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Optimal application of ASHRAE Standard 62.1 for spaces of high transient occupancy
美國冷熱空調工程協會第 62.1 規格在高流動率空間通風的最佳套用

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Abstract

ASHRAE Standard 62.1 is a short and often misinterpreted document outlining ventilation requirements for acceptable indoor air quality. The purpose of ASHRAE Standard 62.1 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. Ventilation code enforcement has been difficult because it is often misunderstood by the code enforcement agency in the local jurisdiction. Present motivation to follow the standard has been driven mostly by liability and risk management concerns. The desire of most design professionals is to meet the minimum obligation of required standards rather than the actual performance of ventilation. This paper addresses two aspects that affect ventilation, imperfect mixing and transient occupancy. Imperfect mixing (or stratification) is the short-circuiting of supplied outdoor air from the diffuser to the exhaust, hence low ventilation effectiveness. When carbon-dioxide (CO2) concentration level is used as an indicator of air quality, transient occupancy makes indoor CO2 concentrations unsteady and difficult to control.

Key Words: ASHRAE Standard 62.1, mixing effectiveness, stratification, ventilation effectiveness

摘要

美國冷熱空調工程協會第 62.1 規格是一個即短又經常被誤解的文件，此文件綱要點在於可接受室內空氣品質所需之基本通風量。美國冷熱空調工程協會第 62.1 規格的目的是去具體指定樓者對於可接受之室內空氣品質所需的最

低通風量，以及減少嚴重身體健康傷害的可能性。因為通風規格經常被當地執法官員誤解，實施通風規格法令一向是艱難的。目前遵守通風法規的推動力大致上是去防止被追訴法律責任以及防止經營冒險擔憂。大部分直接工程設計者想要的只是達成符合最低通風量之要求，而不是為了實際通風成效。本文聲明兩點影響通風因素，分別為非完美空氣混合與流動樓者因素。非完美空氣混合（或成層）是供應的室外空氣從擴散器道排氣口的短路。當二氧化氮濃度被視為空氣品質的顯示者，樓者流動會對室內二氧化氮濃度造成不穩定以及難以控制。

關鍵詞：美國冷熱空調工程協會第 62.1 規格、混合效應、成層、通風效應

1. INTRODUCTION

ASHRAE Standard 62 defines the minimum requirements for mechanical and/or natural ventilation systems intended to provide acceptable indoor air quality in buildings. Since its inception in 1973, the Standard has continuously revised and republished in 1981, 1989, 1999, and 2001 [1]. The standard number was revised from 62 to 62.1 and 62.2 to allow for separation of commercial buildings and low-rise residential buildings [2]. Continuous revision and republication of Standard 62.1 has taken place in 2007, 2010, and 2013 [3]. This paper examines the application of ventilation effectiveness on ASHRAE Standard 62.1 in the event of imperfect mixing in breathing zones of food and beverage service operations.

There are two alternative procedures for obtaining acceptable indoor air quality: (1) the Ventilation Rate Procedure and (2) Indoor Air Quality Procedure. The Ventilation Rate Procedure prescribes a minimum required amount of outdoor air per occupant density of the zone and area-related determinants, as shown in Eq. (1).

$$\dot{V}_{OA-bz} = \dot{V}_{OA-p} \cdot P_z + \dot{V}_{OA-a} \cdot A_z \tag{1}$$

where

$\dot{V}_{OA-bz}$ = breathing zone outdoor airflow rate,

$\dot{V}_{OA-p}$ = outdoor airflow rate required per person as determined by the Standard 62.1,

P_z = zone population (i.e. the number of people in the ventilation zone during typical usage),

$\dot{V}_{OA-a}$ = outdoor airflow rate required per unit area as determined by the Standard 62.1,

A_z = zone floor area (i.e. the net occupied floor area of the ventilation zone).

