VENTILATION SYSTEMS

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Summary

Heating, Ventilating and Air-Conditioning (HVAC) has attained a major industry status and is continuously growing despite the serious challenges being faced. The role of HVAC systems has grown from temperature and humidity control and the supply of outdoor air, to more elaborate control of outdoor and indoor contaminants and odors, providing proper indoor environmental quality (thermal and acoustical comfort and air quality) at the lowest possible energy cost.

Along these lines, the evolution of ventilation systems has also been dramatic during the twentieth century. Natural ventilation was surpassed by mechanical ventilation combined with comfort air conditioning in order to resolve practical problems for the year-round control of the indoor environmental conditions.

The possibilities of HVAC buildings seemed to be trouble-free, until concerns arose about indoor air quality associated with sick building syndrome and the energy crisis with subsequent continuous concerns for energy conservation. These problems have generated the need to pay a lot more attention to design options and equipment...
maintenance, the development of strict standards, and design guidelines that take into consideration all aspects of indoor environmental quality and energy efficiency. This section presents some fundamental information on ventilation and related parameters that can affect its performance related to indoor environmental quality (IEQ) which involves thermal comfort, acoustical comfort, and indoor air quality (IAQ).

An outline of energy conservation measures appropriate for ventilation systems are included at the end.

1. Introduction

Control of the indoor environment has developed over the centuries from simply providing heating for living and working spaces to the use of mechanical cooling systems for more comfortable year round indoor environments by the mid-nineteenth century. However, growing concern about the quality of indoor air and the development of more elaborate central air conditioning systems have given more emphasis to ventilation systems and the control of indoor air quality in relation to airborne contaminants, odors, and irritants. Heating, Ventilating and Air-Conditioning (HVAC) has attained a major industry status and is continuously growing despite the serious challenges being faced.

The energy crisis in the mid-1970s shifted concern to increased equipment efficiency and to improved standards of insulation for the control of heat losses and gains. However, efforts for reducing heating and cooling costs resulted in reduced air infiltration into buildings and reduced use of outdoor fresh air, and gave rise to various indoor air quality problems. At the same time, poor outdoor air quality in urban environments and an increase of indoor contaminant sources have justifiably increased the importance of ventilation systems. The role of HVAC systems has grown from temperature and humidity control and the supply of outdoor air, to more elaborate control of outdoor and indoor contaminants and odors, providing proper indoor environmental quality (thermal and acoustical comfort and air quality) at the lowest possible energy cost. To reach this goal engineers, architects, contractors, technicians, and occupants have developed elaborate ties to maintain the delicate balance and quality of building and indoor environments.

Figure 1. One of the first historic naturally ventilated buildings in Palermo, Italy. Main building facade (left) and the building’s model (right).
The evolution of ventilation systems has been dramatic during the twentieth century. The concern with supplying fresh (outdoor) air to indoor environments became more elaborate as buildings grew in size and as occupants became more demanding for indoor thermal comfort conditions.

The use of outdoor air for natural ventilation, combined with natural cooling techniques and the use of daylight, have been essential elements of architecture since ancient times. Classical architecture with H, L, T or U-shaped floor plans, the use of open courts and limited space depth, and maximized windows to facilitate the interaction of the indoor environment with the outdoors for daylight and natural ventilation.

This was common practice even for large commercial buildings up until the end of the nineteenth century.

Naturally ventilated buildings have been common in several parts of the world from the ancient Hellenic architecture to the Arabian wind towers. A prime example of a naturally ventilated building is the Arabian palace in Palermo, Italy (Figure 1).

Comfort air conditioning with the advancement of mechanical cooling gave rise to new attitudes to luxury with better control of indoor environments despite the outdoor weather conditions. HVAC systems were promoted for providing exceptional indoor comfort conditions and healthier air quality.

Technology advancements led to market growth and cost decreases, to the point that HVAC has become common practice. Building architecture broke loose from its dependence on the outdoor environment, since HVAC could practically provide any kind of indoor conditions despite the outdoor weather.

However, since other critical parameters like energy conservation and sick building syndrome have also come into play, the use of HVAC systems and the function of the building envelope has somewhat followed a circular motion.

