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MEASUREMENTS OF VENTILATION RATES AND VENTILATION EFFECTIVENESS

Andrew K. Persily
Mechanical Engineer
Richard A. Grot
Mechanical Engineer

Center for Building Technology
National Bureau of Standards
USA

ABSTRACT

The ventilation of office buildings has taken on increased importance due to concerns about energy conservation and indoor air quality. Tracer gas techniques have been developed to measure whole building ventilation rates. These measurements have revealed that in many buildings intentional ventilation is similar in magnitude to unintentional air leakage through the building envelope. In some buildings the net ventilation rates are lower than recommendations for minimum outside air intake levels based on ASHRAE Standard 62-1981. Also, due to variations in internal air distribution, specific areas within buildings are ventilated at lower rates than the whole building average. The concept of ventilation effectiveness or efficiency has been developed to quantify air distribution. Ventilation efficiency has been studied in laboratory facilities, but its measurement in actual office buildings requires special procedures.

1. INTRODUCTION

With increased concern about energy use in the space conditioning of buildings, various attempts are being made to improve energy efficiency through building design, construction and operation. One aspect of these energy conservation efforts is the reduction of ventilation and infiltration rates. At the same time, an increasing awareness of indoor air quality has led to concerns about providing sufficient ventilation in buildings. In order to resolve the potential conflict between energy conservation and indoor air quality, research is being conducted to investigate building ventilation, air distribution, interior contaminant levels and pollution control strategies. Tracer gas techniques exist for the measurement of building ventilation rates, and facilitate the study of how these rates vary with weather and time and the comparison of these measured ventilation rates with minimum outside air intake recommendations. Even if whole building ventilation levels are adequate, nonuniform air distribution may lead to certain areas within the building being inadequately ventilated and having potential indoor air quality problems. The concept of ventilation effectiveness or efficiency has been developed to characterize internal air distribution. This paper discusses the measurement of whole building ventilation rates and ventilation effectiveness in mechanically ventilated office buildings.

2. WHOLE-BUILDING VENTILATION MEASUREMENTS

Various tracer gas measurement techniques have been used for many years to study air infiltration and ventilation, primarily in residential buildings, and more recently in large, mechanically ventilated office buildings [1-3]. In this paper, air infiltration refers to uncontrolled air leakage through the building envelope as opposed to air exchange associated with mechanical ventilation and intentional openings, such as windows and vents. Ventilation refers to the net air exchange rate including mechanical ventilation and air infiltration.

2.1 Measurement Techniques

While there are several different tracer gas measurement techniques, the following discussion concerns the tracer gas decay method used by the U.S. National Bureau of Standards. This technique uses sulfur hexafluoride (SF_6) as the tracer and measures the concentration with an electron capture detector gas chromatograph. In this procedure, a small quantity of SF_6 is released into the building and allowed to mix until the concentration is uniform throughout the building. The decay in tracer gas concentration is then monitored, and related to the net ventilation rate according to

$$C = C_o \, e^{-It}, \qquad (1)$$

C is the tracer gas concentration at time t, C_o is the concentration at t = 0, and I is the air exchange rate in units of building volumes or exchanges per unit time. To distribute the tracer gas throughout the building, SF_6 is injected into the supply ducts of the building's air handlers. After a mixing period, the SF_6 concentration is measured at regular time intervals at several sampling locations in the building. The uniformity of the tracer gas concentration throughout the building is verified by measuring the concentration at many locations. The specific sampling locations depend on building design but generally include main return ducts and locations on several different floors. The NBS measurements employ an automated system with a microcomputer controlling tracer injection, air sampling and concentration measurement, monitoring indoor and outdoor conditions and recording the data. The system is typically installed in a building for several weeks during each season of the year to obtain ventilation measurements under a wide range of outside weather conditions.

