several objectives of high quality sustainable design.

HVAC Equipment Cost & Space Requirements

Mechanical heating, ventilating, and air conditioning equipment often account for a large fraction of the cost of construction of new buildings and the renovation of existing buildings. In larger office and institutional buildings, these costs may be expected to range from 35 % to 45 % of construction costs. Consequently, the first cost savings that may be realized by replacing, or at least reducing, mechanical systems for ventilation and cooling by natural ventilation systems is, potentially, quite large.

Yet first cost savings represent only part of the advantage that may be offered by natural ventilation. Mechanical air handling equipment including fans, filters, heating and cooling coils, vertical distribution shafts and ducts, horizontal distribution duct networks, dampers, reheat or VAV boxes and the like, and supply diffusers and return grilles consume vast amounts of space. In larger commercial buildings with conventional all-air systems, an enclosed ceiling space from 0.66 m to 1.32 m (2 ft to 4 ft) high, typically, will be required for the horizontal distribution system components alone – i.e., 0.66 cubic meter per square meter to 1.32 cubic meter per square meter (2 cubic feet per square foot to 4 cubic feet per square foot) of useful floor area. Vertical shaft areas usually range from 1 square meter per 1,000 square meters to 2 square meters per 1,000 square meters (1 square foot per 1,000 square feet to 2 square feet per 1,000 square feet) of floor area served while fan rooms require from 2 % to 4 % of this floor area – together totaling 0.08 cubic meter per square meter to 0.16 cubic meter per square meter (0.25 cubic foot per square foot to 0.50 cubic foot per square foot) of useful floor area [Bradshaw 1993]. For the common commercial building ceiling height of 3.6 m (12 ft), the combined requirements of fans, vertical distribution, and horizontal distribution systems will, therefore, consume 20 % to 40 % of the total volume of the building.

Innovative natural ventilation system designs recover much of this volume as occupiable space by configuring the spatial interior of the building to serve, in essence, as part of the natural ventilation airflow pathway. Not only is space (volume) recovered that may serve more formal architectural objectives, this space may serve to facilitate daylight distribution, by increasing the height to depth of room sections, and to mitigate rapid increases in indoor air pollutants by simply increasing the total volume of air hence contaminant capacity contained within rooms. Alternatively, the space recovered may be used to reduce the total floor-to-floor height in multistory construction to either effect a savings in the cost of building construction or to allow the inclusion of one or more additional floors – and thus the income generated from their rent or sale – within a given urban building height limitation. Note that other innovative systems may also recover building space compared to typical all-air systems.

Duct Cleanliness & Filtration

The spatial, daylighting, air quality, and construction savings benefits that may result from the removal of mechanical air handling systems could, conceivably, exceed the first cost savings offered by replacement of these mechanical systems with natural alternatives. Yet another advantage must also be acknowledged. It is now widely recognized that duct cleanliness and building air quality are intimately linked [Limb 2000] – indeed, it is claimed that ductwork may be a principle source of indoor odors even in new construction [Säateri 1998]. As a result, an entirely new industry has been formed to clean existing ductwork – a potentially difficult and expensive undertaking – and guidelines and standards have been and are being formulated to address this problem [NADCA 1992; NAIMA 1993; ASHRAE 2000; Limb 2000].

Many natural ventilation systems circumvent this problem altogether by, in essence, replacing ductwork with habitable spaces that serve to direct naturally-driven airflows. The routine cleaning and maintenance of these spaces and the ease with which their cleanliness may be inspected provide an inexpensive solution to the general problem of cleaning ventilation airflow paths. On the other hand, natural ventilation systems that admit outdoor air without filtration – still the most common situation in most natural ventilation systems – can, in those urban environments where outdoor dust levels are excessive, result in increased building cleaning and maintenance costs and the annoyance associated with working in a environment with excessive dust and particle loads. (Issues related to outdoor air quality in California are discussed further later in this report.) Consequently, mechanical ventilation systems offer the significant advantage of air filtration but with potential cost and health penalties of unclean ducts while natural ventilation systems, as commonly configured, avoid the duct cleaning problem altogether yet provide little or no filtration of ventilation airflows. Again, it should come as no surprise that research to address these problems is currently underway.

Other Issues

A number of other related issues must be considered when evaluating the potential of natural and/or hybrid ventilation systems including daylighting, acoustical isolation, smoke control and management, rain entrainment, security, and pest control. Of these, the inherent compatibility of daylighting with natural ventilation design strategies is perhaps most significant from an energy point of view. In its survey of U.K. buildings, the Building Research Establishment Conservation Service Unit [BRECSU] data indicate that naturally ventilated buildings typically consume 23 % to 52 % of the energy consumed for artificial lighting in mechanically air conditioned office buildings [BRECSU 2000]. In principle, lighting efficiency should be independent of the ventilation system employed, yet building configurations that serve natural ventilation purposes well are often most appropriate for daylighting strategies that, when applied properly, can significantly offset artificial lighting.

2.3 Future Prospects of Natural Ventilation & the Emergence of Hybrid Strategies

Natural ventilation offers the means to control air quality in buildings, to directly condition indoor air with cooler outdoor air, to indirectly condition indoor air by night cooling of building thermal mass, and to provide refreshing airflow past occupants when desired. While mechanical ventilation systems may also accomplish these goals, natural ventilation systems:

- can offset cooling energy consumption when climate and operational conditions are suitable,
- can offset the fan power required to provide ventilation mechanically,
- potentially provide quantitative health, comfort, and productivity advantages that may, in part, be due to the greater *robustness* of natural ventilation systems,
- provide qualitative advantages of ‘fresh air’ in the minds of most occupants,
- may offer users greater direct control of their environments and, as a consequence, may benefit from less restrictive comfort criteria that results from occupants’ ability to adapt their environment to their immediate perception of comfort,

- can offset a significant fraction of the relatively large first costs associated with conventional mechanical ventilation systems in commercial buildings by simply replacing them with lower cost natural ventilation systems,
- can recover the large spatial requirements that conventional mechanical systems demand and return them to serve formal architectural, daylighting, and air quality objectives or to reduce nonmechanical construction costs, and
- can avoid the duct cleanliness dilemma, and its attendant costs, simply by circumventing the need for ducts altogether.

Yet natural ventilation systems:

- presently lack proven ventilation heat recovery capabilities, although some methods are currently under development,
- are generally difficult to control and are inherently unreliable when natural driving forces are small, and
- presently lack proven filtration capabilities thus may be compromised by environments, particularly urban, with high outdoor particle and gaseous contaminant concentrations.

The potential of natural ventilation systems depends, in part, on the suitability of a given climate, in part, on the design of the natural ventilation system used, and in part, on the advantages offered by mechanical system alternatives. Recent developments in natural ventilation system design have been matched by collateral developments in mechanical ventilation design. Thus, for example, as the development of natural ventilation systems offer a means to ventilate without fan power consumption, research into low pressure ventilation systems answer with mechanical systems with reduced fan power requirements. These and other research developments have led quite naturally to the emergence of so-called *hybrid ventilation systems* that attempt to combine the benefits of both natural and mechanical ventilation in an optimal way [Heiselberg 1999; Heiselberg 2000]. Recent reports of the design and performance of three U.K. buildings clearly indicate the advantages hybrid system may have when compared to both purely natural or purely mechanical ventilation alternatives [Arnold 2000; Braham 2000, Berry 2000]:

> "Independent studies with new buildings using low-energy heat recovery mechanical ventilation integrated into fabric energy storage designs using hollow core slabs have reported better year-round comfort (including summer cooling) standards, together with significantly lower annual delivered and prime energy consumption with lower maintenance requirements than even the best natural ventilation designs." [Braham 2000]

Thus, the future of both natural and mechanical ventilation now clearly lies in the emerging field of hybrid ventilation system design. However, this report is focused on natural ventilation as a stand-alone strategy. Future work will address hybrid approaches in more detail.

3. California Opportunities and Issues

This section discusses opportunities and issues in the application of natural ventilation systems to commercial buildings. These issues include climate suitability, ambient air quality, and codes and standards, and they are discussed in the context of application in the state of California.

3.1 Climate Suitability

One of the most important issues in determining the potential of natural ventilation systems is the suitability of the climate. A method to evaluate climate suitability based on a single-zone model of natural ventilation heat transfer in commercial buildings is presented in this section. This method is applied to specific climatic data to characterize:

- the statistical distribution of the natural direct ventilation rates needed to offset given internal heat gains rates (i.e., due to occupants, equipment and lighting) to achieve thermal comfort during overheated periods, and
- the potential internal heat gain that may be offset by night-time cooling for those days when direct ventilation is insufficient.

The theory and simplifying assumptions underlying this method will be discussed first followed by a presentation of the application of the method using TMY2 climatic data [Marion and Urban 1995] for ten California locations.

Theory

For preliminary climatic suitability analysis, a commercial building may be thermally idealized as a control volume with a uniform temperature distribution, i.e., the common single-zone representation of a building illustrated in Figure 6:

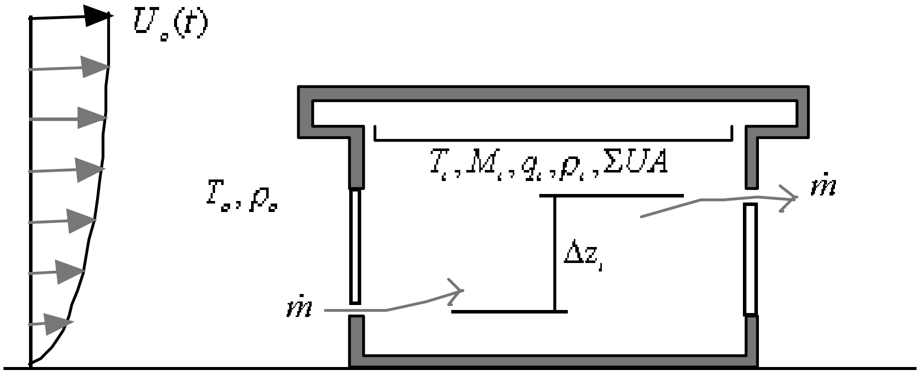


Figure 6 Single-zone model of a building

where:

$U_o(t)$ = the (outdoor) reference wind speed

$T_o(t)$ = the outdoor air temperature

$\rho_o(t)$ = the outdoor air density

$T_i(t)$ = the indoor air temperature

$\rho_i(t)$ = the indoor air density

$q_i(t)$ = indoor internal plus solar gains

M_i = indoor thermal mass

ΣUA = building envelope thermal conductance

$\dot{m}$ = mass flow rate of ventilation air

Δz_i = inlet to outlet elevation change

With these model parameters and variables defined, the dynamic thermal behavior of this single-zone idealization may be defined by requiring the conservation of thermal energy:

$$\begin{pmatrix}\text{heat transfer}\\\text{rate out}\end{pmatrix}+\begin{pmatrix}\text{thermal}\\\text{energy accumulated}\end{pmatrix}=\begin{pmatrix}\text{heat transfer}\\\text{rate in}\end{pmatrix} \qquad (1)$$

or:

Dynamic Model $$KT_i + M\frac{dT_i}{dt} = E \qquad (2)$$

where: $$K = \Sigma UA + \dot{m}c_P \qquad (3)$$

$$E = KT_o + q_i \qquad (4)$$

In this formulation, conductive heat transfer is arbitrarily separated into a rate of heat transfer out equal to the product of the envelope conductance and the indoor air temperature $(\Sigma UA)T_i$ and a rate of heat transfer in $(\Sigma UA)T_o$. Thus, the net conductive heat transfer rate is the more familiar product of the envelope conductance and the outside-to-inside temperature difference $(\Sigma UA)\left(T_o - T_i\right)$. Similarly and more intuitively direct, the ventilative heat transfer rate is separated into a rate out $\dot{m}\,c_p T_i$ – where c_p is the specific heat capacity of air (1.006 kJ/kg·°K or 0.24 kcal/kg·°K for dry air) – and a rate in $\dot{m}\,c_p T_o$. Together, the combined conductive and ventilative heat transfer rate out of the control volume is, thus, $K\,T_i$ where K is the combined conductive and ventilative transfer coefficient defined by Equation (3). This formulation stresses the fact that the response of the thermal system is excited by the sum of conductive, ventilative, and internal gains $K\,T_o + q_i$ that are defined by Equation (4) to be the system *excitation E.*

If either the thermal mass M_i of the building system is negligibly small or the indoor air temperature T_i is regulated to be relatively constant, then the accumulation term of the governing energy balance of the system, Equation (2), may become insignificantly small. Under these conditions the thermal response of the building system will be governed by the steady-state limiting case of Equation (2) or:

Steady State Model $$KT_i = E \qquad (5)$$

This steady-state approximation is the essential basis of the heating and cooling degree day methods used for preliminary determination of annual heating or cooling energy needs and as metrics of a given climate's heating and cooling season. It will also provide an approximate means to characterize the ventilative cooling potential of a given climate.