The first attempts to use HVAC systems and all-air ventilation systems in large commercial buildings in the United States recognized the potential of exploiting the combined effects of natural ventilation with mechanical systems in order to resolve practical problems and limitations.

Since lower floors suffer from noise and odors coming from the street level, natural ventilation can be problematic. Accordingly, for one of the first applications in a 21-storey office building in New York City the mechanical warm air supply and extract ventilation system only served the lower seven floors. Similar practices continued into the late 1930s.

Even from the beginning of the twentieth century, sealed buildings with mechanical ventilation made their appearance. However, HVAC systems were first installed in movie theaters, followed by other recreational environments, auditoriums, hotels, and then residences around the mid-twentieth century, predominantly in the United States. One of the first fully air-conditioned applications was the New York Stock Exchange.
(the cooling and ventilation system, designed by Alfred Wolff and installed in 1904, used ammonia absorption machines to control indoor temperature and humidity and to distribute clean, conditioned air to the trading room). The first skyscrapers and the great majority of large office buildings still relied on natural ventilation.

Technology continued to advance and the terms “air conditioning” and “mechanical ventilation” started coming into common use. Understandably, modern large commercial buildings had to follow the general trend and become fully equipped with HVAC systems for year-round comfort, with the additional prospects of increased property value.

Building architecture could finally break away from the need to have specific building forms and interior space layout to allow for natural ventilation and daylight, since HVAC and electric lighting could allow deep-plan buildings, even to an extreme of not having windows. Interior space layout and exterior building appearance changed dramatically. All-glazed sealed buildings became very popular, especially for large commercial buildings.

However, modern architecture became fully dependent on HVAC systems in order to operate. The possibilities of HVAC buildings seemed to be trouble-free until concerns arose about indoor air quality associated with sick building syndrome and the energy crisis with subsequent continuous concerns for energy conservation.

These problems have generated a need to pay a lot more attention to design options and equipment maintenance, the development of strict standards, and design guidelines that take into consideration all aspects of indoor environmental quality.

A re-evaluation of previously common practices have returned back to mixed modes of HVAC systems and naturally ventilated buildings, combined with new technology features of controls and automation that enhance the positive and minimize the negative aspects, to the benefit of occupants’ comfort and optimum energy use.

Certain practices rediscovered the positive features that promoted good indoor environmental conditions in the past, but were unfortunately “forgotten” when HVAC systems became popular. Now, these practices try to combine the “old know-how” with the conventional HVAC systems, in an effort to get them working together.

For example, natural cross ventilation and the use of wind towers (Figure 2) to enhance system effectiveness, coupled with a building automation system to operate windows and the HVAC system, are a few examples of how traditional systems can be combined in a modern office building design.
The Commerzbank office building (Frankfurt, Germany), the tallest building in Europe (63 floors with a height of 259 m) constructed in 1997 (Figure 3), is another prime example of how HVAC systems can be put to work together with natural ventilation, even in modern high-rise office buildings.

The building utilizes natural ventilation of office spaces through openable windows up to the 50th floor, interior courtyards with naturally ventilated gardens by openable window sections that minimize overheating, and building management systems for optimum control of indoor conditions and operation of the various systems.

The goal is to design, build, and operate healthier buildings that satisfy environmental and energy concerns. These can be achieved by using new technologies like efficient air filtration, floor-level and other improved air distribution techniques, off-peak energy storage, improved efficiency equipment supported by new control and management systems, and proper maintenance, along with traditional methods like natural ventilation, effective external and internal load reduction.

This introductory section presents some fundamental information on ventilation and related parameters that can affect its performance related to indoor environmental quality (IEQ) which involves thermal comfort, acoustical comfort, and indoor air quality (IAQ). The underlying operation of ventilation systems for IAQ includes filtration, humidity control, and contaminant control for both outdoor and indoor sources, at appropriate ventilation rates. An outline of energy conservation measures...
appropriate for ventilation systems are included at the end. Following sections provide greater detail, technical data, and other relevant information on calculations, experimental work, and standardization in the areas of IAQ, natural ventilation, mechanical ventilation, filtration, and energy conservation.

