An Experimental Study of Ventilation Effectiveness in Mechanical Ventilation Systems using a Tracer Gas Method

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The ventilation effectiveness is evaluated as a function of air exchange rate and supply/extract locations in a simplified model chamber using a tracer gas technique of CO_2 gas injected into a supply duct. Ventilation systems consist of supply and extract fans, a CO_2 gas generator, a CO_2 gas analyzer and a test chamber. The ventilation effectiveness is evaluated using a step-down method based on ASTM Standard E741-83. The room mean age of the model chamber is decreased with increasing air exchange rate ranged from 6 to 10 air changes per hour. The ventilation effectiveness of the mechanical inlet/natural extract system is better than that of the mechanical inlet/extract system and the natural inlet/mechanical extract system.

Key Words : Ventilation Effectiveness, Tracer Gas, Step-Down Method, Air Changes per Hour (ACH), Age of Air

Nomenclature

- ACH : Air changes per hour (#/hr)
- C : Concentration (ppm)
- C_e : Concentration of tracer gas at exhaust (ppm)
- C_p : Concentration of tracer gas at point P (ppm)
- $\langle C \rangle$: Time average of concentration (ppm)
- $C(0)$: Initial concentration (ppm)
- t : Time (sec)
- ε_a : Ventilation effectiveness
- $\langle \varepsilon \rangle$: Ventilation efficiency
- τ_{ce} : Mean age of contaminant at the exhaust opening (sec)
- τ_n : Normal time constant (sec)
- τ_p : Local mean age (sec)
- $\langle \tau \rangle$: Room mean age (sec)

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1. Introduction

Air inside the office building is contaminated by a large variety of toxic contaminants (Godish, 1991). Ventilation has become well-recognized part of environmental control for human comfort and is a positive control method to improve the indoor air quality. Where the air movement is induced either by wind or by the effect of temperature difference, the ventilation is called a natural ventilation. On the other hand, where the air movement results from power drive applied to fans, the ventilation method is described as a mechanical ventilation (Martin and Oughton, 1989). Because the natural ventilation is not adequate to get a steady flow rate, the mechanical ventilation is usually used for a steady flow. There are three types of mechanical ventilation systems such as the mechanical inlet and extract system, the mechanical inlet and natural extract system, and the natural inlet and mechanical extract system.

The objective of this study is to analyze the ventilation effectiveness of three types of mechanical ventilation systems for indoor air quality control and management. The ventilation effectiveness as a function of air exchange rate and supply/extract location is evaluated in the simplified model chamber using a tracer gas technique of CO_2 gas injected into a supply duct.

2. Theory

2.1 Mechanical ventilation systems

Figure 1 shows three types of mechanical ventilation systems (Martin and Oughton, 1989). Where air movement is induced either by wind or by the effect of temperature difference, ventilation is termed natural. On the other hand, where air movement results from power drive applied to a fan or fans, the arrangement is described as being mechanical. The mechanical ventilation system is usually used to get a steady flow rate. Since the inlet and extract have to be considered separately, there are three possible combinations.