2.2 Results

NBS has measured ventilation rates in ten recently constructed U.S. office buildings [1-3]. Figure 1 shows a plot of daily average ventilation rates versus inside-outside temperature difference for a twenty-six story office building in Newark, New Jersey. During warm weather, temperature differences less than or equal to about 0 K, the whole building ventilation rate is about 0.6 exchanges per hour. Under heating conditions, temperature differences greater than or equal to about 20 K, the ventilation rate is roughly 0.8 exchanges per hour. During mild weather, outside air is sometimes used to cool the building and ventilation rates are as high as 1.5 exchanges per hour. There are also some low ventilation rates in the mild temperature range because the ventilation rates induced by the enthalpy controller depend on humidity in addition to temperature.

Figure 2 is a similar plot of hourly average ventilation rates versus temperature difference for a five-story building in Huron, South Dakota. This building also has low ventilation rates under cooling and heating conditions, with some higher rates during mild weather. The minimum ventilation rates are on the order of 0.2 exchanges per hour. The data under winter conditions, i.e. temperature differences greater than 10 K, reveal the importance of uncontrolled air leakage through the building envelope. For temperature differences above 25 K, the measured ventilation rate increases slightly with temperature difference. This is because temperature dependent infiltration is increasing and becoming comparable in magnitude to the intentional ventilation. Also, the high ventilation rates between 20 and 30 K are due to wind induced infiltration which becomes a significant portion of the net ventilation rate. Other buildings also exhibit this property, i.e. weather induced infiltration being a significant, or even predominant, portion of the net ventilation rate. Thus, modern building envelopes are not necessarily airtight, and under extreme weather conditions there is little control of the net ventilation rate. Such uncontrolled leakage occurs continuously and can account for a significant waste of energy.