There are two problems associated with the Ventilation Rate Procedure. One, the occupancy level is never steady and the transient nature of building occupancy makes outdoor air ventilation to be either over-ventilated or under-ventilated. Two, the assumption of outdoor air ventilation is that the introduced outdoor air is perfectly mixed with zone air, which is never realistic. To compensate the first problem, ASHRAE Standard 62.1 provides the Indoor Air Quality Procedure which does not set outdoor air ventilation rates but employs both qualitative and subjective air quality evaluation. An empirical method of evaluating indoor air quality is based on the assumption that occupant generated carbon dioxide (CO_2) can be used as a suitable surrogate measure of indoor air quality. Acceptable indoor air quality is achieved if the CO_2 concentration level is maintained under a maximum set-point. A popular method of applying the Indoor Air Quality Procedure is the CO_2-based demand-controlled ventilation (DCV) to meet ASHRAE Standards [4–8]. Even with the Ventilation Rate Procedure, imperfect mixing of introduced outdoor air and zone air is not solved by the demand-controlled ventilation. Thus, consideration of ventilation effectiveness should be applied in spaces of transient occupancy.

2. LITERATURE REVIEW

Tracer gas techniques have a long history of use in determining airflows and ventilations in buildings since 1950 [9–14]. Bohac et al. [15] used CO_2 tracer gas measurements of ventilation rates in bars and restaurants to find 75% of the sampled were under-ventilated with outside air while 80% of the same venues had acceptable ventilation rates based on the actual occupancies. Similar results were found in three Target stores (Florida, Maryland, and Minnesota) that suggest acceptable indoor air quality is attainable with ventilation rates significantly less than what Standard 62.1 Ventilation Rate Procedure mandates [16]. CO_2-based demand-controlled ventilation (DCV) has been a popular method of reducing outside air ventilation when occupant number is low [12,17,18]. The drawback of this control strategy is that it assumes perfect mixing in the zone.

Higher ventilation effectiveness may be achieved in breathing zones with under-ventilation of outside air. Displacement ventilation can provide better thermal comfort and indoor air quality with enhanced ventilation effectiveness [19,20]. Displacement ventilation or stratified ventilation is perfectly suited in spaces of food and beverage services where majority of heat is generated by occupants and equipment rather than heat transfer through room envelopes. With interior heat emission, Xu et al. [21] found the higher heat generation with lower supply air temperature, the stronger of the temperature stratification and the lower contaminant concentration in the breathing zone. Stratified ventilation is preferable for large-space buildings where energy consumption is proportional to the zone height but noise level increases with lowered zone height [22–24].

Studies found breathing zone air quality to be better than the average air quality in a zone with displacement ventilation [25,26]. Although displacement ventilation is known to work well for cooling conditions, the measured contaminant removal effectiveness is better than that predicted for heating conditions [27]. Air distribution performances of various ceiling- and wall-mounted diffusers have been studied [28,29]. Occupants were very satisfied with displacement ventilation when low velocity sidewall diffusers were used [30]. Locations of the supply and return on ventilation effect, as well as personalized ventilation have also been studied [31]. Personalized ventilation has often been studied through computational fluid dynamics (CFD) in airflow analysis of microenvironment [32,33], as opposed to measurements [34]. Measurement studies of microenvironment airflow have extended to kitchen and refrigerated facilities [35,36].

3. VENTILATION EFFECTIVENESS

Both the Ventilation Rate Procedure and the Indoor Air Quality Procedure assume perfect mixing in the air distribution system and building zones. The air distribution system starts from the air-handling-unit (AHU) where unconditioned fresh outdoor air intake is mixed with a fraction of the conditioned returned air in the mixing plenum. Then, the mixed air goes through filters and coils for conditioning before being distributed to ductworks and building zones. However, air mixing is never perfect. Mainkar et al. [37] performed measurements over a range of mixing design configurations. In building zones, air diffusion systems are designed to assure relatively uniform temperature profiles in the occupied region of the space while minimizing drafts. One of the most common design methods is based on the air diffusion performance index (ADPI), which is defined as the percentage of locations within the occupied zone that satisfy minimum requirements for uniform temperature and air velocity [38–40]. A good design produces ADPI of about 80%.

While ADPI is a measure of thermal comfort parameter, issues of mixing also arise with air quality in building zones. For both uniformly generated pollutants within a zone and point pollutant sources, the degree of mixing in the room determines the pollutant removal rate and the degree of contamination within the zone. Due to the location of an air diffuser, a primary mixing region and a secondary mixing region would exist in a room. Previously, the terms “ceiling zone” and “occupied zone” were used. Sandberg [41] first introduced the “two-box” models (the primary and secondary mixing regions) of equal volume to evaluate the ventilation effectiveness, rather than ADPI measurements. Sandberg’s two-box models are called the “displacement system” and “short-circuiting system” as shown in Fig. 1. Later researchers have used Laplace transform techniques to model the ventilation system performance of the two mixing regions [42,43].