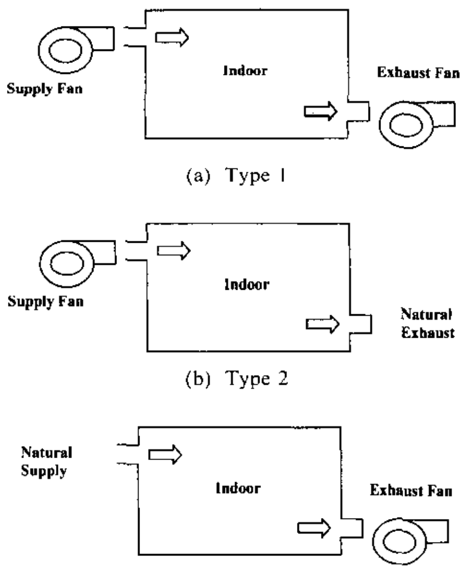


Fig. 1 Three types of the mechanical ventilation systems

The first combination shown in Fig. 1(a) is called a mechanical inlet and extract system. It may be applied to all manner of spaces and is greatly to be preferred to any of the compromise systems. In application, the ratio between the air volume duties of the inlet and extract systems must be selected with care in order to suit the particular application. The second combination shown in Fig. 1(b) is a mechanical inlet and natural extract system. Outdoor air supply in this ventilation system is provided by mechanical means in order to maintain a positive pressure. This ventilation system is usually applied to an operation room and a cleanroom to prevent pollutants incoming. The third combination shown in Fig. 1(c) is a natural inlet and mechanical extract system. Since the air is extracted from the space by mechanical means, the space would maintain a negative pressure. This system is usually adapted to a kitchen ventilation or a restroom ventilation to allow odor or pollutants outflowing. There have been many researches on the ventilation performance with mechanical inlet and extract ventilation system. But the comparative study of the ventilation performance in the three types of mechanical ventilation systems is not conducted.

This study is to analyze the ventilation effectiveness of three types of mechanical ventilation systems for indoor air quality control and management as a function of air exchange rate and supply/extract location. The ventilation effectiveness is evaluated using a tracer gas technique with step-down method based on ASTM standard E741-83 in the simplified model chamber.

2.2 Ventilation effectiveness

In terms of defining the various terms for assessing the in-space ventilation characteristics, Sandberg and Sjoberg (1983) defined ventilation efficiency and ventilation effectiveness using the concept of age of air (Kato, 1992). Han et al. (1999) evaluated ventilation characteristics of an environmental chamber simulating an under-floor air conditioning system for isothermal and cooling supply air conditions using the age of air. A local mean age of air (τ_p) is defined as the average time needed for the supply air to reach the location of interest. A room mean age of air ($\langle\tau\rangle$) can be calculated by averaging local mean ages over the entire room and also be calculated from the concentration time curve at the exhaust. Eq. (1) and Eq. (2) show the local mean age of air (τp) and room mean age of air ($\langle\tau\rangle$) using a step-down method which is defined in ASTM Standard E741-83.

$$\tau_p = \int_0^\infty \frac{C_p(t)}{C(0)} dt \qquad (1)$$

$$\langle\tau\rangle = \frac{\int_0^\infty t \cdot C_e(t)\, dt}{\int_0^\infty C_e(t)\, dt} \qquad (2)$$

The ventilation efficiency can be described as the ability of air distribution system to remove the internally generated pollutants from a building, zone, or space (ASHRAE Handbook, 1997). According to their definition of ventilation efficiency, $\langle\varepsilon\rangle$ summarized in Eq. (3) is derived from a measured concentration of the exhaust air.

$$\langle\varepsilon\rangle = C_e/\langle C\rangle = \tau_n/\tau_{ce} \qquad (3)$$

The ventilation effectiveness (ε_a) can be described as an air distribution system's ability to deliver ventilation air to a building, zone, or space (ASHRAE Handbook, 1997). One of the most important factors determining the air quality is the flow pattern of the supplied outdoor air within the room. A room mean age of the supplied air is usually used to measure the air flow pattern. As a reference, the nominal time constant (τ_n) is defined as the ratio between the total volume of the room and the ventilation flow rate, and it is equal to the room mean age in complete mixing. The ventilation effectiveness (ε_a) for the whole room is defined in the following equation (Etheridge and Sandberg, 1996).

$$\varepsilon_a = \tau_n/2\langle\tau\rangle \qquad (4)$$

This ventilation effectiveness may be obtained by simply measuring the tracer gas concentration in the exhaust duct. For most studies, the ventilation effectiveness is more useful to HVAC (Heating, Ventilation and Air Conditioning) system design than the ventilation efficiency (ASHRAE Handbook, 1997). In this study, the ventilation characteristic with the mechanical ventilation systems is evaluated by the ventilation effectiveness.

3. Experimental Apparatus and Test Procedure

Figure 2 is a schematic diagram of the ventilation test system. It consists of the supply fan (DongKun, DB-118) to provide the clean air into the chamber, the exhaust fan (DongKun, DB-118) to suck the air out of the chamber, a tracer gas supply system to generate the tracer gas, the tracer gas analyzer to measure the concentration of tracer gas with time, and the model chamber. The model chamber has the dimension of $0.84 \times 0.68 \times 0.7$ m^3,and has a circular opening of 4cm in diameter.