Figure 3. The tallest building in Europe using natural ventilation. General view of the building (left), building cross section and outline of natural ventilation and stack effects (center), detail of the court yards viewed from inside (top right picture), and cross section and outline of natural ventilation (bottom right picture) [Source: Commerzbank, 2000.]

2. Ventilation Systems

The indoor environment quality has a direct impact on the well-being and health of building occupants. This comes as a direct result of the fact that:

- “Most people spend 60–90% of their time indoors” (American Lung Association);
- “50% of ALL illness is either caused or aggravated by polluted indoor air” (American College of Allergists);
- “Indoor air is found to be up to 70 times more polluted than outdoor air” (Environmental Protection Agency).

Air ventilation plays a dominant role in achieving and maintaining comfort conditions and acceptable indoor environmental quality in any environment. Ventilation supplies the necessary amounts of fresh air, either by:
- Natural ventilation: the outdoor air enters into the space and the indoor air exits from the space as a result of physical processes (wind and temperature differences). The ventilation rates depend on the prevailing outdoor (e.g. variability of wind velocity and direction) and indoor conditions, and thus there is limited control. However, when it is properly designed it can improve indoor thermal comfort conditions and air quality at no energy cost. Natural ventilation is effective in terms of its positive impact for improving the indoor thermal comfort conditions in summer and for the control of indoor air quality when it occurs through large openings (i.e. windows or doors). The size, space, and opening geometry, play a determinant role on the resulting air flow rates. Infiltration, that is air coming through very small openings (cracks) is another way that outdoor air can enter into a space. However, this air flow is associated with heat losses during winter (cold outdoor air coming into the space) and heat gains during summer (warm outdoor air coming into the space), thus increasing the heating and cooling loads. Infiltration has a small contribution in the fresh air supply of a space but it does not play a role in terms of improving the indoor thermal comfort conditions. The air flow is too low to have any meaningful impact on summer thermal comfort, while in winter infiltration can result in disturbing cold drafts.

- Mechanical ventilation: the outdoor air is supplied and the indoor air is exhausted by mechanical means using fans and ductwork. The air flow can be controlled in terms of quantity, velocity, quality, and thermal conditions, at the expense of higher energy consumption. Several systems and techniques are available for the proper handling of indoor air quality problems (using various types of filters) and for energy conservation.

- Hybrid ventilation: the outdoor air supply is primarily based on natural ventilation assisted with simple fans to enhance the effectiveness and control the air flow rates, at a minimal energy cost.

The quantity of outdoor air that needs to be brought into the space is determined by national standards, depending on the function of the space. The air movement into the space must be handled with care, since there is a direct influence of air velocity on occupant comfort.

Outdoor air quality will influence indoor conditions, thus one needs to exercise caution when using untreated outdoor air. This is of great importance especially in large metropolitan cities, where outdoor air may be heavily polluted with particulate and gaseous contaminants. Health standards may impose limits on the use of untreated outdoor air, which as a result, limits the effectiveness of natural ventilation techniques and influence comfort conditions in naturally ventilated buildings. Ventilating a space with polluted outdoor air can heavily impose on indoor air quality, which may result in occupant health problems. Alternatively, the use of mechanical ventilation and air conditioning systems can be used to clean the outdoor air from atmospheric dust. However, it is not possible to treat outdoor air for gaseous contaminants. In any event, the use of mechanical ventilation and air conditioning will increase the energy consumption and operational cost of the building. It is also essential that the filtering system is well maintained, to prohibit the growth of microorganisms which can even be fatal.
Increasing the ventilated air to maintain acceptable indoor air quality means that more outdoor air has to be heated during winter and cooled during summer, thus increasing the energy cost. The importance of ventilation, both as an indoor environmental quality issue and as the single largest heat loss/gain component, makes ventilation the most important design challenge for HVAC systems.

Bibliography


Arnold D. (1999). The evolution of modern office buildings and air conditioning, *ASHRAE Journal* 41(6), 40–54, June. [This paper is part of a series of articles commemorating a century of innovation in the HVACR arts and sciences. Traces the growth of the office building, their need for environmental control, and the introduction of mechanical ventilation. Identifies the first buildings designed to accommodate equipment for modern air conditioning, naturally ventilated skyscrapers and the advent of the fully air conditioned office building.]