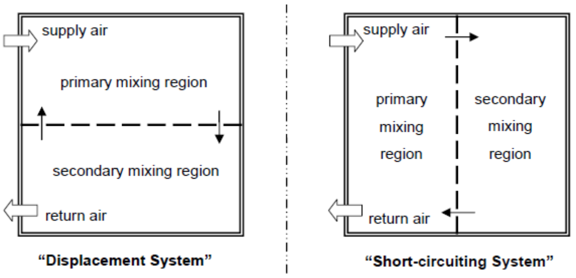

Figure 1 Sandberg’s two-box models

Janssen [44] derived a stratification model for ventilation effectiveness in a typical ventilation system. When a fraction of the supply air that stratifies and bypasses directly to the return air outlet, the amount of outdoor air supplied to the space is:

$$V_S = V_{OA} + R \cdot S \cdot V_S \qquad (2)$$

where

V_{OA} = the amount of outdoor air,

R = the amount of re-circulated factor,

S = the stratification factor (or mixing factor).

The amount of unused outdoor air (short-circuited air) that is exhausted is:

$$V_E = (1-R)\cdot S\cdot V_S \tag{3}$$

The ventilation efficiency (effectiveness) can be defined as:

$$E_v = \frac{(V_{OA}-V_E)}{V_{OA}} \tag{4}$$

Substituting Eq. (2) and Eq. (3) into Eq. (4):

$$E_v = \frac{[(1-R\cdot S)\cdot V_S]-[(1-R)\cdot S\cdot V_S]}{[(1-R\cdot S)\cdot V_S]}$$

$$E_v = \frac{(1-R\cdot S)-(S-R\cdot S)}{(1-R\cdot S)}$$

Then, the ventilation effectiveness of a zone is defined as:

$$E_v = \frac{(1-S)}{(1-R\cdot S)} \tag{5}$$

Eq. (5) defines the effectiveness with which the outdoor air is circulated to the occupied space in terms of the stratification factor (S) and the re-circulation factor (R). When both stratified airflow and re-circulation (i.e. $R \neq 1$) occur, outdoor air can pass through the system without ever being used to dilute contaminants at the occupied level. The ventilation effectiveness varies with the specific location of the zone, the percentage of the re-circulation, and the stratification factor. The stratification factor is equivalent to the mixing effectiveness of room airflow. When there is no stratification (S = 0, E_v = 100%), the Ventilation Rate Procedure uses fixed outdoor airflow rates on occupied zones.

4. TRANSIENT OCCUPANCY

When spaces are unoccupied for several hours and then occupied, operation of the ventilation system may be delayed to use the capacity of the air in the space to dilute contaminants. This applies to cases where the inside contaminants are associated only with human occupancy and where contaminants are dissipated by natural means during long vacant periods. The operation of the ventilation system can then be delayed until the concentration of contaminants reaches the acceptable limit associated with the minimum ventilation requirements at steady state.

The Indoor Air Quality Procedure allows the outdoor air ventilation to be lower than the fixed flow rates required by the Ventilation Rate Procedure through demand-controlled ventilation. An empirical method of evaluating indoor air quality is based on the assumption that occupant generated CO_2 can be used as a suitable surrogate measure of indoor air quality. Acceptable indoor air quality is achieved if the CO_2 concentration level is maintained under a maximum set-point.