A tracer gas technique is used to evaluate ventilation effectiveness. The simplest tracer gas technique is the decay method known as the step-down method, which is a standardized procedure for establishing the mean age of the air (Farand. et al. 1986 ; Lagus and Persily, 1987). The mixing fans are switched on and the chamber is filled with tracer gas to a suitable concentration level. After a period of mixing, the mixing fans are switched off and the test starts. The concentration

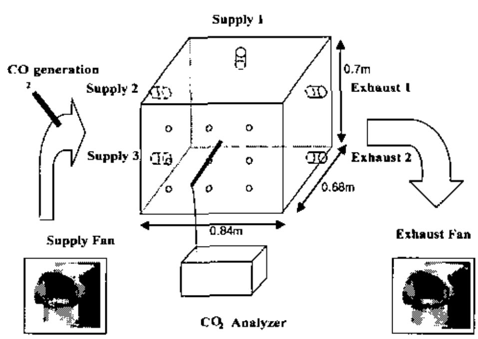


Fig. 2 Schematic diagram of a model chamber for measuring the ventilation effectiveness

Table 1 Test Conditions for the measurements of the Ventilation Effectiveness

Parameters		Conditions
Chamber Dimension (L×W×H)		$0.84 \times 0.68 \times 0.7m^3$
Ventilation Type	Type 1	mechanical inlet and extract
	Type 2	mechanical inlet and natural extract
	Type 3	natural inlet and mechanical extract
Supply and Extract Locations	Case 1	upper supply and upper extract
	Case 2	down supply and down extract
	Case 3	ceiling supply and upper extract
	Case 4	upper supply and down extract
	Case 5	down supply and upper extract
	Case 6	ceiling supply and down extract
Air Changes per Hour	6 ACH	6(=$2.4m^3$/hr)
	8 ACH	8(=$3.2m^3$/hr)
	10 ACH	10(=$4m^3$/hr)
Tracer Gas		CO_2
CO_2 Gas Analyzer		CMCD 10P(Kanomax, Japan)

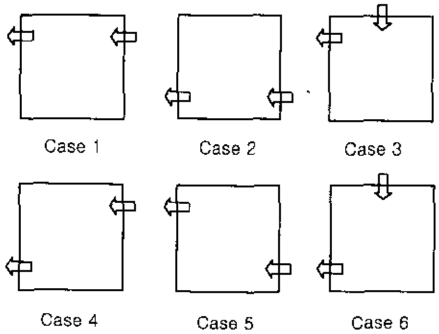


Fig. 3 Six supply and extract cases in the combination of three supply locations and two extract locations.

is then allowed to decay to base level before the test is stopped. Variations of the gas concentration as a function of time are measured at various supply/extract locations and air exchange rates with the CO_2 gas monitor (CMCD 10P, Kanomax, Japan) using a principle of nondispersive infrared absorption. The tracer gas concentration is measured at 9 locations in the chamber and in the exhaust duct.

Table 1 shows the test conditions for the measurements of the ventilation effectiveness as a function of ventilation type, supply/extract locations and air exchange rates. Since the inlet and extract have to be considered separately, there are three possible ventilation types such as mechanical inlet and extract system, mechanical inlet and natural extract system, and natural inlet and mechanical extract system. Six supply and extract cases in the combination of three supply locations and two extract locations are shown in Fig. 3. Air exchange rates have three conditions from 6 air changes per hour (ACH) to 10 ACH. The CO2 gas is selected as the tracer gas in this study. An ideal tracer gas should not be a normal constituent of the environment to be investigated, be easily measurable, be non-toxic and non-allergenic to permit its use in occupied spaces, be non-reactive and non-flammable so that its movement is easily traced, and be economical to use. No single tracer gas fulfills all the requirements mentioned. A wide variety of gases have been employed and have been chosen to exploit a specific characteristic. NO, CO_2, SF_6 and freons Of all the gases used as tracers, are most wide used. A CO_2 gas has proven useful as a tracer gas (Farant, 1986).