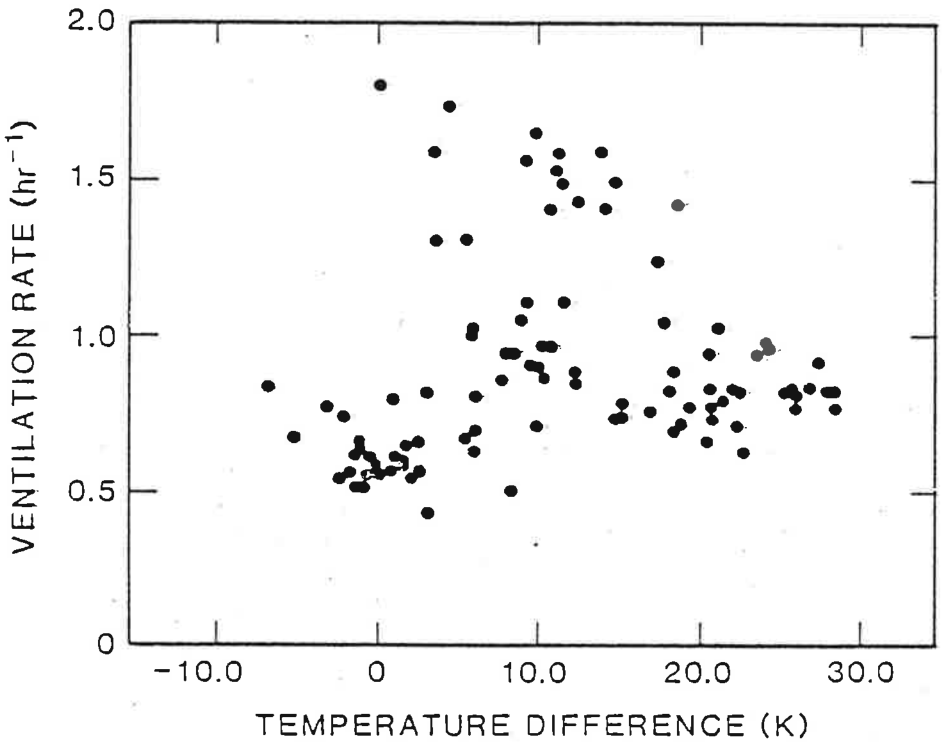

Figure 1 Daily Average Ventilation Rates for the Newark Building

It is interesting to compare measured ventilation rates to standards for minimum outside air requirements. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) has established minimum recommended building ventilation rates [4]. Table 1 lists minimum ventilation rates, in units of exchanges per hour, based on this standard and from the measured data for nine office buildings located throughout the U.S.[3] The ventilation rates are based on the standard's recommendation for outside air intake per person in L/s, the number of occupants per 100 m^2 of floor area, the building floor area and the building volume. The ASHRAE standard makes different recommendations depending on whether or not smokers are present in the building, and both ventilation rates are shown. When smoking is permitted, ASHRAE recommends using the ventilation rates for smoking conditions. The measured rates are averages over many measurements under conditions of minimum outside air intake, excluding measurements during severe weather when infiltration may dominate.

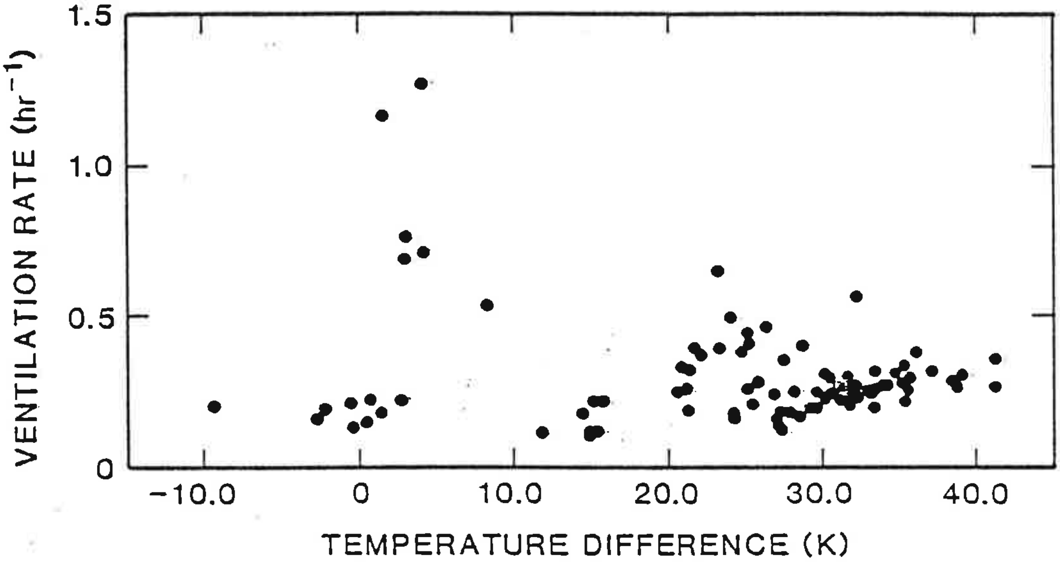

Figure 2 Hourly Average Ventilation Rates for the Huron Building

Table 1 Minimum Ventilation Rates in Nine Office Buildings

Building Location	ASHRAE 62-1981 Smoking	ASHRAE 62-1981 Non-Smoking	Measured
Anchorage	0.67	0.17	0.26
Ann Arbor	0.38	0.09	0.47
Columbia	0.41	0.10	0.62
Fayetteville	0.41	0.10	0.32
Huron	0.49	0.12	0.13
Newark	0.63	0.16	0.55
Norfolk	0.69	0.17	0.62
Pittsfield	0.42	0.10	0.38
Springfield	0.46	0.12	0.55

Table 1 reveals that three buildings, Ann Arbor, Columbia and Springfield, are ventilated above the smoking standard. In Ann Arbor and Springfield, this is primarily due to large amounts of uncontrolled infiltration. The buildings in Newark, Norfolk and Pittsfield are ventilated at levels close to the smoking standard, while the last three, Anchorage, Fayetteville and Huron, are ventilated below the recommended smoking level. In fact, Anchorage and Huron are close to the non-smoking recommendations. Thus, some modern office buildings are being ventilated at lower levels than may be advisable according to the ASHRAE standard. In other cases, extremely leaky building envelopes lead to large, uncontrollable ventilation rates with a significant energy penalty.