The so-called *heating balance point temperature* T_{o-hbp} establishes the outdoor air temperature below which heating must be provided to maintain indoor air temperatures at a desired internal heating set point temperature T_{i-hsp}. Hence, when outdoor temperatures exceed the balance point temperature direct ventilative cooling can usefully offset internal heat gains to maintain thermal comfort. At or below the balance point temperature, ventilative cooling is no longer useful although ventilation should still be maintained at the minimum level required based on air quality considerations.

At the heating balance point the combined conductive and ventilative heat loss from the building just offsets internal gains or, using the steady state approximation:

$$\textit{Heating Balance Point}\text{:}\ K\left(T_{i-hsp}-T_{o-hbp}\right)=q_i \tag{6}$$

Solving this equation for the balance point temperature and expanding we obtain:

$$T_{o-hbp}=T_{i-hsp}-\frac{q_i}{\dot{m}_{\min}c_p+\Sigma UA} \tag{7}$$

where the ventilation flow rate has been set to the minimum ventilation rate required for air quality control $\dot{m}_{\min}$.

The heating balance point temperature, based on a prescribed heating set point temperature equal to the lowest indoor air temperature that is acceptable for thermal comfort, establishes a lower bound of acceptable outdoor temperatures for ventilative cooling. The outdoor air temperatures equal to the highest acceptable temperature for thermal comfort establishes an upper bound above which ventilative cooling will not be useful. Here, this limiting temperature will be assumed to be equal the indoor cooling set point temperature T_{i-csp} above which mechanical cooling would normally be activated to maintain thermal comfort. In addition, indoor air humidity must be limited to achieve comfortable conditions and to avoid moisture-related problems.

Distinct thermal comfort limits or *comfort zones* may be identified for summer conditions, when occupants tend to wear lighter clothing, and winter conditions, when occupants tend to wear heavier clothing. However, due to internal gains, natural ventilation may be expected to be useful to limit overheating in commercial buildings during both summer and cooler periods of the year. Consequently, for ventilative cooling of commercial buildings it is useful to use a combined comfort zone that covers all seasons of the year.

A reasonable comfort zone for ventilative cooling, based on combining ASHRAE's winter and summer comfort zones [ASHRAE, 1997], would be delimited by lower and upper dry bulb temperatures of 20 °C (68 °F) and 26 °C (79 °F) and a dew point temperature of 17 °C (63 °F) as illustrated in figure 7. Thus for all subsequent considerations:

- the indoor heating set point temperature will be assumed to be $T_{i-hsp}=20\,^{\circ}\mathrm{C}$ (68 °F),
- the indoor cooling set point temperature will be assumed to be $T_{i-csp}=26\,^{\circ}\mathrm{C}$ (79 °F), and
- indoor air humidity will be limited to a dew point temperature of $T_{i-dp}=17\,^{\circ}\mathrm{C}$ (63 °F).

Recent surveys of comfort in naturally ventilated office buildings in the U.K. indicate occupants tolerate a larger range of temperatures than in air-conditioned buildings. This is thought to be due to occupant *adaptive* behavior that is fostered by these buildings [Olesen 2000, Oseland 1998]. When occupant adaptive behavior is considered, the upper limit of the comfort zone may, arguably, be increased by approximately 2 °C (4 °F) in still air conditions and even more when occupants can control local air speeds. Furthermore, slightly higher relative humidities may be tolerated when local air speeds of around 1.5 m/s (27 ft/min) are available [Martinez 2000]. Thus, the comfort zone used here may be considered somewhat conservative if adaptive behavior is considered and the ventilation system is designed to provide relatively high local air speeds.

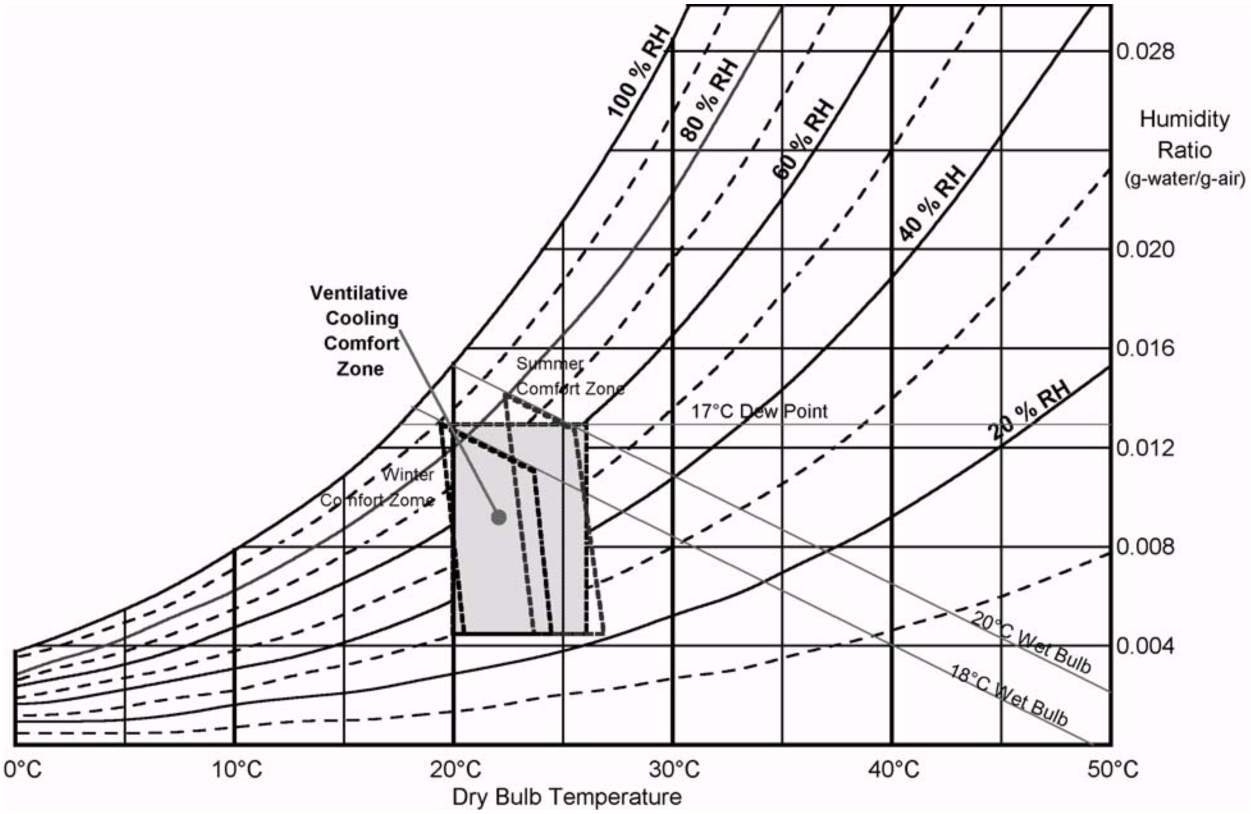


Figure 7 Comparison of the ventilative cooling comfort zone used in the present study with ASHRAE summer and winter comfort zones [ASHRAE 1997].

Thus, direct ventilative cooling will be considered to be useful (although perhaps not sufficient) when outdoor conditions fall below both the cooling set point and the dew point limit yet above the outdoor heating balance point temperature determined based on the indoor heating set point temperature limit above. Formally, these conditions may be defined as:

Direct Ventilative Cooling Criteria:

$$T_{o-hbp}(q_i, T_{i-hsp} = 20\,^\circ\mathrm{C}) \le T_o \le T_{i-csp} = 26\,^\circ\mathrm{C} \quad \text{and} \quad T_{o-dp} \le 17\,^\circ\mathrm{C} \tag{8}$$

For night ventilative cooling, no lower limit need be placed on outdoor air temperatures and while the air humidity limit is not likely to be immediately important for thermal comfort reasons, it will be maintained to avoid moisture-related problems in building materials and furnishings:

Night Ventilative Cooling Criteria:

$$T_o \le T_{i-csp} = 26\,^\circ\mathrm{C} \quad \text{and} \quad T_{o-dp} \le 17\,^\circ\mathrm{C} \tag{9}$$

Method

With the theory and comfort criteria established above, a method to evaluate the suitability of a given climate for ventilative cooling may be formulated. This method involves a procedure for estimating the ventilation rate needed to offset internal gains when direct ventilation can be effective and a second procedure for estimating the internal gains that may be offset by nighttime ventilation when direct ventilation is not useful.

DIRECT VENTILATION

Relative to their enclosed volume, commercial buildings typically have relatively small envelope surface areas yet require relatively large minimum ventilation rates for air quality control. Consequently, the conductive conductance of commercial buildings ΣUA may be expected to be small relative to the minimum ventilative conductance $\dot{m}_{\min} c_p$:

$$\dot{m}_{\min} c_p >> \Sigma UA \qquad (10)$$

Thus, the heating balance point temperature of commercial buildings – which is approached from above as ventilation is reduced to the minimum value needed for air quality control – may be estimated by introducing the condition of Equation (10) into Equation (7) to obtain:

$$T_{o-hbp} = T_{i-hsp} - \frac{q_i}{\dot{m}_{\min} c_p + \Sigma UA} \approx T_{i-hsp} - \frac{q_i}{\dot{m}_{\min} c_p} \qquad (11)$$

or, in terms of rates per unit floor area of building:

$$T_{o-hbp} \approx T_{i-hsp} - \frac{q_i / A}{\left(\dot{m}_{\min} / A\right) c_p} \qquad (12)$$

When outdoor air temperatures exceed this balance point temperature, yet fall below the upper limit of the comfort zone – here, taken as the indoor cooling set point temperature T_{i-csp} – ventilation can offset a given internal gain. Again, assuming ventilative conductance dominates heat transfer (i.e., $\dot{m} c_p >> \Sigma UA$), the ventilation rate required to offset internal gains while maintaining indoor air temperatures within the comfort zone, $\dot{m}_{cool}$, may be estimated using the steady state model, Equation (5). Given the width of the comfort zone $(T_{i-csp} - T_{i-hsp})$, however, two possibilities must be considered. When outdoor air temperatures fall within an increment of $(T_{i-csp} - T_{i-hsp})$ above the balance point temperature, the minimum ventilation rate will suffice:

$$\dot{m}_{cool} = \dot{m}_{\min} \quad when \quad T_{o-hbp} \le T_o \le T_{o-hbp} + (T_{i-csp} - T_{i-hsp}) \qquad (13)$$

Above this range, the ventilation rate will have to increase as outdoor air temperatures increase:

$$\dot{m}_{cool} = \frac{q_i}{c_p (T_{i-csp} - T_o)} \quad when \quad T_{o-hbp} + (T_{i-csp} - T_{i-hsp}) < T_o \le T_{i-csp} \qquad (14)$$

or, in terms of rates per unit floor area of building:

$$\dot{m}_{cool} / A = \frac{q_i / A}{c_p (T_{i-csp} - T_o)} \quad when \quad T_{o-hbp} + (T_{i-csp} - T_{i-hsp}) < T_o \le T_{i-csp} \qquad (15)$$

Equations (12), (13), and (15) may be used to determine periods when direct ventilative cooling may be applied and to estimate the ventilation rates needed to maintain thermal comfort during these periods. For comparative purposes, it will be useful to further express the ventilation rates in terms of an equivalent air change rate ACH in air changes per hour (h^{-1}) by assuming an average story height of the building, H, as:

$$ACH \approx \frac{\dot{m}_{cool}}{A\,H} \tag{16}$$

NIGHTTIME COOLING

To account for night cooling an alternative strategy must be employed. When daytime outdoor temperatures exceed the upper comfort limit – here, taken as the cooling set point temperature T_{i-csp} – direct ventilation is no longer useful. One may be able to offset daytime internal gains, however, by cooling the building's thermal mass with outdoor air during the previous night if, of course, the outdoor air temperature drops below the cooling set point temperature during the night. When this is possible, the heat transfer rate at which energy may be removed from the buildings thermal mass q_{night} approaches, in the limit for a very massive building:

$$q_{night} \approx \dot{m}c_p\left(T_{i-csp} - T_o\right) \;\; when \;\; T_o < T_{i-csp} \tag{17}$$

The total energy removed from the building's thermal mass during the evening may then be used to offset internal gains on the subsequent workday. On average, the internal gain that may be offset $\overline{q}_{cool}$ is thus simply equal to the integral of the night removal rate divided by the workday time period Δt:

$$\overline{q}_{cool} = \int_{nighttime} q_{night} \Big/ \Delta t \tag{18}$$

Here, it is useful to rewrite this relation in terms of average cooling rate per unit floor area per air change rate by algebraic manipulation:

$$\frac{\overline{q}_{cool}/A}{\dot{m}/A\,H} = \frac{\int_{nighttime} c_p\left(T_{i-csp} - T_o\right)dt}{H\,\Delta t} \;\; when \;\; T_o < T_{i-csp} \tag{19}$$

Equation (19) will be used to estimate the internal gain that may be offset (i.e., for very massive construction) for a nominal unit nightime air change rate to maintain thermal comfort.