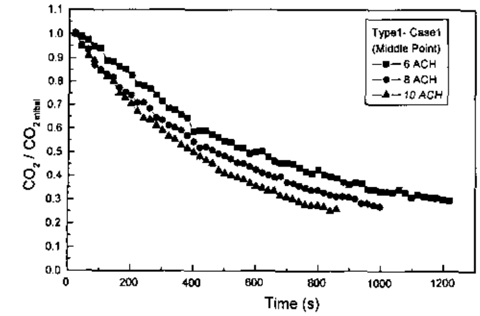
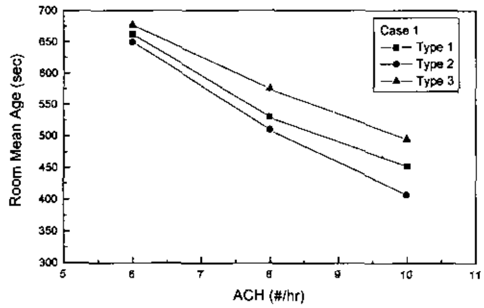


Fig. 4 Concentration variation of a tracer gas in the combination of Type 1 and Case 1 as a function of air exchange rate (6, 8, 10 ACH)

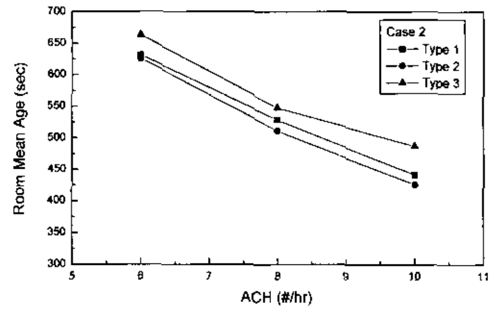
4. Results and Discussion

4.1 Ventilation effectiveness with air exchange rate

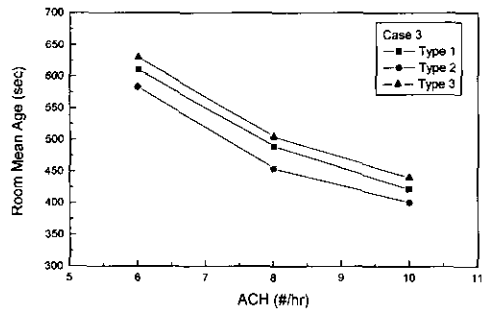
Figure 4 shows the concentration variation of the CO_2 gas as a function of air exchange rate ranged from 6 ACH to 10 ACH. The concentration variation of the CO_2 gas is measured at the middle point of the model chamber in the combination of Type 1 (mechanical inlet and extract



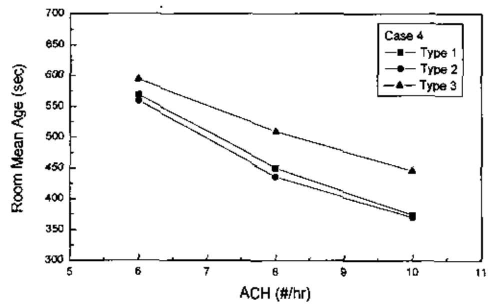
(a) Case 1 (upper supply and upper extract)



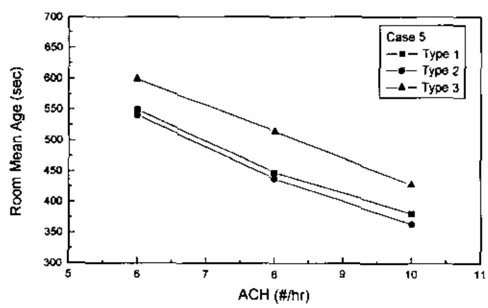
(b) Case 2 (down supply and down extract) (continued)