2.3 Local Variations in Ventilation

In the above ventilation measurements, there are many examples of nonuniform air distribution within the buildings. A dramatic example in the Newark building has been described previously [1]. In this building the SF_6 concentration was sampled on several individual floors of the building, and the results were quite similar on all of the floors except for two. On these two floors the initial SF_6 concentration was significantly less than in the rest of the building, as was the SF_6 decay rate. This indicates that the supply air rate for these floors was less than for the rest of the building, and therefore these floors had lower ventilation rates. Other examples of such large scale variations in ventilation have been observed, and similar problems may also exist within individual rooms. When specific areas suffer from poor air distribution, they may have indoor air quality problems even if the whole building or room is adequately ventilated. The quantification of air distribution uniformity involves the concepts of ventilation effectiveness or efficiency.

3. QUANTIFYING AIR DISTRIBUTION

The concept of ventilation efficiency has been developed to quantify the air distribution within a ventilated space. Several definitions and associated measurement procedures exist and experimental studies have been performed [5-9]. Most of the experimental work has been done in controlled laboratory test facilities. In this section ventilation efficiency is discussed, along with the measurement of ventilation efficiency in mechanically ventilated office buildings.

3.1 Definitions of Ventilation Efficiency

There are several different definitions of ventilation efficiency. One group of ventilation efficiency definitions, referred to here as "concentration efficiencies," are based on relations between pollutant or tracer gas concentrations in the supply air, the exhaust air and at locations in the ventilated space. Many concentration efficiency approaches employ a two-zone model of office ventilation in which the space is divided horizontally into two distinct zones, which are assumed to be perfectly mixed. The lower zone is referred to as the occupied zone. One definition of ventilation efficiency based on steady-state pollutant concentrations is referred to as the relative ventilation efficiency ε_j by Sandberg [5], and is denoted by ε_{II} by others [6,7]. This quantity is defined by

$$\varepsilon_j = (C_e - C_s) / (C_j - C_s). \tag{2}$$

C_e is the steady-state concentration in the exhaust air, C_s the concentration in the supply air and C_j the concentration in the occupied space. In general this ventilation efficiency is used to describe situations in which the pollutant is generated at a constant rate within the occupied space. When the space is perfectly mixed, $C_e = C_j$ and $\varepsilon_j = 1$. If a significant portion of the supply air "short-circuits" the occupied zone, i.e. flows directly into the exhaust vent without mixing in the room, then ε_j is less than one, a generally undesirable situation. Such short-circuiting has been suggested as a potential problem in U.S. office buildings where both the supply and exhaust vents are located in the ceiling. If the supply and exhaust vents are far apart, e.g. one at floor level and the other at ceiling height on the other side of the room, and the mixing is not perfect, then one has an approximation of piston flow and the ventilation efficiency is greater than one. This is generally a favorable situation. There are also transient ventilation efficiencies based on decay rates of pollutant or tracer gas concentrations [5-7,9]. Ventilation efficiencies based on distributions of the residence times of the supply air or internally generated pollutants have also been defined [8].

There has been a significant number of ventilation efficiency measurements in laboratory test facilities [5-9]. These test rooms have controllable intake and exhaust opening positions, supply air temperatures, ventilation rates and internal thermal loads. In these experiments, ventilation efficiencies have been measured as a function of opening position and type, air flow rate, thermal load and temperature difference between the supply and room air. While these experiments have been extremely valuable, the test conditions are generally quite different from those encountered in real buildings. In real offices, air also enters and leaves from locations other than the supply and exhaust vents. There are leaky windows, doors to other offices and additional openings in the boundary of the space. Under these conditions the supply and exhaust concentrations are no longer well characterized. The extent to which the other air flows affect ventilation efficiency is not clear, nor are there ventilation efficiency definitions appropriate to these conditions.