ASHRAE (1997). *Fundamentals Handbook*, Thermal Comfort—Ch. 8, and Indoor Environmental Health—Ch. 9, Atlanta: American Society of Heating Refrigerating and Air Conditioning Engineers. [This is part of a four Handbook series published by ASHRAE. The Handbooks are revised every four years. The two chapters review the principles and provide general information, with references to other related chapters and ASHRAE Standards for more details.]

ASHRAE Standard 55 (1992). *Thermal Environmental Conditions for Human Occupancy*, 17 pp. Atlanta: American Society of Heating Refrigerating and Air Conditioning Engineers. [This standard specifies the combinations of indoor space environment and personal factors that will produce thermal comfort conditions acceptable to 80% or more of the occupants within a space. Addresses temperature, thermal radiation, humidity, and air speed. It is a prescriptive standard intended for occupants with primarily sedentary activity. There is currently a proposal for a revision to include an analytical method based on the PMV theory.]

ASHRAE-Standard 62 (1999). *Ventilation for Acceptable Air Quality*, 27 pp. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. [The purpose of this standard is to specify minimum ventilation rates and indoor air quality that will be acceptable to human occupants and are intended to minimize the potential for adverse health effects. The Standard is split into 62.1—Ventilation and Acceptable Indoor Air Quality in Commercial Buildings and 62.2—Ventilation and Acceptable Indoor Air Quality in Low Rise Residential Buildings. ANSI/ASHRAE Standard 62–1999 is under continuous maintenance. This process allows ASHRAE to update the standard on an ongoing basis through the addition of addenda that have completed ASHRAE's public review and consensus procedures.]

psychrometrics, comfort indices, predictive algorithms, research activities, and experimental data. Provides extensive bibliography."

Berglund L. G. (1998). Comfort and Humidity, *ASHRAE Journal* **40**, 35–41, August. [This paper discusses how humidity affects human perception of comfort. Examines humidity and comfort from the standpoints of thermal sensation, thermal balance, environmental acceptability, high and low humidity and perceived air quality. Concludes that humidity affects comfort both directly and indirectly. At a given temperature, decreased humidity results in occupants feeling cooler, drier, and more comfortable. For the sedentary person, a 30% change in relative humidity has the same effect on thermal balance and thermal sensation as 1 °C change in temperature.]

Bluyssen P., and Fanger, P. O. (1991). Addition of olfs from Different Pollution Sources Determined by a Trained Panel. *International Journal of Indoor Air Quality and Climate* **1**(4), 417–421. [This paper is based on the proposed off-decibel units to evaluate the amount of outdoor air required for “perceived” good air quality indoors and the approach to defining the units using a trained panel. The total contaminant load for the occupied space is determined by adding all contaminant sources from occupants, carpets, furnishings and the ventilation system.]


CIBSE (1999). *Guide A—Environmental Design*, 336 pp. London: Chartered Institution of Building Services Engineers. [This guide brings together the information required for the design of heating, ventilation and air conditioning systems. It covers topics on Environmental criteria for design, External design data, Thermal properties of building structures, Air infiltration and natural ventilation, Thermal response and plant sizing, Internal heat gains, Moisture transfer and condensation.]

CIBSE (2000). *Application Manual 13—Mixed Mode Ventilation*, 77 pp. London: Chartered Institution of Building Services Engineers. [This manual provides advice on the advantages and pitfalls of mixed mode ventilation that is combining natural ventilation with mechanical ventilation and/or cooling. Properly integrating these systems with passive building elements and finding the best methods of control results to improved energy efficiency.]

DIN 4109 (1989). *Sound Insulation in Buildings, Requirements and Testing*, 220 pp. Berlin: Germany Deutsches Institute fur Normung e.V. [This is a German standard on construction examples and calculation methods, sound insulation in buildings. It provides guidelines for planning and execution, proposals for increased sound insulation and recommendations for sound insulation in personal living and working areas.]