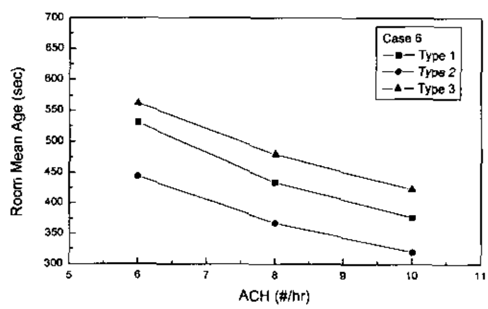
(c) Case 3 (ceiling supply and upper extract)



(d) Case 4 (upper supply and down extract) (continued)

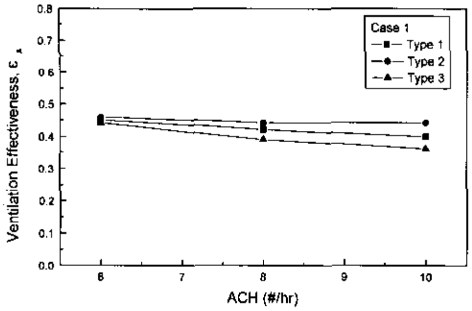


(e) Case 5 (down supply and upper extract)

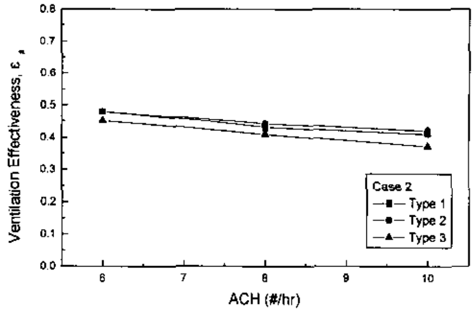


(f) Case 6 (ceiling supply and down extract)

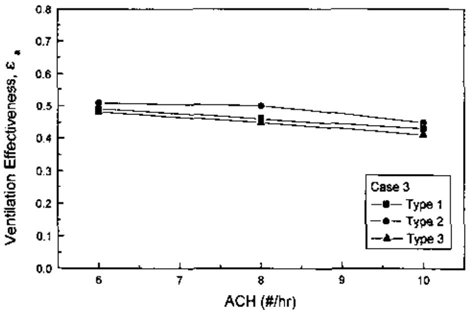
Fig. 5 Test results of room mean age as a function of air exchange rate at the test conditions of Case 1 to Case 6



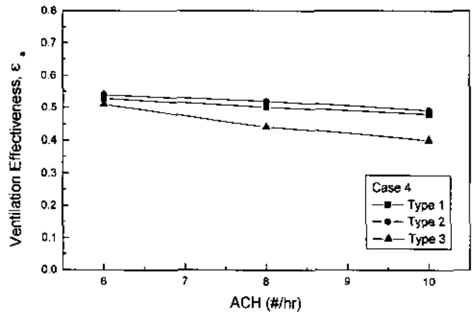
(a) Case 1 (upper supply and upper extract)



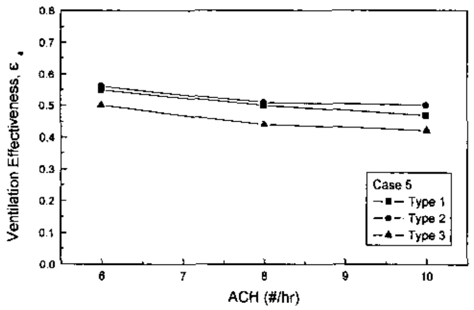
(b) Case 2 (down supply and down extract) (continued)



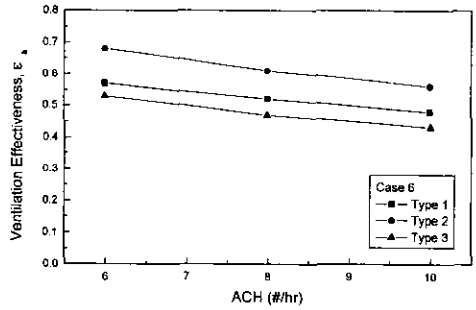
(c) Case 3 (ceiling supply and upper extract)



(d) Case 4 (upper supply and down extract) (continued)



(e) Case 5 (down supply and upper extract)



(f) Case 6 (ceiling supply and down extract)

Fig. 6 Test results of ventilation effectiveness as a function of air exchange rate at the test condition of Case 1 ~ Case 6

system) and Case 1 (upper supply and upper extract). The chamber filled with CO_2 gas at 3000 ppm after a period of mixing. The concentration is then allowed to decay to base level about 400 ppm. The half concentration time of CO_2 gas as a function of air exchange rates 6,8 and 10 ACH corresponds to 600,500 and 400 seconds, respectively. The CO_2 gas concentration is decayed exponentially with increasing air exchange rate.