If the CO_2 generation rate for all occupants equals the removal rate in any enclosed space due to air exchange, then a steady-state condition is said to have occurred. However, in most cases, it is unlikely that steady-state condition will be met under typical restaurants, cafeteria/fast-food dining, bars, and cocktail lounges conditions since occupancy levels and corresponding CO_2 generation rates are never constant long enough to achieve this condition. To calculate the concentration (C) of a substance as a function of time (t), the generation rate $(\dot{N}_{gen})$, the ventilation rate $(\dot{V})$, and the room volume (V) must be known or estimated. The conservation of mass (m) for a control volume (cv) is:

$$\left.\frac{\partial m}{\partial t}\right|_{CV} = \sum \dot{m}_{in} - \sum \dot{m}_{out} + \sum \dot{m}_{gen} \qquad (6)$$

In engineering practices, it is customary to use volumetric flow rate $(\dot{V})$ of air to replace mass flow rate $(\dot{m})$ of air because volume values are frequently used in sizing air-handling equipment. If the concentration changes with time, the conservation of CO_2 in the space (C_{space}) is:

$$V\left.\frac{\partial C_{space}}{\partial t}\right|_{CV} = (C_{in}\cdot\dot{V}_{in}) - (C_{out}\cdot\dot{V}_{out}) + \dot{N}_{gen} \qquad (7)$$

where

C_{in} = inlet CO_2 concentration of outdoor air (C_{OA}),

C_{out} = outlet CO_2 concentration of space return air.

In a perfectly mixed region, the concentration of the space (C_{space}) is always equal to the outgoing concentration. For incompressible flow with constant air density, the flow rates are equal, ($\dot{V}_{in}$ = $\dot{V}_{out}$ = $\dot{V}$), then:

$$V\left.\frac{\partial C_{space}}{\partial t}\right|_{CV} = (C_{OA}\cdot\dot{V}) - (C_{space}\cdot\dot{V}) + \dot{N}_{gen} \qquad (8)$$

4.1 Equilibrium Analysis

For the case of steady-state CO_2 concentration:

$$V\left.\frac{\partial C_{space}}{\partial t}\right|_{CV} = 0 \qquad (9)$$

Then, Equation (8) becomes:

$$(C_{OA}\cdot\dot{V}) - (C_{space}\cdot\dot{V}) + \dot{N}_{gen} = 0 \qquad (10)$$

where C_{space} becomes the steady-state concentration ($C_{S.S.}$) of the space after some time (t). Then:

$$\dot{N}_{gen} = \dot{V}\cdot(C_{SS} - C_{OA}) \qquad (11)$$

Therefore, the required outdoor air flow rate needed to maintain the steady-state CO_2 concentration below a given limit is given by the simple mass balance equation:

$$\dot{V} = \frac{\dot{N}_{gen}}{C_{SS} - C_{OA}} \qquad (12)$$

CO_2 generation rate depends primarily on the physical activity which is the metabolic rate per unit of surface area, in met units (1 met = 58.2 W/m^2 or 18.4 $Btu/h\text{-}ft^2$). An average adult engaging in office activity (1.2 met) generates about 0.0052 L/s (0.011 cfm). Based on Eq. (12), Fig. 2 was plotted to show the relationship between outdoor air ventilation rates and their corresponding steady-state CO_2 concentrations of the space. Fixed outdoor CO_2 concentrations of 300 ppm, 350 ppm, and 400 ppm were assumed for this example.

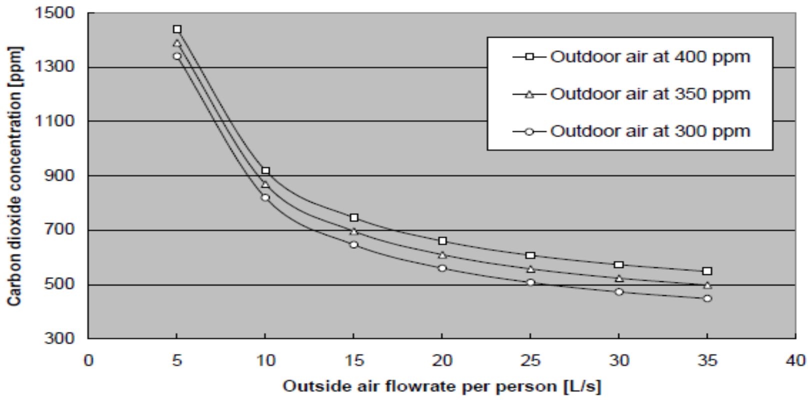

Figure 2 Correlations of outdoor air ventilation rates and their corresponding indoor CO_2 concentration levels at equilibrium　($\dot{N}_{gen}$ = 0.0052 L/s per person)