Climate Suitability Evaluation Algorithm

The relations and criteria established above were used to develop a multi-step algorithm to evaluate the suitability of a given climate for ventilative cooling. Given detailed records of outdoor dry bulb and dew point temperatures the algorithm involves the following steps:

A. Problem Specification: The cooling and heating set point temperatures, limit on dew point temperatures, specific internal gains, and minimum specific ventilation rate, or the equivalent air change rate are specified. Specifically, in this analysis:

- The cooling set point temperature was set equal to the upper limit of the ventilative cooling comfort zone, $T_{i-csp} = 26\,°C$ (79 °F)
- The heating set point temperature was set equal to the lower limit of the ventilative cooling comfort zone, $T_{i-hsp} = 20\,°C$ (68 °F)

- The limiting outdoor dew point temperature was set equal to the upper limit of the ventilative cooling comfort zone, $T_{o-dp} = 17\,°\mathrm{C}$ (63 °F)
- Specific internal gains of 10 W/m^2 (3.2 Btu/ft^{2}h), 20 W/m^2 (6.3 Btu/ft^{2}h), 40 W/m^2 (12.6 Btu/ft^{2}h), and 80 W/m^2 (25.2 Btu/ft^{2}h) were considered. The low end of this range corresponds to the combination of state-of-the-art low-energy lighting systems combined with minimal plug-loads in addition to relative low occupant densities. The upper end corresponds to very intensive lighting, plug loads, and occupancy levels that might be associated with, for example, commodities trading floors. While this range is commonly considered for commercial building design purposes, recent research indicates the upper levels of this range may no longer be realistic [Komor 1997, Wilkins and Hosni 2000].
- ASHRAE Standard 62 [ASHRAE 1999] prescribes minimum ventilation rates for commercial buildings. Here, the rates specified for offices will be used to establish a typical minimum specific ventilation rate. Due to relatively low occupancy levels (e.g., 7 persons per 100 square meters (7 persons per 1100 square feet)) and moderate rate requirements (i.e., 10 Liters per second per person (21 cubic feet per minute per person)) for offices, the specific ventilation rate required for offices is 0.7 L/s•m^2 (0.14 ft^3/min•ft^2) ($\dot{m}_{\min} / A \approx 0.0084$ kg/s•m^2 (0.0017 lb/s•ft^2) for air at standard conditions). For an assumed story height of $H = 2.5$ m (8.2 ft), this minimum specific ventilation rate corresponds to an air change rate of about 1.0 h^{-1}.

B. Balance Point Temperature Computation: Compute the outdoor heating balance point temperature for each specific internal gain considered as follows:

$$T_{o-hbp} \approx T_{i-hsp} - \frac{q_i / A}{c_p \dot{m}_{\min} / A}$$

For the conditions specified above in Step 1, we obtain the following results in Table 1.

Table 1 Heating balance point temperatures for a range of specific internal gains.

	Specific Internal Gains (q_i / A)			
	10 W/m^2	20 W/m^2	40 W/m^2	80 W/m^2
T_{o-hbp}	8.1 °C	– 3.8 °C	– 27.6 °C	– 75.2 °C

It is evident from these numbers that internal gains expected in commercial buildings can quite easily extend the ventilative cooling season well into winter months.

C. Direct Ventilative Cooling Evaluation: For each hour of an annual climatic record for a given location proceed through the following steps:

C.1. If $T_o < T_{o-hbp}$ no ventilative cooling will be required.

C.2. If $T_{o-hbp} \le T_o \le T_{o-hbp} + \left(T_{i-csp} - T_{i-hsp}\right)$ and $T_{o-dp} \le 17\,°\mathrm{C}$ (63 °F) the cooling ventilation rate may be maintained at the minimum ventilation rate, $\dot{m}_{cool} = \dot{m}_{\min}$ while the indoor air temperature T_i floats between the balance point temperatures. Record the corresponding air change rate $ACH \approx \dot{m}_{cool} / (A\,H)$.

C.3. If $T_{o-hbp} + \left(T_{i-csp} - T_{i-hsp}\right) \le T_o < T_{i-csp}$ and $T_{o-dp} \le 17\,^{\circ}\mathrm{C}$ (63 °F) the minimum cooling ventilation rate needed to maintain indoor air conditions within the comfort zone (i.e., at the cooling set point temperature) may be computed as:

$$\frac{\dot{m}_{cool}}{A} = \frac{q_i / A}{c_p (T_{i-csp} - T_o)}$$

Record the corresponding air change rate $ACH \approx \dot{m}_{cool} / (A\,H)$.

C.4. Else if $T_o > T_{i-csp}$ or $T_{o-dp} > 17\,^{\circ}\mathrm{C}$ (63 °F) then ventilative cooling is not useful. Record this condition for subsequent evaluation of cooling using nighttime ventilation.

D. Nighttime Ventilative Cooling Evaluation:

D.1. Scan the results of step C to identify days for which direct ventilative cooling was not useful for at least one daytime hour.

D.2. For each day identified in D.1, compute the (limiting) rate at which thermal energy can be removed from the building's thermal mass for each hour of the proceeding night (i.e., from 6 p.m. to 6 a.m.) as:

$$q_{night} \approx \dot{m} c_p \left(T_{i-csp} - T_o\right) \text{ when } T_o < T_{i-csp} \text{ and } T_{o-dp} \le 17\,^{\circ}\mathrm{C} \text{ (63 °F)}$$

D.3. Using the results from 4.2 compute the average internal gain that may be offset $\overline{q}_{cool}$ the next day:

$$\frac{\overline{q}_{cool} / A}{\dot{m} / A\,H} = \frac{\int_{nighttime} q_{night}\, dt}{H\, \Delta t}$$

Climatic Data

In the application of this method that follows, TMY2 (Typical Meteorological Years) data were used [Marion and Urban 1995]. The TMY2 data sets were devised to be “typical year” data sets intended to be used to evaluate typical year meteorological conditions. Thus, the TMY2 data should be useful for evaluating the climatic suitability (potential) of a given site for natural ventilation applications in buildings for typical year conditions. Another option when evaluating the performance of a specific (proposed) natural ventilation system would be to consider extreme year rather than typical year conditions. Levermore and his colleagues have taken this position, defining an extreme year as the mid-year of the upper quartile of 20 years’ climatic data ordered by the average daily mean temperatures for July, August, and September [Levermore et al. 2000].

Discussion of Method

A method to evaluate the climate suitability of a given location for direct ventilative cooling and complimentary nighttime ventilative cooling of a building's thermal mass has been presented. Importantly, the method may be applied, in principle, to ventilative cooling achieved by natural, mechanical, or mechanically assisted natural means. This method allows the building designer to quickly evaluate the feasibility and potential effectiveness of ventilative cooling strategies, given knowledge of the likely internal gains in the building, and make first estimates of the ventilation rates required to effect these strategies.

The proposed method has a rational physical basis and therefore should be considered relatively general. Furthermore, the method has been devised to provide building designers with useful preliminary design guidance relating to the levels of ventilation required to implement the direct and nighttime cooling strategies.

The method is not without its faults, however. First, estimates of the internal gains that may be offset by nighttime cooling are based on the assumption that the building has, essentially, infinite thermal mass. Thus, these results may significantly overestimate the benefit of nighttime cooling. This fault could be corrected with a measure of heat transfer efficiency that reflects the anticipated level of thermal mass available in the building, but this correction would require additional research using a dynamic formulation of the building heat transfer.

As presented, the climate suitability analysis tacitly assumed the temperature of the ventilation exhaust was equal to the indoor occupied zone temperature – a condition that would be met if the building zone was well-mixed. The analysis, being based on a control volume approach, need not be limited to a well-mixed zone assumption – the exhaust air temperature should simply reflect the intended operation of the ventilation system being used. If, for example, one seeks to drive ventilation airflows primarily by buoyancy forces then allowing temperature stratification within the building offers some advantages [Linden 1999, Hunt et al. 2000, Hunt et al. 2001]. In such a case, exhaust air temperatures could exceed comfort limits (e.g., the indoor cooling set point) by an increment corresponding to that resulting from acceptable or likely stratification, say, $\Delta T_{strat} = T_{i-strat} - T_{i-csp}$. For direct ventilative cooling, then, the ventilation rate per unit floor area needed to offset a given internal gain (i.e., Equation 1.15) would be modified as:

$$\dot{m}_{cool}/A = \frac{q_i/A}{c_p(\Delta T_{strat} + T_{i-csp} - T_o)} \quad when \quad T_{o-hbp} + (T_{i-csp} - T_{i-hsp}) < T_o \le T_{i-csp}$$

and analysis would proceed as before. Thus, for example, if a designer feels a 4 ºC stratification increment is acceptable (i.e., if exhaust temperatures can exceed the upper comfort limit by 4 ºC) then the analysis would proceed with the temperature term of the denominator above increased by 4 ºC thus reducing the ventilation rate needed at any time step during the analysis.

In this way, the reduced ventilation rate benefit of utilizing thermal stratification – in combination with displacement ventilation – may be accounted for. The risk of compromising thermal comfort by radiant exchange from warm ceilings should, however, be considered. For all but the tallest commercial buildings, however, wind forces are likely to play a more important role in natural and hybrid ventilation systems than buoyancy forces as will be discussed in the next chapter – thus consideration of thermal stratification may not be necessary.

Also, the method presumes direct ventilative cooling should be the strategy of first resort and nighttime ventilative cooling should only be considered as a complement to direct cooling. As such, this method does not evaluate the potential of nighttime ventilative cooling as a primary strategy. Conceivably, in some climates or for certain applications nighttime cooling may be more appropriate as the primary strategy. This situation should be investigated in the future.

Application to California climates

This method was applied to the ten California locations with TMY2 hourly annual climatic data available. While the ten locations, listed in Table 2 below, do not statistically represent the state in terms of population or climate, they do include both coastal and inland climates that cover much of the latitudinal range of the state.

Table 2 California locations used for initial climate suitability evaluation.

Coastal	Inland
San Diego	*Daggett*
Long Beach	*Bakersfield*
Los Angeles	*Fresno*
Santa Maria	*Sacramento*
San Francisco	
Arcata	

Computed results follow in Table 3. Data in this table is organized in two sets – a set of four columns that report the direct ventilative cooling results:

- the average air change rate required to effect direct ventilative cooling for each of four specific internal gain rates for each of the ten California locations – *when direct cooling is effective*,
- the variation of the air change rate about the average value to be expected for each case – evaluated by computing the standard deviation of the ventilation rates computed to achieve thermal comfort, and
- the fraction of the year direct cooling is effective for each case – i.e., the number of hours direct ventilation is effective out of the total number of hours in a year's record.

A final column reports the results for complimentary night cooling:

- the average specific internal gain that can be offset by a nominal unit air change rate of (previous) nighttime cooling for overheated days (i.e., those days when direct ventilative cooling is not effective for all hours from 6 a.m. to 6 p.m.),
- the fraction of overheated days that may, potentially, be cooled using nighttime ventilation,
- and the total number of days during the year that nighttime cooling may, potentially, be effective.

These statistics have been devised to provide design guidance for preliminary considerations. To facilitate preliminary design considerations, the direct ventilative cooling results are shaded to distinguish the ranges of ventilation required. Results in white or light gray boxes will require, on average, ventilation rates in the 0 h^{-1} to 5 h^{-1} and 5 h^{-1} to 10 h^{-1} ranges respectively – both quite possible using commonly available natural ventilation strategies. Results in medium and darker gray (10 h^{-1} to 15 h^{-1} and above 15 h^{-1}) may be difficult to achieve using available natural ventilation strategies.

For example, the results for Bakersfield show that an average ventilation rate of 3.4 h^{-1} ± 8.7 h^{-1} may be expected to provide direct ventilative cooling when the specific internal gain is 10 W/m^2 (3.2 Btu/ft^2h). Furthermore, for this location, direct ventilative cooling may be expected to be useful 64 % of the hours of the year for this same specific internal gain. Nighttime cooling can be used in this climate to compliment direct cooling for 93 days of the year that accounts for 94 % of the expected overheated days. Thus 6 % of these overheated days (approximately 11 days) would require mechanical air conditioning to achieve thermal comfort. During the 159 days with possible nighttime ventilative cooling, internal gains can be offset at the rate of 3.2 W/m^2-h^{-1} ± 2.6 W/m^2-h^{-1} (1.0 Btu/ft^{2}h-h^{-1} ± 0.81 Btu/ft^{2}h-h^{-1}). Thus to offset a specific internal gain of 10 W/m^2 (3.2 Btu/ft^{2}h), the nighttime ventilation rate would have to be 10 ÷ 3.2 ≥ 3.1 h^{-1} on average. (Here, the ≥ sign is used as the $\overline{q}_{cool}$ computation is based on the assumption that the building is thermally massive.)