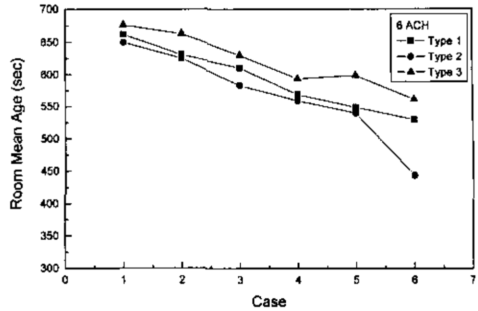
Figure 5 shows the experimental results of the room mean age as a function of air exchange rate at the locations of supply and extract from Case 1 to Case 6. As shown in the Fig. 5(a), the room mean age of 6,8 and 10 ACH in the combination of Type 1 (mechanical inlet and extract system) and Case 1 (upper supply and upper extract) corresponds to 670 seconds, 540 seconds and 450 seconds, respectively. The difference of the room mean age between 6 and 8 ACH, 8 and 10 ACH is about 100 second. It is believed that the air velocity becomes fast with increasing the air exchange rate and the fresh air reaches at the entire room rapidly.

Figure 6 shows the test results of the ventilation effectiveness describing the ability of air distribution system to deliver the ventilation air to a building, zone, or space as a function of air exchange rate at the test condition of Case 1 ~ Case 6. As shown in the Fig. 6(a), the ventilation effectiveness of 6, 8 and 10 ACH in the combination of Type 1 (mechanical inlet and extract system) and Case 1 (upper supply and upper extract) corresponds to 0.45, 0.42 and 0.40, respectively. The ventilation effectiveness decreases by 2%~3% with increasing the air exchange rate in three types and six cases. Especially, Case 1 (upper supply and upper extract) has the ventilation effectiveness under 0.5 which corresponds to the ventilation effectiveness in complete mixing. This result indicates that the real air exchange rate does not follow well controlled air exchange rate with increasing the air exchange rate. It is believed that the air flow in the room is not mixing with increasing the air velocity and the short circuiting happens locally.

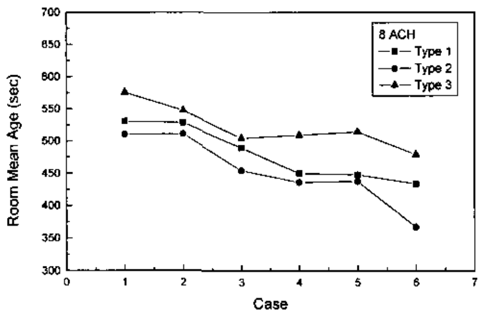
4.2 Ventilation effectiveness with supply and extract locations

A flow pattern of the chamber is dependent on the supply and extract locations. The differences of the flow pattern with supply and extract locations affect the ventilation effectiveness of the ventilation system. There are six supply and extract cases in the combination of three supply locations and two extract locations as shown in Fig. 3. The effect of the supply and extract location to ventilation effectiveness is evaluated with six cases.

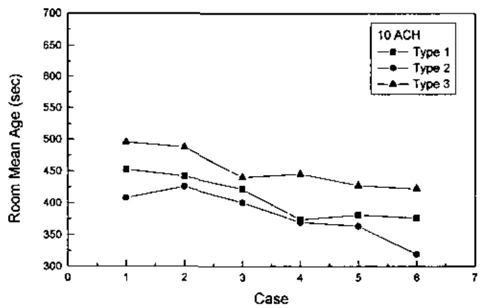
Figure 7 shows the test results of room mean age as a function of supply and extract location. The results of the room mean age in Case 4 (upper supply and down extract), Case 5 (down supply and upper extract) and Case 6 (ceiling supply and down extract) at 6 ACH are ranged from 500 seconds to 600 seconds. The room mean ages in Case 4, Case 5 and Case 6 are shorter by 100 seconds than that in Case 1 (upper supply and upper extract), Case 2 (down supply and down extract) and Case 3 (ceiling supply and upper extract). The trend of the room mean age at the air exchange rate of 8 ACH and 10 ACH is