4.2 Transient Analysis

For the case of transient condition, the initial space concentration is assumed equal to the outdoor air concentration, so the space concentration gradually increases and decreases as people go in and out of the occupied space while outdoor air ventilation continues. By normalizing the space concentration (C_{space}) to the difference between space and outdoor air concentration, the differential equation, Eq. (8) was rearranged, then:

$$\frac{\partial}{\partial t}(C_{space}-C_{OA})=(C_{space}-C_{OA})\cdot\left(\frac{\dot{V}}{V}\right)+\left(\frac{\dot{N}_{gen}}{V}\right) \tag{13}$$

Because $\dot{N}_{gen}$ may vary with time if the number of people in the space varies with time, the general solution to this differential equation becomes:

$$(C_{space}-C_{OA})=\exp^{-\left(\frac{\dot{V}\cdot t}{V}\right)}\cdot\left(\int\frac{\dot{N}_{gen}}{V}\cdot\exp^{\left(\frac{\dot{V}\cdot t}{V}\right)}dt+\text{constant}\right)$$

$$(C_{space}-C_{OA})=\frac{\dot{N}_{gen}}{\dot{V}}+\left(\text{constant}\cdot\exp^{-\left(\frac{\dot{V}\cdot t}{V}\right)}\right)$$

If the initial CO_2 concentration of the space is denoted as $C_{space,t=0}$ when $t = 0$, then:

$$(C_{space}-C_{OA})=\frac{\dot{N}_{gen}}{\dot{V}}\cdot\left(1-\exp^{-\left(\frac{\dot{V}\cdot t}{V}\right)}\right)+(C_{space,t=0}-C_{OA})\cdot\exp^{-\left(\frac{\dot{V}\cdot t}{V}\right)} \tag{14}$$

The air change time constant ( ), which is the inverse of the space's air exchange rate, can be defined as:

$$\tau=\frac{V}{\dot{V}} \tag{15}$$

Then, Eq. (14) becomes:

$$(C_{space}-C_{OA})=\frac{\dot{N}_{gen}}{\dot{V}}\cdot\left(1-\exp^{-\left(\frac{t}{\tau}\right)}\right)+(C_{space,t=0}-C_{OA})\cdot\exp^{-\left(\frac{t}{\tau}\right)} \tag{16}$$

Eq. (16) represents the general solution to transient occupancy with 100% outdoor airflow rate $(\dot{V})$.

When people first come into a space, $C_{space\ t=0} = C_{OA}$, then the second term on the right-hand side of Eq. (16) is zero, so:

$$(C_{space} - C_{OA}) = \frac{\dot{N}_{gen}}{\dot{V}} \cdot \left(1 - \exp^{-\left(\frac{t}{\tau}\right)}\right) \tag{17}$$

Furthermore, if the occupancy stays constant with $\dot{N}_{gen}$ = constant, and $\dot{V}$ = constant, on the basis of the number of people present and the ventilation airflow rate to properly ventilate for this number, then eventually the space concentration would reach steady-state ($C_{space,S.S.}$):

$$\frac{\dot{N}_{gen}}{\dot{V}} = (C_{space,S.S.} - C_{OA}) \tag{18}$$

Then, Eq. (17) can be simplified to:

$$\frac{C_{space} - C_{OA}}{C_{space,S.S.} - C_{OA}} = 1 - \exp^{-\left(\frac{t}{\tau}\right)} \tag{19}$$

On the other hand, when all occupants leave the space after the space had been occupied for some time, $\dot{N}_{gen}$ = 0. Then, as a result of the cancellation to the first term on the right-hand side of Eq. (16):

$$(C_{space} - C_{OA}) = (C_{space,t=0} - C_{OA}) \cdot \exp^{-\left(\frac{t}{\tau}\right)} \tag{20}$$

Then:

$$\frac{C_{space} - C_{OA}}{C_{space,t=0} - C_{OA}} = 1 - \exp^{-\left(\frac{t}{\tau}\right)} \tag{21}$$

For a constant outdoor CO_2 concentration, Eq. (19) applies to the buildup of indoor CO_2 concentration with time without outdoor air ventilation after people have entered the space. Eq. (21) applies to the decay of indoor CO_2 concentration with time when the ventilation system is operating and there are no people present to contribute to the supply of CO_2 generation. Eq. (19) may be used to determine the delay time to start ventilating outdoor air given a required steady-state space concentration set-point and its nominal time constant (*t*). Eq. (21) applies after working hours and may be used to trace the decrease of CO_2 concentration as the ventilation system operates after people leave for the day. The time required for both equations to reach steady-state depends on the air exchange rate of the building. The air exchange rate is simply the ratio of the volumetric flow rate of the sir entering a space to that space's interior volume, which is the inverse of the nominal time constant ( ), as shown in Eq. (15).