Table 3 Climate suitability statistics for ten California locations

	Direct Cooling				
	10 W/m^2	20 W/m^2	40 W/m^2	80 W/m^2	Night Cooling[1]
Arcata					
Vent. Rate or Cooling Potential	**(1.1 ±0.4) h^{-1}**	**(1.7 ±0.8) h^{-1}**	**(3.3 ±1.7) h^{-1}**	**(6.7 ±3.4) h^{-1}**	**10.5 ±1.5 $W/m^2 \bullet h^{-1}$**
% Effective[2]	**74 %**	**100 %**	**100 %**	**100 %**	**100 % (2 days)**
% Heating	**26 %**	**0 %**	**0 %**	**0 %**	
Bakersfield					
Vent. Rate or Cooling Potential	**(3.4 ±8.7) h^{-1}**	**(5.7 ±16.1) h^{-1}**	**(11.5 ±32.2) h^{-1}**	**(22.9 ±64.3) h^{-1}**	**(3.2 ±2.6) $W/m^2 \bullet h^{-1}$**
% Effective[2]	**64 %**	**77 %**	**77 %**	**77 %**	**94 % (159 days)**
% Heating	**12 %**	**0 %**	**0 %**	**0 %**	
Daggett					
Vent. Rate or Cooling Potential	**(3.4 ±8.9) h^{-1}**	**(5.8 ±16.5) h^{-1}**	**(11.6 ±32.9) h^{-1}**	**(23.2 ±65.8) h^{-1}**	**(3.7 ±2.9) $W/m^2 \bullet h^{-1}$**
% Effective[2]	**60 %**	**71 %**	**71 %**	**71 %**	**86 % (169 days)**
% Heating	**11 %**	**0 %**	**0 %**	**0 %**	
Fresno					
Vent. Rate or Cooling Potential	**(2.9 ±7.2) h^{-1}**	**(4.6 ±12.8) h^{-1}**	**(9.2 ±25.6) h^{-1}**	**(18.3 ±51.1) h^{-1}**	**(4.3 ±2.8) $W/m^2 \bullet h^{-1}$**
% Effective[2]	**63 %**	**81 %**	**81 %**	**81 %**	**100 % (161 days)**
% Heating	**18 %**	**0 %**	**0 %**	**0 %**	
Long Beach					
Vent. Rate or Cooling Potential	**(2.3 ±5.6) h^{-1}**	**(4.4 ±11.1) h^{-1}**	**(8.7 ±22.1) h^{-1}**	**(17.4 ±44.3) h^{-1}**	**(6.2 ±2.7) $W/m^2 \bullet h^{-1}$**
% Effective[2]	**88 %**	**91 %**	**91 %**	**91 %**	**92 % (95 days)**
% Heating	**3 %**	**0 %**	**0 %**	**0 %**	
Los Angeles					
Vent. Rate or Cooling Potential	**(1.7 ±1.9) h^{-1}**	**(3.3 ±3.8) h^{-1}**	**(6.6 ±7.7) h^{-1}**	**(13.2 ±15.4) h^{-1}**	**(6.6 ±2.2) $W/m^2 \bullet h^{-1}$**
% Effective[2]	**96 %**	**97 %**	**97 %**	**97 %**	**100 % (55 days)**
% Heating	**1 %**	**0 %**	**0 %**	**0 %**	
Sacramento					
Vent. Rate or Cooling Potential	**(2.3 ±6.5) h^{-1}**	**(3.8 ±11.6) h^{-1}**	**(7.6 ±23.2) h^{-1}**	**(15.1 ±46.4) h^{-1}**	**(7.0 ±2.2) $W/m^2 \bullet h^{-1}$**

% Effective[2]	**69 %**	**88 %**	**88 %**	**88 %**	**100 %** **(142 days)**
% Heating	**19 %**	**0 %**	**0 %**	**0 %**	
San Diego					
Vent. Rate or Cooling Potential	**(1.8 ±3.3) h^{-1}**	**3.6 ±6.5 h^{-1}**	**(7.2 ±13.0) h^{-1}**	**(14.5 ±26.1) h^{-1}**	**(3.6 ±2.3) $W/m^2 \bullet h^{-1}$**
% Effective[2]	**91 %**	**92 %**	**92 %**	**92 %**	**90 %** **(52 days)**
% Heating	**1 %**	**0 %**	**0 %**	**0 %**	
San Francisco					
Vent. Rate or Cooling Potential	**(1.3 ±1.3) h^{-1}**	**(2.2 ±2.6) h^{-1}**	**(4.5 ±5.1) h^{-1}**	**(8.9 ±10.3) h^{-1}**	**(8.6 ±2.6) $W/m^2 \bullet h^{-1}$**
% Effective[2]	**90 %**	**99 %**	**99 %**	**99 %**	**100 %** **(12 days)**
% Heating	**10 %**	**0 %**	**0 %**	**0 %**	
Santa Maria					
Vent. Rate or Cooling Potential	**(1.4 ±1.8) h^{-1}**	**(2.4 ±3.4) h^{-1}**	**(4.9 ±6.9) h^{-1}**	**(9.7 ±13.8) h^{-1}**	**(11.2 ±2.8) $W/m^2 \bullet h^{-1}$**
% Effective[2]	**82 %**	**99 %**	**99 %**	**99 %**	**100 %** **(17 days)**
% Heating	**17 %**	**0 %**	**0 %**	**0 %**	

[1] Night cooling for subsequent days when direct cooling is not effective.

[2] For direct cooling % = hours effective ÷ 8760 h; for night cooling % = days effective ÷ days needed.

white = 0 h^{-1} to 5 h^{-1}

░ light gray = 5 h^{-1} to 10 h^{-1}

▒ medium gray = 10 h^{-1} to 15 h^{-1}

▓ dark gray > 15 h^{-1}

The data presented in Table 3 has been plotted in the form of *bubble* plots for the six coastal locations and the four inland locations – Figure 8 and Figure 9. In these plots the center of each bubble locates the average ventilation rate required for each of the four specific internal gain rates considered and the size of the bubble indicates the relative efficacy of direct ventilative cooling. Thus larger bubbles located lower in the plot indicate direct ventilative cooling is not only feasible (vis a vis ventilation rate required) but effective.

As might be expected, Table 3 and Figure 8 show that the coastal climates of California are potentially well suited to natural ventilation with respect to climatic considerations. For most of these locations, the direct ventilative cooling approaches 90 % to 100 % effectiveness with most of the ineffective hours representing either times when heating is required or times that could be cooled through night ventilative cooling. Equally significant is the fact that, for buildings with moderate internal gains in most of these locations, the required cooling can be achieved with very achievable average air change rates of about 5 h^{-1} or less. Additionally, with the exception of Long Beach, the required air change rates have reasonable standard deviations less than or about equal to the averages. The required air change rates for the buildings with higher internal loads may be achievable with new and developing natural ventilation technology.

On the other hand, natural ventilation appears to be less promising for the hotter, more humid climates of inland California. As shown in Table 3 and Figure 9 for the four inland locations, both direct and night ventilative cooling have a lower percentage effectiveness and require larger air change rates (with much larger standard deviations) then for the coastal locations. Despite that, a significant ventilative cooling potential exists for these locations. However, some type of hybrid system with mechanical cooling may be more successful in these situations.

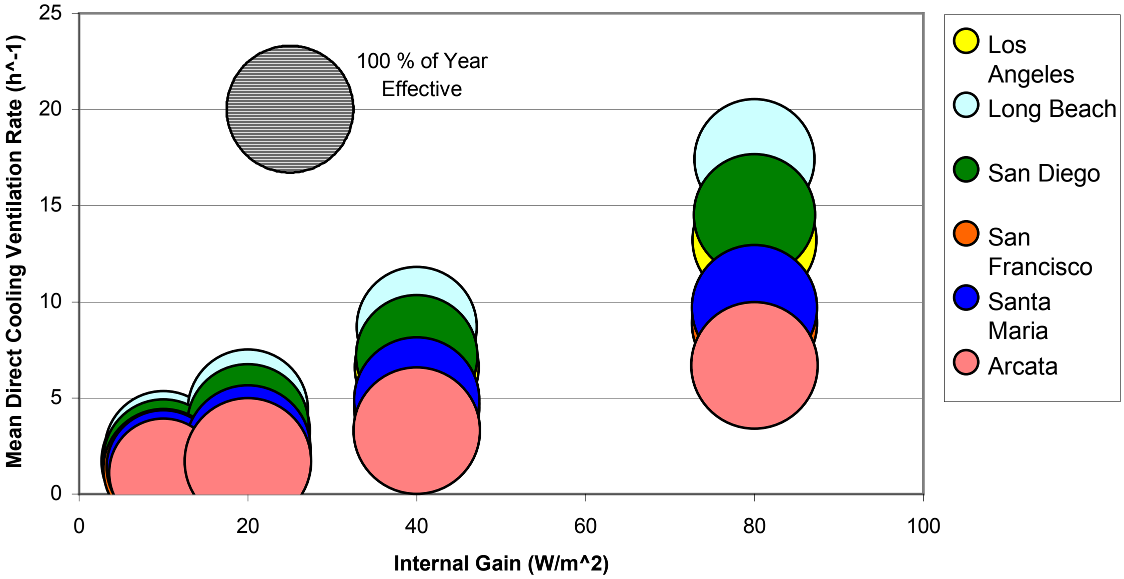


Figure 8 Direct ventilative cooling results for the coastal locations.

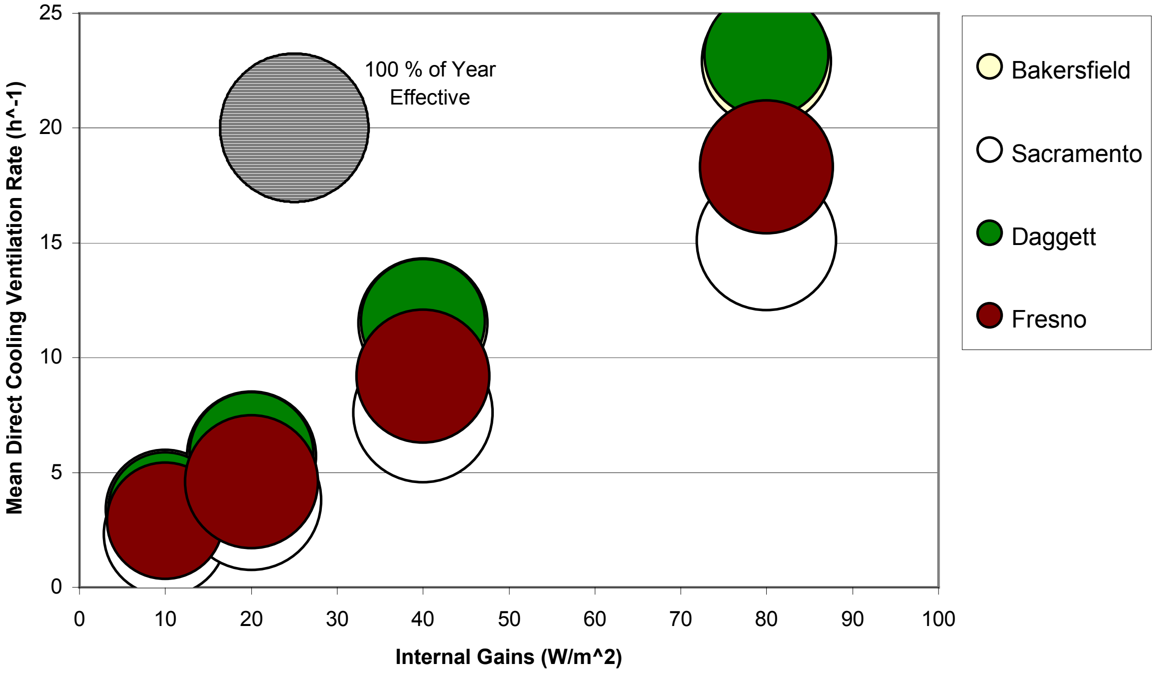


Figure 9 Direct ventilative cooling results for the inland locations

3.2 Ambient Air Quality

A second important issue in determining the potential for natural ventilation systems in California and elsewhere is the impact of ambient air quality. While poor ambient air quality affects both mechanical and natural ventilated buildings, there are two reasons for greater concern with natural ventilation. First, as discussed in the review section, typical natural ventilation systems do not incorporate filtration. Although the filtration in mechanical ventilation systems does not remove all contaminants from the outdoor air, it generally includes some form of particle filtration. Second, in order to perform ventilative cooling, natural ventilation systems may introduce far greater quantities of outdoor air into the building.