3.2 <u>Ventilation Efficiency Measurements in Office Buildings</u>

As mentioned above, the complexities of actual office buildings make it difficult to apply existing definitions of ventilation efficiency. Figure 3 is a schematic of a ventilated office space with the supply and exhaust vents located in the office ceiling. Zones 1 and 2 comprise a two-zone model of an office with zone 1 being the occupied portion. A lack of mixing between zones 1 and 2 corresponds to the problem of short-circuiting described earlier. Zone 3 is the rest of the building, zone 0 is the outside and Q_{ij} is the flow from zone i to zone j. While a two-zone office model subject only to ventilation system air flows, as in the experimental test rooms, can be described by four air flows, the three zone system in figure 3 is characterized by twelve air flows. The two-zone situation can be completely characterized with measurement techniques using only a single tracer gas, but the realistic situation shown in figure 3 can not be described in such a simple manner. The single tracer ventilation efficiencies can be measured in real offices, but the results do not adequately describe the office ventilation. Whole building measurements of ventilation efficiency can also be made with a single tracer gas, but again the existence of air flows through the building envelope complicates the situation. Thus, single tracer gas techniques may give only an indication of the ventilation efficiency in an office building, but they do not provide a complete description of the ventilation.

In order to completely characterize ventilation effectiveness in office buildings one needs to employ multi-zone analysis techniques. Multi-zone air flow analysis has been described previously and involves the use of several tracer gases to determine all the flow rates of interest [10-12]. In one particular approach, a different tracer is injected at constant and known rates into each of the three zones in figure 3. Once equilibrium is established, one measures the concentration of each tracer gas in each zone. By performing a mass balance of the tracer gases and air flows, one can solve for the twelve flow rates in figure 3. These flow rates are not associated with existing definitions of ventilation efficiency, but they completely characterize the ventilation of the office being tested.

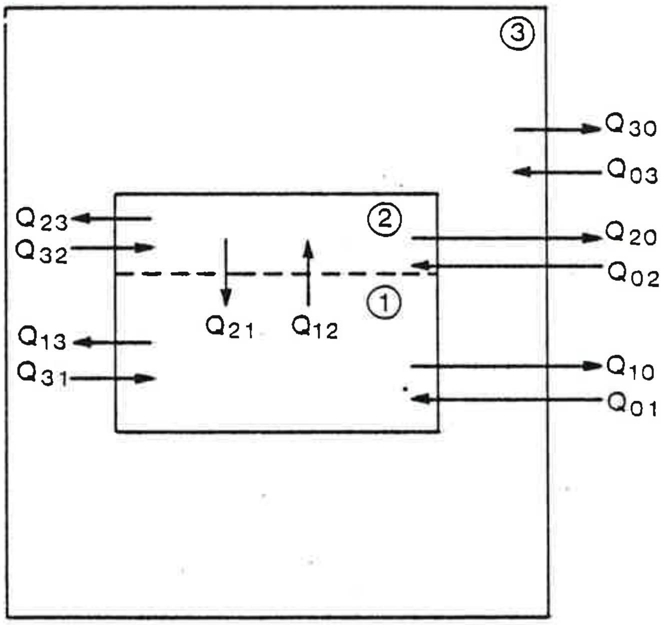

Figure 3 Schematic of a Three-Zone Model of Office Ventilation

4. SUMMARY

Concerns about energy use and indoor air quality have led to increased attention to office building ventilation. Tracer gas measurements of whole building ventilation rates have revealed that uncontrolled air leakage through the building envelope is often comparable in magnitude to the intentional ventilation. In addition, some buildings are being ventilated at lower rates than recommended in ASHRAE Standard 62-1981. Variations in the uniformity of internal air distribution may lead to local air quality problems, whether or not the entire building is ventilated at an adequate rate. Various definitions of ventilation efficiency have been developed to quantify air distribution and much valuable research is being done in experimental test facilities. The situation in actual office buildings, however, is much more complicated than in the test rooms and the existing definitions of ventilation efficiency are not adequate to characterize the ventilation effectiveness. Multi-zone tracer gas analysis techniques provide a complete description of office ventilation.

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