The time it takes for the space concentration to reach steady-state depends on the time constant ( ). This time constant is determined when the first-order concentration growth or decay reaches 62.3% of its final value, as shown in Fig. 3. Typical hour-by-hour energy estimating code considers steady-state model when 95% of its equilibrium is reached. In other words, when three time constant (3) is greater than one hour, a transient model would require finite difference methods.

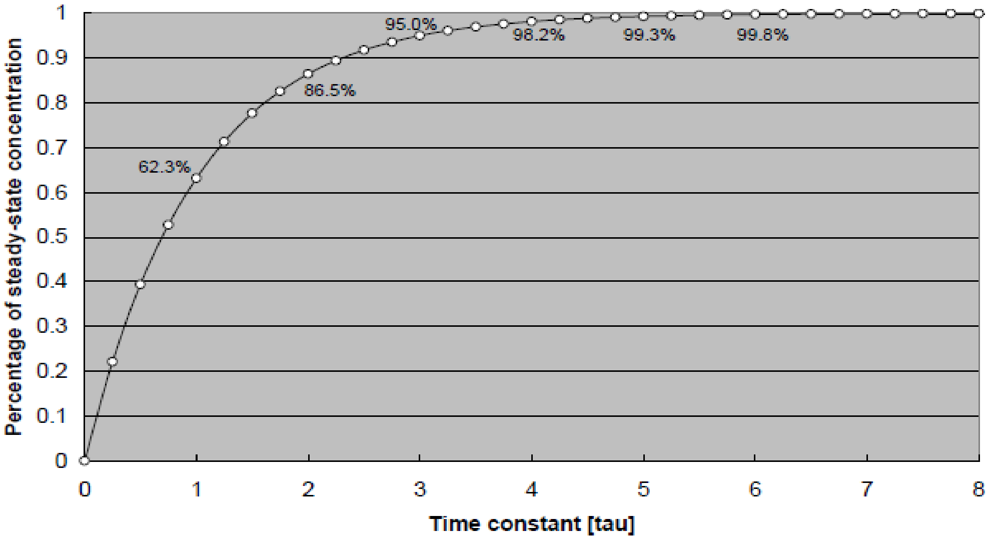

Figure 3 Percentage of the final equilibrium reached at different time constants

5. CONCLUSION

When applying either one of the two ASHRAE Standard 62.1 Procedures, close attention must be paid to the methods of room air distribution and ventilation effectiveness to the breathing zone. Stagnant must be avoided in areas of occupancy. Diffuser jet throw far from the exhaust area should help minimizing short-circuiting of ventilated air. With high ventilation effectiveness ($S \rightarrow 0$, $E_v \rightarrow 100\%$), the minimum required outdoor air flow rate (of Standard 62.1) is adequate. With low ventilation effectiveness ($S \rightarrow 1$, $E_v \rightarrow 0\%$), the minimum required outdoor air flow rate (of Standard 62.1) is insufficient unless supplied outside air is delivered directly to the breathing zone before fully mixed with the zone air. Penalty of energy cost to condition more outdoor air is not what design engineers and building owners want.

The amount of outdoor air may fall below the minimum required flow rates set forth by the ASHRAE Standard 62.1 so long as the indoor air quality is maintained at or above a certain level. When CO_2 concentration is used as an indicator of air quality, indoor air quality varies as occupants move in and out of the zone. CO_2 demand-controlled ventilation (DCV) systems are suitable to combat the problems of transient occupancy. Annual feedback of conserved energy cost and increased work productivity of occupants in healthy environments should be enough to encourage more building owners to consider employing DCV systems

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