Ideally, one would develop a metric to express the suitability of the outdoor air quality in a given location as has been presented above for climate suitability. Unfortunately, the issue is not nearly so straightforward due to knowledge gaps such as the lack of specific health-based, contaminant concentration limits for indoor air and less standardized ambient air quality data compared with weather data. However, ASHRAE Standard 62-1999 [ASHRAE 1999] requires that the outdoor air used for ventilation in buildings meet the National Primary Ambient-Air Quality Standards set by the U.S. EPA [EPA 1987] which sets concentration limits for sulfur dioxide, particles (as PM10), carbon monoxide, ozone, nitrogen dioxide, and lead. Additionally, California has established somewhat more restrictive ambient air quality limits than the national standards for some of these contaminants [CARB 2001].

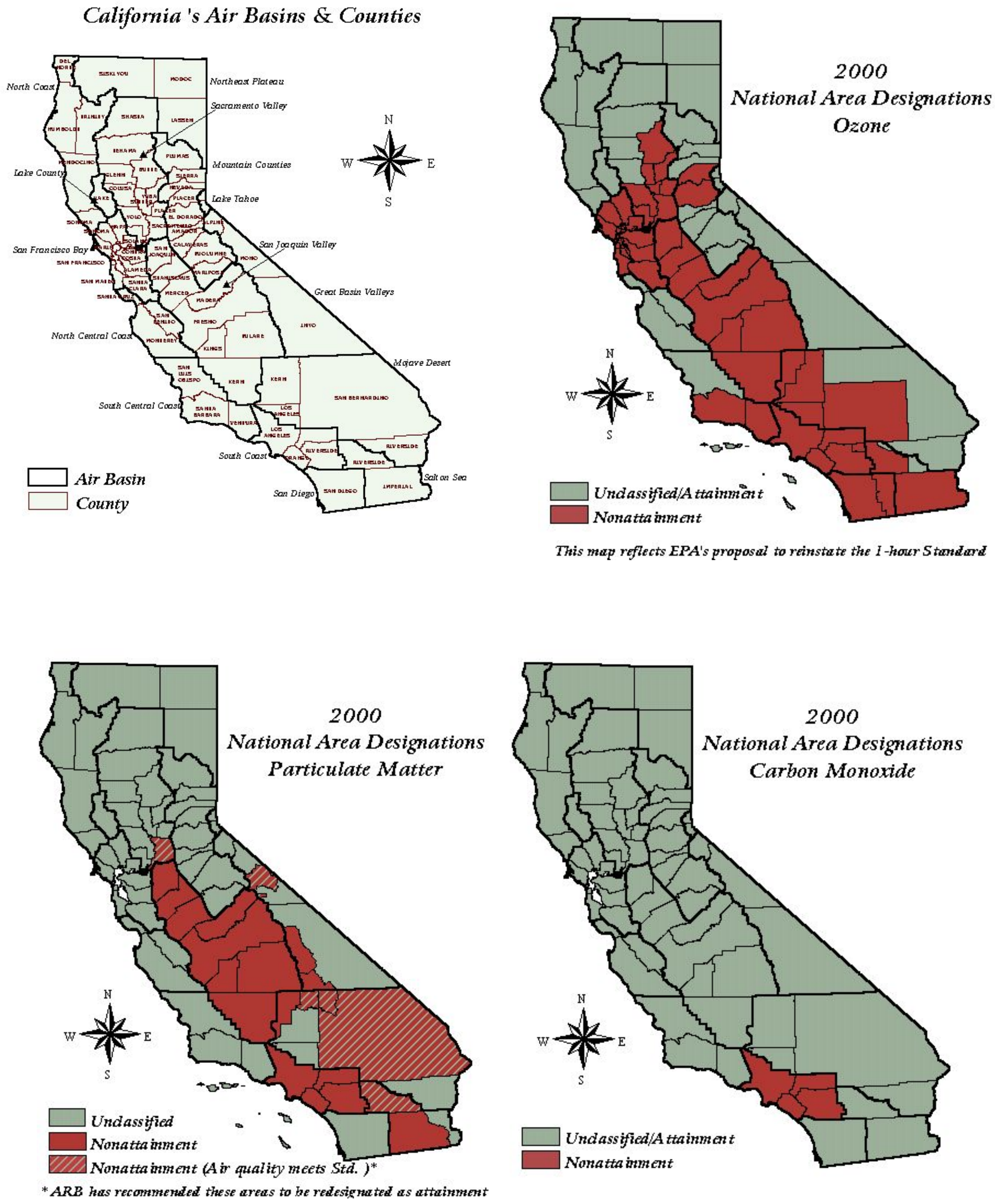
Standard 62 allows several alternatives for determining whether the local ambient air quality meets the prescribed limits including monitoring data of the U.S. EPA or appropriate state or local environmental protection authorities. If outdoor air contaminant levels exceed the limits, Standard 62 recommends that the outdoor air be treated to control the offending contaminants. As discussed earlier, natural ventilation systems typically do not include air filtration, however, the air cleaning equipment typically included in mechanical ventilation systems is unlikely to significantly impact the concentrations of ambient air pollutants other than coarse particles (i.e., larger than about 3 μm).

Although the acceptability of ambient air for ventilation purposes must be evaluated locally, available ambient air quality data for California [CARB 2001] were reviewed to gain some insight to the issue on a regional level. For the purpose of ambient-air quality evaluations, California is divided into 15 regions called air basins (Figure 10). If the air quality in an area violates an ambient air quality standard that region is designated with the status of nonattainment. This summary addresses nonattainment status based on the national standards. A nonattainment status alone, however, does not tell the complete story of the severity of an ambient air quality problem because it does not address the magnitude, frequency, or localization of the air quality violation.

California has undertaken many emission control measures for the last three decades and, as a result, significant improvements have been made in ambient air quality. However, three of the criteria contaminants still pose a problem for portions of the state as indicated by nonattainment. Most of the major, urban areas of California are nonattainment for the national 1-hour standard for ozone (see Figure 10). Some additional areas (Shasta, Tehama, Western Nevada, Amador, Calaveras, Tuolumne, and Mariposa counties) are nonattainment for the new, proposed 8-hour standard for ozone. Statewide attainment status for ozone is not expected in the near future. A significant portion of the state is also nonattainment for PM10 (see Figure 10). Four areas (the Coachella Valley, the Owens Valley, the San Joaquin Valley, and the South Coast Air Basin) are classified as serious PM10 nonattainment areas and are not expected to meet standards for many years. The South Coast Air Basin is designated nonattainment for national CO standards (see

Figure 10). However, this problem is specifically limited to a portion of Los Angeles County and is expected to be mitigated in the coming years. The city of Calexico also has carbon monoxide concentrations that violate the national standards but has not been designated nonattainment.

Although the nonattainment issues discussed above seem to discourage the application of natural ventilation systems in much of California, opportunity still lies in the fact that pollutant concentrations that violate the air quality standards may be local and/or seasonal phenomena even within nonattainment regions. Obviously, the local variation indicates that natural ventilation may still be a viable option for some buildings within these nonattainment areas. Also, as seen in Figure 10, the areas with better ambient air quality include much of the coastal area which was shown to have high climate suitability for natural ventilation as discussed in Section 3.1. Perhaps less obvious is the possibility that an area with a seasonal ambient air quality problem may be able to take advantage of some type of hybrid HVAC system that reduces outdoor air intake and/or treats outdoor air during the problem seasons. Even if ambient concentrations of some pollutants exceed recommended limits, the indoor levels may be acceptable due to deposition or other removal mechanisms. A multizone IAQ model such as CONTAM could be used to predict indoor pollutant concentrations resulting from various scenarios of different ventilation rates, ambient concentrations, and indoor generation or removal processes.



This map reflects EPA's proposal to reinstate the 1-hour Standard

*ARB has recommended these areas to be redesignated as attainment

Figure 10 – California Air Basins and Attainment Designations

3.3 Standards and Regulatory Context

Natural ventilation has long been recognized by ventilation standards and building codes, though never in terms of specifying engineering-based design methods. This section discusses the standards and regulatory context relevant to natural ventilation, specifically ASHRAE Standard 62 and the California Energy Efficiency Standards (Title 24).

ASHRAE Standard 62

ASHRAE Standard 62-1999 currently allows natural ventilation of buildings via a short statement in Section 5.1. That section states that "Ventilating systems may be mechanical or natural. … When natural ventilation and infiltration are relied upon, sufficient ventilation shall be demonstrable. When infiltration and natural ventilation are insufficient to meet ventilation air requirements, mechanical ventilation shall be provided." The standard is not specific as to the meaning of "demonstrable" or "sufficient ventilation." An official interpretation of the standard, issued as Interpretation #8 in 1993 (reissued as #16 in 2000), states that the ventilation requirements associated with the standard's Ventilation Rate Procedure (i.e., Table 2) is not the only acceptable means of realizing such demonstration. The interpretation refers to calculation methods in the ASHRAE Fundamentals Handbook and opening area requirements in building codes. Therefore, it is not clear whether natural ventilation systems need to provide the same ventilation rates as those required by the standard for mechanical systems. The noted interpretation implies that natural ventilation systems need not provide these rates, but the standard is not very clear about this exception.

ASHRAE Standard 62-1999 has been under revision since 1997 when it was converted to continuous maintenance. Since then a number of discrete modifications or addenda have been developed that revise specific portions of the standard. Several have been approved (none of which address natural ventilation), and a number are still under development. Addendum 62j, which specifically addresses natural ventilation, is one such addendum, but it has only recently been approved for publication.

Addendum 62j attempts to partially clarify the standard's requirements with respect to natural ventilation. This addendum still allows natural ventilation systems in lieu of or in conjunction with mechanical systems. For natural ventilation systems, it contains the following requirements:

> Naturally ventilated spaces shall be permanently open to and within 8 m (25 ft) of operable wall or roof openings to the outdoors.
>
> The openable area of these openings shall be a minimum of 4 % of the net occupiable floor area.
>
> The means to open required operable openings shall be readily accessible to building occupants whenever the space is occupied.

The addendum allows for "engineered natural ventilation systems" that do not necessarily meet these requirements, but the authority having jurisdiction must approve them. The requirement for operable opening areas based on floor area is in fact consistent with most building codes.

ASHRAE Standard 62-1999 also addresses the acceptability of outdoor air quality, which is certainly relevant to natural as well as mechanical ventilation systems. The standard currently requires that outdoor air quality be evaluated by the following three-step procedure:

1. Determine if the area in which the building is located meets the EPA NAAQS (National Ambient Air Quality Standards) or equivalent state or local environmental protection authorities. Alternatively, the building is located in a community similar in population, geographic and meteorological settings and similar in industrial patterns to a community

having acceptable ambient air quality as determined by authorities having jurisdiction. Or the building is in a community with a population of less than 20,000 people, and the air is not influenced by one or more sources of substantial ambient air pollution. Or air monitoring for three consecutive months shows that the air quality meets the EPA NAAQS.

2. Determine if the outdoor air contains other contaminants, not contained in the EPA NAAQS that have been identified as of concern by other authorities cognizant of air quality.
3. If after completing steps 1 and 2 there is still a reasonable expectation that the air is unacceptable, sampling shall be conducted via NIOSH procedures and the acceptability of the outdoor air quality should otherwise be evaluated.

If the ambient air quality exceeds the EPA NAAQS, the standard states that it should be cleaned, but the standard does not require such cleaning. The standard also states that if the best available technology does not remove the offending contaminants, the amount of outdoor air may be reduced during periods of poor ambient air quality, though the standard provides no detail as to the level or duration of such a reduction.

The current requirements for ambient air quality evaluation are not particularly clear as to how one complies, and therefore these requirements are the subject of two addenda under development as part of the revision of ASHRAE Standard 62. One addendum provides more specific requirements on assessing outdoor air quality, and requires air cleaning if the EPA NAAQS requirements for PM10 are violated. Another draft addendum requires cleaning if the NAAQS limits for ozone are violated, though it currently contains several exceptions that would limit the applicability of this requirement. Both of the addenda are still in the draft form and may change before they are approved.

Title 24, California's Energy Efficiency Standards for Residential and Nonresidential Buildings

Title 24, Part 6 (July 1999) discusses natural ventilation under Section 121 Requirements for Ventilation. The requirements are very similar to those discussed with reference to addendum 62j to ASHRAE Standard 62-1999. The only differences are that the openings must be within 6 m (20 ft) of the opening instead of 8 m (25 ft) and that the openings must be greater than 5 % of the floor area instead of 4 %.

The current versions of ASHRAE Standard 62-1999 and its addenda, California’s Title 24 Energy Efficiency Standards and most building codes allow the use of natural ventilation. All of the requirements are in terms of accessible openings that are sized based on 4 % to 5 % of the floor area of the ventilated space. None of these documents consider climatic conditions or ambient air quality in their requirements, though ASHRAE Standard 62 does require an assessment of outdoor air quality. While engineering-based approaches are likely to result in more reliable designs, none of the standards require their use. At the same time, they do not disallow them.