(a) 6 ACH



(b) 8 ACH



(c) 10 ACH

Fig. 7 Results of room mean age as a function of supply/extract location

found to be similar to the result of 6 ACH. It is believed that the air flows in Case 4, Case 5 and Case 6 are spread well over the whole room compared with the air flows in Case 1, Case 2 and Case 3 which have the short circuiting locally.

Figure 8 shows the test results of the ventilation effectiveness as a function of supply and extract locations. The ventilation effectiveness of Case 4 (upper supply and down extract), Case 5 (down supply and upper extract) and Case 6 (ceiling supply and down extract) in the combination of Type 1 (mechanical inlet and extract system) and

6 ACH corresponds to 0.53, 0.55 and 0.57, respectively. The ventilation effectiveness of Case 4, Case 5 and Case 6 is larger by 8%～10% than that of Case 1 (upper supply and upper extract), Case 2 (down supply and down extract) and Case 3 (ceiling supply and upper extract).

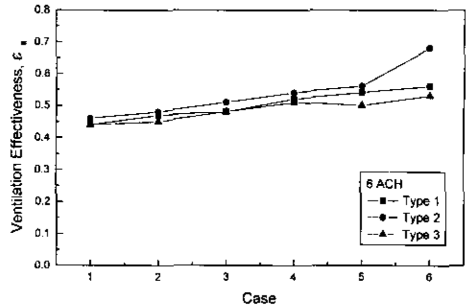
The difference of the ventilation effectiveness as a function of supply and extract location is due to airflow patterns in a given space. The airflow pattern in a space can be classified into the three forms such as mixing flow, short circuiting flow and unidirectional flow (Bearg, 1993). The complete mixing is air flow distribution pattern where the supply air is instantaneously and uniformly mixed with the room air, such that the concentration of all constituents in the air is uniform, and the ventilation effectiveness for complete mixing would be 0.5.

In Case 1 (upper supply and upper extract), Case 2 (down supply and down extract) and Case 3 (ceiling supply and upper extract), the airflow is concentrated at upper region and lower region relatively. This flow pattern is called as the short circuiting flow. In short circuiting flow, a large proportion of the supply air flows directly to the extract air device without passing the occupied zone. As shown in the Fig. 8 the ventilation effectiveness of Case 1, Case 2 and Case 3 with short circuiting flow is under 0.5 which is ventilation effectiveness in complete mixing.

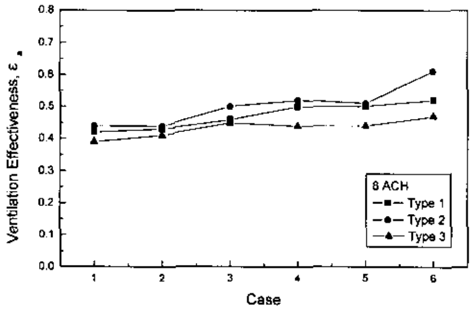
The flow pattern of the Case 4 (upper supply and down extract), Case 5 (down supply and upper extract) and Case 6 (ceiling supply and down extract) is a kind of mixing and unidirectional flow patterns. The supplied air moves through the room and is spread uniformly over the whole cross section. This kind of flow pattern has a little short circuiting compared with the flow patterns in Case 1, Case 2 and Case 3. As shown in the Fig. 8 the ventilation effectiveness of Case 4, Case 5 and Case 6 is over 0.5.

Therefore the ability to deliver the supply air to the space in Case 4, Case 5 and Case 6 representing the mixing and unidirectional flows is better than in Case 1, Case 2 and Case 3 representing the short circuiting flow.