EN 1886 (1998). *Ventilation for buildings—Air handling units: Mechanical Performance*, 16 pp. Brussels: The European Committee for Standardization. [This European standard covers topics on mechanical ventilation and equipment, air-conditioning systems, air control devices, air filters, performance and strength of materials, mechanical and performance testing, leak tests, thermal testing, sound insulation, and testing procedures and equipment. It provides mathematical calculations.]

Etheridge D. and Sandberg M. (1996). Building Ventilation Theory and Measurement, 764 pp. Chichester: John Wiley and Sons Ltd. [This book includes fundamentals and theory and is therefore deeply mathematical. Topics cover mechanisms, flow through envelope openings, mathematical models, mass transport, mixing, momentum, buoyancy, air flow in rooms, flow through large openings, experimental techniques for evaluating flow characteristics, multi-zone representation of buildings, tracer gas methods for ventilation and age of air evaluation, scale models and computational fluid dynamics. It considers both natural and mechanical ventilation. It includes detailed bibliography.]


Humphreys M. A. (1976). Field Studies of Thermal Comfort Compared and Applied. Building Services Engineer 44, 5–27. [This paper presents several field surveys for thermal comfort conditions and comparisons against the predictions from the PMV theory. The survey data do not fully agree with the PMV predictions.]


Limb M. (1997). Ventilation and Acoustics in Buildings. An Annotated Bibliography, 48 pp. Coventry: AIVC. [This publication is aimed at researchers, designers, and engineers seeking an overview of current developments into acoustic control within buildings and their impact on current ventilation practices, the document analyses over fifty of the most important publications in the area. It includes design guidance, noise transmission throughout a building, buffer rooms and atria, HVAC system noise, acoustics and indoor air quality, acoustic measurement and calculation methods, novel uses for acoustics in buildings.]

Limb M. (1999). An Annotated Bibliography: Impact of Urban Air Pollution on the Indoor Environment, 34 pp. Coventry: AIVC. [This publication highlights recent literature that has focused on the impact of urban pollution on the indoor environment. The main areas include typical pollutants and sources, measurements in buildings, specific case studies, remedial measures.]


prENV 1752 (1999). Ventilation for Buildings, Design Criteria for the Indoor Environment, 76 pp. Brussels: The European Committee for Standardization. [This European prestandard covers topics on ventilation equipment, air-conditioning systems, thermal comfort, air quality, design, control equipment, design calculations, environmental parameters (temperature, humidity etc), air quality and pollution, acoustic measurement, with calculations and modeling, and acceptable levels.]

Simmonds P. (1993). Thermal Comfort and Optimal Energy Use, ASHRAE Transaction, 99, Part 1, Paper no CH–93–10–4, pp. 1037–1048. [This paper reviews the work of Fanger on the “thermal index” that could express a subject’s thermal sensation in a climate deviating from the optimum. This work shows the results obtained when replacing dry-bulb temperatures with a predicted mean vote (PMV) calculation. The fluctuations of the PMV are (within limits) acceptable to the occupants. Simulation techniques are used to determine building loads and control strategies. These control strategies are then optimized to minimize the operating cost while controlling the HVAC system to meet comfort criteria in the occupied zone.]

©Encyclopedia of Life Support Systems (EOLSS)
Stanke D. (1999). Ventilation through the years. *ASHRAE Journal* 41, 40–43, August. [This paper considers what ASHRAE recommends for ventilation rates and why, and how recommended airflow is determined for a space and for a mechanical ventilation system. Examines how the answers to these questions have evolved over the years in successive editions of ASHRAE Standard 62. Supplies a table summarising some of the key differences among the various versions of Standard 62.]

Zhivov A. M., McLaughlin J. K., and Priest J. B. (1994). International Differences in Indoor Environments Quality Standards and Guidelines. In E. L. Besch, ed. *Proceedings of Engineering Indoor Environments*, IAQ 94. St. Louis, MI., pp. 67–78. [This paper outlines differences and similarities that exist among air quality standards, thermal comfort standards, ventilation, standards, energy conservation standards and diagnostic protocols from The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE); the International Organization for Standardization (ISO); the Center for European Standardization (CEN); the Commission of European Communities (CEC); the Nordic Committee on Building Regulations (NKB); and Gasstroii (GOST/SNiP)].

**Biographical Sketch**

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