4. Design and Analysis of Natural Ventilation Systems

This section discusses the design and analysis of natural ventilation systems. It begins with a discussion of past and current design approaches employed in the U.S., and then presents a general design methodology based largely on methods implemented in the European building community, in particular, the methodology presented by CIBSE in *Applications Manual AM10: 1997 - Natural ventilation in non-domestic buildings* [Irving andy Uys 1997]. This and other similar design methodologies have emerged from the European building communities in recent years to meet the greater demands now placed on natural ventilation systems to provide thermal comfort and acceptable indoor air quality while conserving nonrenewable energy. These 'first generation' analytical design methods were developed to replace the largely empirical approaches used in the past, which are still prevalent in the U.S. The approaches being employed in Europe are presently being replaced by the development of 'second generation' design methods to support the development of hybrid natural and mechanical ventilation systems – again methods that not only include physical design strategies but analytical tools to support the design development and design evaluation of systems utilizing these strategies. Following the general design methodology, a summary of current design and analysis tools is presented followed by a plan to develop design tools in future phases of this project. Additional design and analysis methods development needs are discussed at the end of this section.

The current state of natural ventilation design in U.S. commercial buildings can be viewed as embodying two approaches, one based on long-standing building code requirements and the other reflecting a more recent emphasis on operable windows as a means of providing improved indoor environments and saving energy. The first approach, referred to in an earlier section of this report, is based on building code requirements of a specific fraction (generally 4 % or 5%) of operable vent area relative to the occupiable floor area. This requirement has existed for decades and has been assumed by many to provide adequate ventilation and has resulted in the provision of no mechanical ventilation in many commercial buildings, particularly smaller buildings. This "code-based" approach neglects the issue of whether these operable vents or windows are actually open, how much ventilation they provide under various weather conditions and their ability to distribute ventilation to all portions of the occupied space. More recently, partly in conjunction with the interest in so-called "green" or "sustainable" buildings, there has been a renewed interest in natural ventilation for the reasons noted above (e.g., improved indoor environments and energy savings). A number of buildings have been designed and built employing features intended to provide improved energy efficiency and indoor environmental quality. Many of these buildings have employed some form of natural ventilation ranging from simply operable windows to more advanced concepts such as ventilation shafts and clerestories. However, few if any, of these natural ventilation systems are designed based on engineering considerations of the driving forces due to weather or of the resultant ventilation rates or air distribution patterns. In order to bring natural ventilation technology more in line with other aspects of building system design and to ensure that natural ventilation systems perform adequately, it is important that sound, engineering-based design methods are developed and employed.

4.1 General Design Methodology

The following is presented as a comprehensive methodology aimed at providing sound, engineering-based design methods for naturally ventilated buildings. The method presented here has been implemented in the European building community. CIBSE's *Good Practice Guide 237* [CIBSE 1998] boils down the design of natural ventilation systems, presented in CIBSE AM10 [Irving and Uys 1997], to an eight-step process.

1. Develop design requirements
2. Plan airflow paths
3. Identify building uses and features that might require special attention
4. Determine ventilation requirements
5. Estimate external driving pressures
6. Select types of ventilation devices
7. Size ventilation devices
8. Analyze the design

Develop design requirements – This step consists of establishing design requirements against which the success of a building design can be measured. This step should also establish, early on, whether or not the option of implementing natural ventilation is viable from both a practical and economic perspective. Consideration should be given to the indoor environmental requirements with respect to internal heat gains, air quality and humidity; space requirements; prevailing and extreme weather conditions; ambient pollutant levels; and construction and operating costs.

Plan airflow paths – This step consists of selecting the overall type of natural ventilation strategy to use. It requires the establishment of airflow paths of the outdoor air into the occupied spaces of the building and then out through planned exhaust locations. Consideration must be given to the orientation of the building to prevailing winds, surrounding terrain and obstructions; external pollutant sources; and potential stack flows. Consideration should also be given to implementing mechanically assisted and mixed-mode ventilation strategies as well as the use of night cooling of the building thermal mass.

Identify building uses and features that might require special attention – This step requires the designer to consider issues that might affect the behavior or effectiveness of a natural ventilation system. Issues include the presence of relatively large heat gains, internal obstructions to airflow, indoor and outdoor pollutant sources, envelope leakage characteristics, and acoustic isolation.

Determine ventilation requirements – This step requires the designer to determine the airflow rates required to satisfy the previously determined design requirements. As previously described, ventilation is provided for four basic purposes including air quality control, direct cooling (advective and personal) and indirect night cooling. Ventilation for air quality control typically establishes minimum ventilation rates based on existing ventilation standards and building codes. Weather data and internal loads are used to determine required flow rates during the different seasons of the year for both direct and indirect cooling purposes. This step should highlight circumstances that may lead to excessive heat gain that could reduce the likelihood of cooling by natural means. These circumstances will either require modifications to design building configuration (e.g. shading to reduce solar gain) or indicate when and how much mechanical ventilation and conditioning might be required (e.g., to overcome insufficient driving forces or extreme climatic conditions).

Estimate external driving pressures – This step requires the designer to select or determine the driving forces to which the building is likely to be subjected including wind and stack-induced and to determine the design conditions to be used in selecting and sizing the ventilation devices. If detailed analysis is to be performed, then detailed weather data will be needed. This could be in the form of measured data or other available design weather data (e.g. WYEC2, TMY2, etc.).

Select types of ventilation devices – This step requires the designer to identify the locations in the previously planned airflow paths at which ventilation devices will be required and the types of devices that will be used in those locations. The locations are typically inlets and outlets through the building envelope and openings within the space through which ventilation air is intended to flow. Ventilation devices include windows, trickle vents, exhaust stacks, louvers and doorways, and mechanical assist fans. The flow characteristics of these devices must also be identified. These characteristics typically consist of relationships between the airflow rate through the device and the pressure difference across it.

Size ventilation devices – This step requires the designer to determine the size of the ventilation devices that were selected in the previous step. Sizing can be performed using either explicit or implicit methods. Explicit methods are based on equations relating driving forces (e.g., wind and stack-driven flows) to airflow characteristics and sizes of the ventilation devices. Implicit methods require sizes of the ventilation devices to be used to determine airflow through them, so this process is often an iterative one in which the designer selects from available devices, analyzes their effectiveness in meeting design ventilation requirements, and iteratively selects devices until a viable solution is obtained. The use of sizing methods and tools can be very helpful in minimizing or even eliminating the iterations depending on the complexity of the design. The sizing of ventilation devices can be complicated by a potentially large number of unknown design parameters. Therefore, this process requires sound engineering judgment in providing additional design constraints to see the sizing process to fruition.

Analyze the design – This step requires the designer to thoroughly evaluate the design for its effectiveness in providing ventilation rates to meet the design requirements. This includes evaluating the design under various weather conditions and heat loads, determining potential situations where design goals might not be met, evaluating the effects of “unintentional” envelope leakage, and evaluating the potential “misuse” of occupant-controlled ventilation devices. The use of analysis tools can be very beneficial here to provide detailed simulations of the behavior of the building design including airflow rates, pressure relationships between zones, contaminant/exposure information, temperatures, and energy use.

4.2 Natural Ventilation Analysis and Design Tools

This section presents a summary of the currently available tools for designing and analyzing natural ventilation systems. In this discussion, *analysis* refers to the process of predicting building response given building system characteristics and driving forces (i.e., wind, buoyancy, and mechanical driving forces) while *design* refers to the inverse problem of determining building system characteristics (e.g., the size of a ventilation opening) given desired building response – the *design requirements* – and expected driving forces. Mathematical *models*, based on physical idealizations of building systems often represented by diagrammatic *models*, are necessarily common to both analysis and design *tools*. Two broad classes of models may be distinguished:

- *macroscopic* models (e.g., multi-zone building models) based on physical idealizations of building systems as collections of control volumes whose behavior may be described by algebraic or ordinary differential equations, and
- *microscopic* models (e.g., computational fluid dynamics or CFD models) based on numerically approximate solutions of systems of partial differential equations (e.g., the Navier-Stokes equations for fluid flow) wherein the physical domain of the “system” is subdivided into a relatively fine mesh.

As analysis tools may be used in an iterative, trial and error manner to search for acceptable building characteristics, the distinction between a design and analysis tool is not often made. In this discussion, however, a sharp distinction will be maintained.

The focus of this discussion is on tools that incorporate a macro-model of buildings (e.g. single-zone and multi-zone tools) as opposed to a micro-model as implemented by CFD tools. There are several limiting factors that render CFD impractical as a ventilation design tool including the fact that CFD cannot be applied to a whole building, the difficulty in establishing boundary conditions and the large computational and personnel cost involved in implementing CFD even for more manageable projects. This is not to say that CFD analysis tools are not useful in the design process; they can be very beneficial in analyzing temperature, airflow and contaminant fields within individual zones of a building, particularly within large spaces such as atria.

Existing Analysis Methods and Tools

Depending on design requirements, analysis of natural ventilation systems will require consideration of energy, airflow (due to both natural and mechanical driving forces), and contaminant transport. The complex interaction between these coupled characteristics makes it difficult to fully address them all in a single, generally applicable method or tool. This has led to the development of a wide range of different analysis tools to address these characteristics in varying levels of detail and often on an individual basis. Analysis tools typically fall into three basic categories of single-zone, multi-zone or computational fluid dynamics.

Single-zone models consider the entire building to consist of a single volume of well-mixed air with no internal partitions. Envelope penetrations can be defined in varying levels of detail depending on the model. Penetrations can be further defined to include intentional flow paths as well as unintentional leakage paths and can be distributed vertically along the façade. Consideration can be given to wind, buoyancy, or both effects on the airflow through the paths. Some methods also account for thermal characteristics of the building envelope and structure, for example the NatVent program [Orme 1999]. Single-zone models are generally good for first-cut calculations, but are not as useful as multi-zone analysis, because inter-zonal airflow paths are not accounted for. They can also be useful in performing quick comparisons between different building configurations but with uncertain accuracy and even correctness [Allard 1998].

Multi-zone models can be used to describe a building as a set of zones that are interconnected by airflow paths. The zones are typically well-mixed, i.e., the air within the zone is considered to be at the same state throughout the zone at any given time (e.g. temperature, pressure and contaminant concentration). These models can provide much greater detail than their single-zone counter parts, as commonly configured, and can be used to perform single-zone analysis as well. The more advanced models can require a fair amount of detailed input depending on the complexity of the building representation being implemented. There are several multi-zone modeling software tools now available both commercially and in the public domain that provide very flexible handling of airflow and contaminant transport, including mechanically induced airflows, such as CONTAM, COMIS, and BREEZE [Orme 1999]. These tools provide the ability to perform steady-state as well as transient (quasi-steady) analysis that enable simulations up to a year, including the use of design or measured weather data.

While the aforementioned multi-zone analysis tools are very useful for isothermal conditions, they generally lack the heat transfer analysis capabilities that would prove quite useful in the analysis of natural ventilation systems. There are other programs available that handle the heat transfer aspects of building analysis such as EnergyPlus/DOE-2, ESP-r, AIOLOS and IDA ICE [Crawley, et al. 2000, Leal 2000, Allard 1998, Bring, et al. 1999]. These typically don't handle the airflow and contaminant transport analysis like the multi-zone modeling tools. The DOE-2 energy analysis program only handles non-HVAC system airflows in the form of user input envelope infiltration rates. Given, these leakage rates, the program calculates the energy requirements to condition the infiltration air, but doesn't account for differences in these leakage rates due to buoyancy and wind driven effects. The multi-zone analysis tools, COMIS and CONTAM, have been integrated with another thermal analysis tool, TRNSYS. TRNSYS is a modular environment that enables independently developed modules to be integrated into an already very powerful analysis system. COMIS and CONTAM modules have been created and implemented within the TRNSYS environment to enable the analysis of the energy requirements due to air infiltration [Dorer and Weber 1994, Dols and Walton 2000].

Existing Design Methods and Tools

The eight-step process presented in section 4.1 provides a general approach to designing natural ventilation systems. It will be presented here as the "process of choice" while recognizing that other design approaches could be applied as well. The eight-step process often occurs in three distinct phases:

- Conceptual Design – steps 1, 2, 3, and 4,
- Design Development – steps 5, 6, and 7, and
- Design Performance Evaluation – step 8.

The following presents a brief review of existing methods associated with these phases of the process. Details of outdated empirical methods are left out, but references are provided to more detailed presentations of these methods.

Conceptual Design

A series of international European research programs supported in part by the International Energy Agency, building on the earlier work of the British Research Establishment, have led to the development of a number of publications that provide general guidelines and some rules of thumb to aide the designer in the conceptual design phase [Allard 1998, Irving and Uys 1997, CIBSE 1998, Petherbridge, et al. 1988, BRE 1999, and BRE 1994]. For example, the BRE Digest *Natural Ventilation in Non-domestic Buildings* suggests single-sided ventilation schemes be limited to rooms with sectional widths no greater than 2.5 times their ceiling heights and operable window areas approximately equal to 5 % of the room floor area. For wind-driven cross ventilation, on the other hand, this Digest suggests sectional widths can be as much as 5 times the ceiling height.

As new design strategies have been put forward, including more ambitious uses of night cooling and, most recently, hybrid combinations of natural and mechanical ventilation, these publications and especially the rules of thumb contained within them have quickly become dated. Nevertheless, the more general fundamental strategies presented remain valid and the associated guidelines useful.

Design Development

A variety of tools for use in the design development phase have been published over the years including:

- sizing rules of thumb,
- non-dimensional design graphs based either on fundamental theory or correlation studies using more detailed simulation tools,

- spreadsheet programs,
- specialized simulation programs intended to be used iteratively to search for acceptable ventilation component sizes,
- general purpose airflow simulation programs also used iteratively, and
- analytical methods used to determine component sizes more directly given a specification of design requirements and environmental conditions.

For general reviews of these tools, see Li, et al. [999], Allard [1998], and Orme [2000].

The simpler tools are invariably based on single zone models of building systems that ignore internal resistances to airflow and seldom account completely for the coupled thermal airflow interactions that are characteristic of natural ventilation airflow systems. In principal, the former shortcoming can be accepted because, properly, internal resistances to airflow should be minimized by design. However, without supporting analysis, the designer may not know whether this objective has been realized. In some wind-driven natural ventilation systems the coupled thermal airflow interactions may not be critical, but in most systems, especially when used for cooling, all of these interactions are important and must be considered.

In developing tools to directly size ventilation components given design requirements and environmental conditions two types of design problems may be distinguished. A so-called ‘first-order’ design problem is one wherein design requirements are defined in terms of required ventilation rates while a ‘second-order’ design problem is defined in terms of either thermal or air quality design requirements. Suffice to say, ‘first-order’ design problems are more readily defined and solved than ‘second order’ problems; indeed most design is approached as a ‘first order’ problem whether approached directly or iteratively.

Axley has presented a general approach to the ‘first-order’ design problem that is based on the same theory currently used in multi-zone airflow analysis programs like CONTAM and COMIS. This method is based on accounting for pressure changes that must occur in ventilation “loops” formed by following a ventilation flow path from inlet to exhaust and back to the inlet again. The “pressure loop method” allows for direct sizing of airflow components, accounts for both buoyancy (stack) and wind-induced airflow, and can be applied to multi-zone building idealizations to account for internal resistances to airflow such as doorways and transoms. Furthermore, this approach may be applied using statistical representations of environmental conditions for specific locations to better account for local environmental impacts. The method may be applied manually or, since it shares the same theoretical base, it may be implemented within the interface of existing multi-zone programs [Axley 2001a].

The pressure loop component sizing method is based on the macroscopic multi-zone view of a building and includes the interconnection between zones represented by pressure-flow relationships. These pressure-flow relationships are typical of those found in existing multi-zone analysis tools and include power law, effective leakage area, orifice, quadratic, self-regulating, duct and fan components. While the analysis tools require the user to define the physical characteristics of these flow components and then calculates the airflow rates through them, the sizing method requires the user to define the design airflow rates through the components and determines the physical characteristics of the components to provide the required flow rates.

The following is an outline of the *Loop Equation Design Method*.

1. Layout the global geometry and multi-zone topology of the passive ventilation flow loops for each zone within the building.
2. Identify an ambient pressure node and additional pressure nodes at entries and exits of each flow component along the loops.
3. Establish design conditions: wind pressure coefficients for envelope flow components, ambient temperature, wind speed and direction, interior temperatures, and evaluate ambient and interior air densities.
4. Establish first-order design criteria (i.e., a ventilation objective) and apply continuity to determine the objective design airflow rates required for each passive ventilation flow component.
5. Form the forward loop equations for each loop established in Step 1 above by systematically accounting for all pressure changes while traversing the loop.
6. Determine the minimum feasible sizes for each of the flow components by evaluating asymptotic limits of the loop equation for the with-wind and without-wind cases separately.
7. Develop and apply a sufficient number of technical or non-technical design rules or constraints to transform the under-determined design problem defined by each loop equation into a determined problem.
8. Develop an appropriate operational strategy to accommodate the regulation of the passive ventilation system for variations in design conditions.

Examples of the application of this method to both residential and non-residential buildings are presented in Axley (2001a, 2000a, 2000b, 1999a and 1999b). The method can, with difficulty, be done by hand or, more readily, be carried out using spreadsheet or symbolic mathematical analysis software.

In the example diagram shown in Figure 11, based on the Inland Revenue building, England [Irving and Uys 1997], three loops are relevant. For the upper loop passing through the ambient pressure node 13 to the surface node 14 and on through nodes 15, 18, 19, 20, and 21 back to node 13, the accumulated pressure differences due to wind from 13 to 14 plus those due to flow through inlet vent “e”, the buoyancy change from 15 to 18, flow through exhaust “g”, and the buoyancy changes from 18 to 20 and from 20 back to 13 must, necessarily, sum to zero. The wind-driven pressure changes are determined by given approach wind velocity and characteristic wind pressure coefficients for the building form and the buoyancy pressure changes depend on given zone and outdoor air temperatures thus leaving the pressure drops in the discrete flow components to be the only unknows. Given required ventilation rates, then, the pressure drops in these flow components may be directly related to the component size characteristics (e.g., opening area of the inlet, cross-sectional area and height of the stack, etc.). The pressure loop equations, thus, link the environmental conditions (i.e., wind speed and direction and assumed temperatures) and design requirements directly to ventilation system component sizes. Thus these loop equations may be used to directly size these components [Axley 2001b].

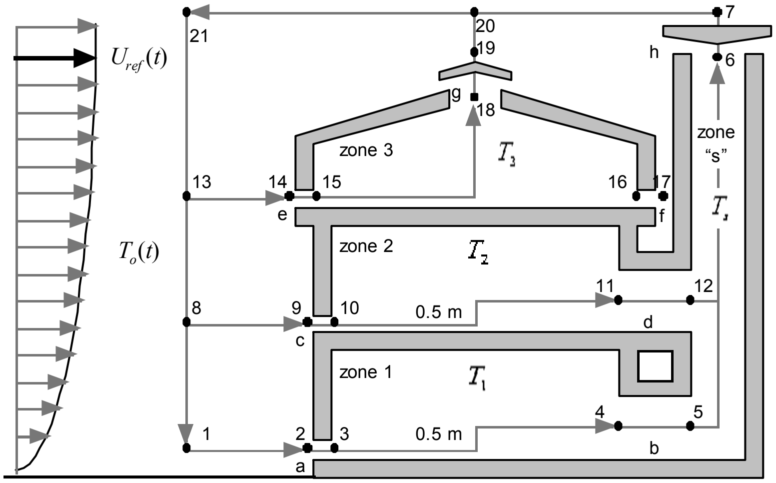


Figure 11 Sample Diagram Displaying Pressure Loops

The "loop method," in its current formulation, is based on multi-zone airflow analysis theory that assumes, in effect, steady conditions of airflow prevail. It, therefore, does not account for unsteady airflow phenomena nor does it account directly for unsteady coupled airflow and thermal interactions. The former shortcoming is commonly believed to be minor, although due to this shortcoming the application of the loop method to single-sided ventilation and backdrafting phenomena would be misguided. The later shortcoming is likely to be more important as the "loop method's" application to the important night cooling natural ventilation strategy is very limited. The extension of the method to night cooling and other ventilation strategies where the coupled thermal airflow interactions need to be more faithfully considered is, however, not out of the question and should be considered.

Design Performance Evaluation

Increasingly stringent air quality and energy efficiency demands have made design performance evaluation critical to the success of natural ventilation systems. This involves the simulation of the performance of the proposed building system to evaluate both the temporal and spatial variation of air quality and thermal comfort provided and the energy consumption required (e.g., to condition ventilation air). Given the need for spatial and temporal detail, multi-zone airflow analysis tools have become the method of choice for performance evaluation. Here, again, it would be best to use multi-zone analysis tools that account for the coupled thermal airflow interactions yet these tools demand further development before they may reasonably be applied in practice.

4.3 Plan for Analysis and Design Tools

As previously stated, the design of natural ventilation systems is currently accomplished by iteratively applying analysis tools until design requirements are satisfied. The reasons for this relate to the very complex nature of building design itself, i.e., there is perhaps an infinite set of design possibilities. The trick is to narrow the focus of design to attack a manageable subset of the possibilities and to implement engineering judgment to identify and satisfy design requirements. While it is very unlikely that the need for analysis tools can be completely eliminated at this time, tools that can minimize the iteration process are needed to assist the design engineer in narrowing their focus. This section presents a general outline of plans to develop both design and analysis tools for natural ventilation systems including a design tool based upon the *Loop Equation Design Method*.

Design Tools

In terms of natural ventilation design tools, one such tool is the *Loop Equation Design Method* presented above. This tool appears to be a promising method for sizing of natural ventilation components due to its generality, practicality and direct consideration of stack and wind-driven airflow that is critical in addressing natural ventilation airflow. The method can even be used to address infiltration and mechanically assisted airflow that is essential in considering the design of hybrid ventilation systems. As indicated, the method has been presented as a "paper" method that would greatly benefit from being implemented within existing building analysis tools. This implementation could provide a method of visualizing and defining pressure loops, relieve the designer of the burden of forming and solving the proper equations, provide a seamless transition into the analysis phase of design, and even provide a method of documenting the design process.

A tool to implement the *Loop Equation Design Method* should provide the user with the means to perform the eight steps presented above. Because proper implementation of the method requires engineering judgment, the tool should also provide significant guidance in applying that judgment. Multi-zone modeling tools typically provide most of the capabilities called for in items 1 through 3 including establishing the global geometry and topology of zones and interconnecting flow paths, specifying an ambient pressure node and intrinsically the inlet and outlet pressure nodes of airflow components, and establishing the design conditions. Specification of the ventilation flow loops is the main and non-trivial requirement needed in these tools. Step 4 is a relatively simple matter of providing a means of defining airflow components as natural ventilation design types and allowing for the input of a first-order design requirement. The tool could also be made to calculate component-specific requirements from more general requirements such air changes per hour. Steps 5 through 6 comprise the main computational portion of the method and are fairly straightforward in terms of setting up the representative loop equations based on the "design" form of the airflow components (i.e. the inverse of the analysis form). However, Step 7 will likely require a significant amount of user-interaction to impose design constraints, and could prove to be a very challenging aspect of implementing the method with minimum burden to the user. Depending on the design constraints (e.g. multiple-loop constraints), there is a potential for the need to solve a relatively difficult set of nonlinear equations. Providing detailed guidance would likely prove to be very beneficial to the user. Step 8 entails consideration of how to operate ventilation systems to maintain design requirements under conditions other than the extreme design cases by perhaps varying inlet and outlet damper positions or implementing mechanical assistance. This step might also entail a more detailed analysis of the design for annual weather patterns to determine the extent to which design requirements are exceeded or under-achieved.

Analysis Tools

The needs for analysis tools are broken down here into immediate needs and those that are less immediate and should be considered for future implementation. The immediate needs are those that will provide support for analysis of ventilation components described in Axley (2000a), such as self-regulating vents and the numerical methods to handle them. The less immediate needs are those that would further the treatment of phenomenon that are not typically addressed in multi-zone airflow analysis tools yet are very important to the analysis of natural ventilation systems. These needs include the treatment of heat transfer, non-trace contaminants such as moisture, and building controls. These are discussed later in this report in the section on *Additional Development and Opportunities.*

Development Plans for Next Phase of this Project

Based on the previous discussion of natural ventilation design and analysis, it appears that the most feasible plan would be to implement the *Loop Design Method* within an existing multi-zone simulation environment. This would greatly leverage existing multi-zone analysis capabilities and also provide a relatively seamless transition between design and analysis stages of the design process. It is also proposed that a pre-design tool be developed based upon the *climate suitability analysis*, presented earlier, to simplify the process of evaluating the potential application of natural ventilation to various climates.

DESIGN TOOLS

Two design tools are proposed for development – one to implement the climate suitability method and another to implement the Loop Design Method. The climate suitability tool would provide preliminary estimates of the ventilation rates needed to achieve direct cooling for a variety of internal gain levels and the minimum night cooling ventilation rate that would be required to offset internal gains of the following day. This would lead to the following four-step design process:

- Step 1: use climate suitability results for your climate to determine preliminary required daytime and night time ventilation rates
- Step 2: layout global geometry and topology following CIBSE guidelines or using one of many built precedents
- Step 3: use *Loop Design Method* to get preliminary sizes of all components and establish primitive aspects of operation/control strategy.
- Step 4: use annual analysis to evaluate the performance of the now specified system and iteratively refine design (e.g., component sizes and possibly global geometry and topology) and control strategy.

It is proposed that the *Loop Design Method* be implemented within the existing multi-zone analysis environment of CONTAM [Dols et al. 2000]. CONTAM is a public domain program that provides users with an intuitive graphic interface to develop models, or graphic idealizations, of specific building ventilation system proposals. It currently provides an interface that could be used to implement steps 1 through 4 of the loop method as described above. The specifics of how to implement the method need to be worked out, but the following presentation indicates the tasks and issues that should be addressed.

A. Develop loop selection interface – This would provide the user with the means to identify specific ventilation loops and assign airflow component types to these loops. Presently, the CONTAM interface provides the user with the tools to create schematic plan diagrams of building airflow systems by drawing floor plans and placing airflow component icons on a graphic "sketchpad." To implement the loop method within the CONTAM interface, the user would have to additionally identify specific ventilation loops for investigation and component sizing. This could be as simple as providing another input parameter for each airflow component designating loop numbers of which the flow component is a member or by allowing the user to link airflow components graphically to define specific loops. It would be desirable to provide validation of the component sets to insure that they do actually form closed loops. This could be done either programmatically, or visually by providing the user with an elevation view of a building cross-section and displaying the loops on this view. Alternatively, graph theoretical methods are available that could be used to identify all independent ventilation loops that then could be presented to the user for selection for subsequent design development – reasonably a 'second generation' approach to implementation.

B. Develop inverse airflow components – CONTAM airflow component equations are formulated in the so-called "forward" form while the loop method uses these same equations in "inverse form" – a form relating the pressure drop across components to the volumetric (or mass) flow rate and characteristic design variables (e.g. characteristic duct cross-section and height dimensions for a stack or a threshold flow rate for a self-regulating vent). Most, but not all, CONTAM component equations have been transformed to inverse form for use in the loop method [Axley 2001]. The remaining component equations will need to be transformed and a small number of additional flow component relations will need to be added to the CONTAM library of components (e.g., self-regulating vents and stack terminal devices).

C. Develop loop equation assembler routines – Computational routines will be needed to form the loop equations based upon the user-defined loops, inverse flow components types, and relevant design conditions including design airflow rates, indoor and ambient air temperatures, wind speed and direction, and relative component height. These routines do not actually solve the loop equations, rather they accumulate the numerically determined pressure changes that occur when progressing around any given loop that are needed to evaluate asymptotic limits on component sizes (i.e., characteristic design variables). These numerically determined pressure changes result from wind and buoyancy effects and, importantly, pressure drops across individual components whose sizes have been fixed in the design development process.

D. Develop asymptotic limit evaluation routines – At any stage in design development (i.e., as the user systematically fixes component sizes) the results of loop equation assembly may be used to determine limiting sizes of the remaining airflow components of each loop. Computational routines will have to be developed, most reasonably as procedure calls to the component routines currently available in CONTAM, to compute these limits and to present these limits to the user. In most cases this will involve rather trivial algebraic routines. In a few cases, however, implicit methods may have to be used to evaluate these limits. This is not expected to be particularly problematic.

E. Develop design development iteration interface – Design development will involve the iterative repetition of the routines developed in Task *B* and *D* as the designer systematically fixes sizes of specific components. This not only recognizes the fact that a variety of acceptable design solutions can be formulated, but allows the user/designer to impose practical design constraints on the selection process (e.g., due to discrete available component sizes or simply preferences related to architectural considerations such as preferred window sizes). This interface should also allow the simultaneous consideration of multiple environmental states – typically for low wind and average wind conditions for two or more seasons – so that the designer can also develop operational strategies in parallel. A typical example here would be the specification of a self-regulating vent setting for winter and summer conditions.

ANALYSIS TOOLS

The more immediate needs for analysis tools include the implementation of airflow components that have been developed specifically for implementation in natural ventilation systems. Specifically, the self-regulating vent should be implemented. Models of this component are known to lead to numerical instability in the current solver of CONTAM. Thus the development of the important self-regulating component models will demand the collateral development of an improved, more robust solver. Lorenzetti has developed a number of solution strategies that have demonstrated promising results in trial runs within the CONTAM environment [Lorenzetti 1999a, 1999b, 1999c, 2000]. Consequently the development of improved solvers appears to be quite feasible and perhaps extendable to a more general set of airflow components. This would also provide an increased capability to handle components that have yet to be developed.

4.4 Additional Developments and Opportunities

This section presents additional capabilities and opportunities for promoting the design and analysis of naturally ventilated buildings in the U.S. that would serve to improve analysis and design capabilities of existing and proposed methods and tools. A list of proposed analysis capabilities is presented as well as a proposal to organize meetings to promote the practice of designing naturally ventilated buildings in the U.S.

Coupled Thermal-Airflow Analysis

The need to couple heat transfer with multi-zone airflow modeling capabilities has been recognized for some time. Thermal and airflow interactions are characteristic of natural ventilation airflow systems. Indeed, leading researchers in the field state emphatically and unequivocally that the practical design of natural and hybrid ventilation systems demands analysis of these coupled interactions.

Efforts are underway on several fronts to perform this integration. However, numerical problems of stability, convergence, and solution multiplicity have yet to be completely resolved when performing this integration. Hence, in order to implement this integration or coupling of thermal and airflow analysis, trade-offs are often made in the “tightness of coupling” [Woloszyn 2000].

An unreleased research version of the CONTAM family of programs, designated internally as CONTAM97R, has been recently used in modeling studies of a six story Dutch Tax Office building in a number of U.S. climates. Initial comparisons of measured and predicted building performance are not only encouraging but clearly demonstrate the critical need for such complete modeling (Axley 2001b).

Non-trace “Contaminant” Analysis

Multi-zone analysis tools typically provide airflow and contaminant dispersal analysis (i.e., for air quality evaluation). Without exception, available contaminant dispersal analysis tools assume air contaminants exist at trace levels and, thus, do not influence the buoyancy of the airflow. Recent interest in so-called “evaporative down-draught chimneys” wherein a water spray is used to evaporatively cool and induce downward airflow in inlet chimneys and thereby force warmer air out of exhaust chimneys has forced the need for non-trace “contaminant” analysis (i.e., treating water vapor content as a “contaminant”). This particular natural ventilation cooling strategy is based on ancient Middle Eastern precedents and, in its technically more developed versions, appears to be a very attractive strategy for hot arid urban environments. Again, the research version of CONTAM – CONTAM97R – includes non-trace analysis capabilities based on fundamental theory but these capabilities have yet to be studied systematically for purposes of validation and practical application.

Dynamic Control of Ventilation Systems

While considerable and important progress in passive strategies of controlling natural ventilation systems has been achieved in the past decade, it is now clear that passive control devices – most notably self-regulating vents – may be complemented by active control of system settings. Furthermore, the improved performance demonstrated by very recent hybrid ventilation systems that necessarily demand active control places an even greater need on the development of modeling tools to simulate active control of ventilation systems. Yet again, the internal research version of CONTAM – CONTAM97R – includes control analysis capabilities but these capabilities have yet to be studied systematically for purposes of validation and practical application.

All of the aforementioned capabilities have been addressed to varying degrees, and some would be more readily adapted into current analysis environments. Addressing these issues individually is critical in developing the techniques, but an integrated design and analysis environment would greatly benefit designers of natural ventilation systems. This environment should be as simple to use as possible, but the complex nature of the problems addressed with these tools can only be simplified so much without compromising their general applicability. This is why multi-zone analysis is proving to be beneficial, because it greatly reduces the complexity of the building systems while maintaining the level of sophistication necessary to capture the overall nature of building behavior.

Design Symposia and Workshops

Innovation in natural and hybrid ventilation systems is being driven in Europe largely by aggressive and forward looking professional design firms. In a very real sense, their efforts are outpacing research in the field and, as a result, are setting research agendas. Recognizing the need to communicate new ideas within the profession these European design professionals – often identified as "building environmental engineers" – have organized a number of symposia. Perhaps foremost among these symposia is the Intelligent Building Design symposia held annually for the last six decades with the most recent symposium organized by TRANSSOLAR Energietechnik GmbH of Stuttgart.

Similar symposia could be mounted in the U.S. This would most reasonably be done early-on by selecting the most innovative presentations from the European symposia and inviting the presenters to participate in a regional or national symposium in the U.S. To take full advantage of the specialized knowledge these practitioners currently have, design workshops should be organized to complement such a symposium.

5. Summary

Natural ventilation offers the means to control air quality in buildings, to directly condition indoor air with cooler outdoor air, to indirectly condition indoor air by night cooling of building thermal mass, and to provide refreshing airflow past occupants when desired. When compared to mechanical ventilation alternatives and depending on climate and other factors, natural ventilation systems can reduce first and energy costs, recover the valuable building space typically used by all-air mechanical systems, potentially provide health, comfort, and productivity advantages, and may offer users greater control of their environments leading to less restrictive comfort criteria. Yet natural ventilation systems presently lack proven ventilation heat recovery and filtration capabilities, are generally difficult to control and are inherently unreliable when natural driving forces are small. The key to overcoming these shortcomings and realizing the potential advantages of natural ventilation is the emergence of hybrid natural and mechanical system strategies.

Three important considerations specific to the application of natural ventilation to commercial buildings in California are climate suitability, ambient air quality, and relevant codes and standards. A new ventilative cooling metric was described and used to demonstrate that the coastal climates of California are potentially very well-suited to natural ventilation. The hotter, inland locations are less suited to a simple natural ventilation strategy but may be able to benefit from night cooling or hybrid system strategies. A review of ambient air quality data indicates that much of California fails to meet the national standards for one or more contaminant. However, since ambient air quality problems may vary by season, time-of-day, and locality, natural ventilation strategies may still be considered acceptable at all times in some areas and part of the time in other areas through innovative hybrid systems. While relevant national, state, and local building codes and standards allow natural ventilation in commercial buildings, they provide minimal guidance on acceptable application. Again, hybrid systems may eventually be more acceptable due to greater assurance that sufficient ventilation rates can be maintained at all times.

Finally, there is a lack of proven, fundamental-based tools and processes for design and analysis of natural ventilation systems in commercial buildings. A plan developing new design and analysis guidance and tools is described.

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Appendix A: CEC RFP Issues

The California Energy Commission (CEC) Public Interest Energy Research (PIER) Request for Proposals for the Buildings Energy Efficiency Program Area identified four key issues of concern. These four issues identify energy problems facing buildings in California and present opportunities to have a significant positive impact. This appendix discusses the relationship of the application of natural ventilation systems to the four key issues based on information in this report.

Issue #1 Energy consumption is rapidly increasing in hotter, inland areas as new building construction increases in these areas.

A key intent of natural ventilation systems is the reduction of energy consumed to cool and ventilate buildings. As discussed in this report, natural ventilation is not a technology ideally suited to the hotter, inland areas of California as ambient air cooler than the indoor cooling setpoint and of sufficient dryness is required to adequately cool a building. However, natural ventilation could be used in these areas either as a night cooling system or as in conjunction with a mechanical cooling system as a hybrid strategy.

Issue #2 Development of energy efficient products and services needs to adequately consider non-energy benefits, such as comfort, productivity, durability, and decreased maintenance.

Since natural ventilation systems directly affect building ventilation systems and rates, the potential exists to have a significant impact on occupant comfort and productivity. That impact could be either positive or negative depending on the natural ventilation system design, installation, operation and maintenance. Some published studies have reported improved occupant health and comfort in naturally ventilated commercial buildings. While it is not possible to estimate potential impacts on productivity for any given building, Fisk and Rosenfeld (1997) have estimated that nationwide impacts of better indoor environments are in the billions of dollars.

Since natural ventilation systems rely on natural driving forces instead of mechanical fans and air-conditioning to control comfort and IAQ in buildings, they may not reliably control comfort and IAQ under all ambient conditions. Proper design, maintenance, and operation of is critical to attaining acceptable performance from natural ventilation systems.

Issue #3 Building design, construction, and operation of energy-related features can affect public health and safety.

The above discussion addressing Issue #2 also applies to public health. Natural ventilation systems could have either a negative or positive impact on public health, and therefore care needs to be taken in their application. In addition, natural ventilation could have a negative impact on the moisture load in non-residential buildings in humid climates. Since most of the moisture load for many non-residential buildings is brought into a building through ventilation, increasing ventilation and eliminating or reducing air-conditioning can increase this moisture load.

Issue #4 Investments in energy efficiency can affect building and housing affordability and value, and the state's economy.

As discussed in response to Issue #1, natural ventilation systems can reduce building cooling and fan energy use and, therefore, reduce operating costs to improve building affordability and value. However, these potential savings will vary widely depending on building type, climate and other factors. No significant impacts are expected on the energy-related costs of construction.