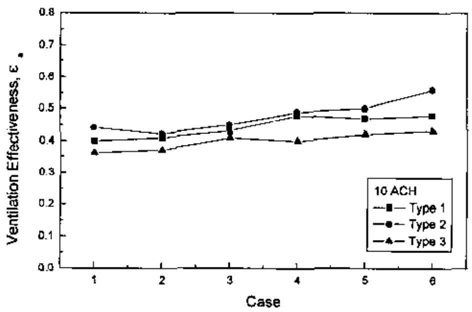
Figure 9 shows the ventilation effectiveness with three types of mechanical ventilation systems. The ventilation effectiveness of three types of mechanical ventilation systems has the same trend of the ventilation effectiveness in the combination of all supply/extract locations and air exchange rates. The ventilation effectiveness of Case 4 (upper supply and down extract), Case 5 (down supply and upper extract) and Case 6 (ceiling supply and down extract) is larger by 8% ～10% than that of Case 1 (upper supply and upper extract), Case 2 (down supply and down extract) and Case 3 (ceiling supply and upper



(a) 6 ACH

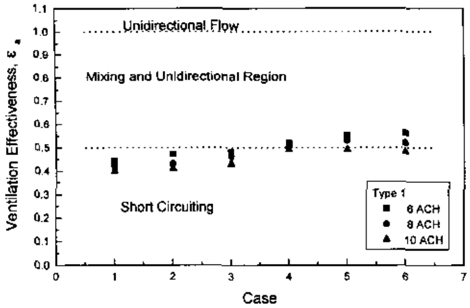


(b) 8 ACH

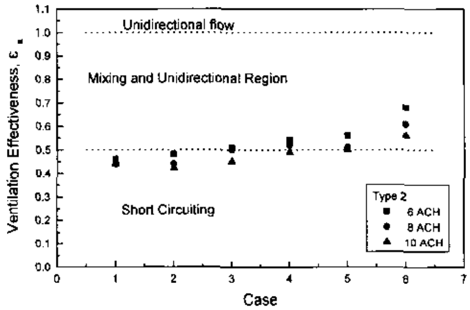


(c) 10 ACH

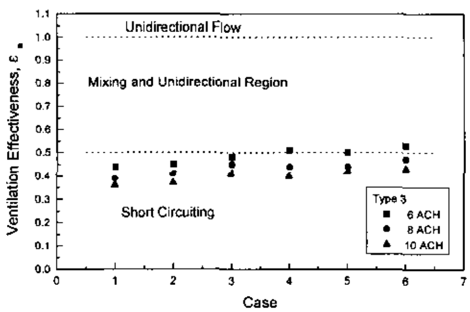
Fig. 8 Results of ventilation effectiveness as a function of supply/extract location



(a) Type 1



(b) Type 2



(c) Type 3

Fig. 9 Comparison of ventilation effectiveness as a function of supply/extract location

extract) in three types of mechanical ventilation systems. As shown in the Fig. 8 and Fig. 9, the ventilation effectiveness in Type 2 (mechanical inlet and natural extract system) is better than in Type 1 (mechanical inlet and extract system) and in Type 3 (natural inlet and mechanical extract system). The difference of the ventilation effectiveness is due to the source of flow pattern with three types of mechanical systems. The Type 2 maintains a positive pressure in the room. Therefore, the flow pattern in Type 2 is like a unidirectional flow pattern which was from high pressure supply site to low pressure extract site and has a little short circuiting region locally compared with Type 1 and Type 3.

5. Conclusions

The room mean age and the ventilation effectiveness are evaluated as a function of air exchange rate and supply/extract location in the simplified model chamber using a tracer gas technique based on ASTM standard E741-83. The conclusions can be summarized as follows.

(1) The ventilation effectiveness decreases by 2%~3% with the increase of the air exchange rate from 6 ACH to 10 ACH. This result indicates that the real air exchange rate does not follow well controlled air exchange rate with the increase of the air exchange rate.

(2) The differences of the flow patterns with supply and extract locations affect the ventilation effectiveness of the ventilation system. The ventilation effectiveness of mixing and displacement flow such as Case 4, Case 5 and Case 6 is larger by 8%~10% than that of short circuiting flow such as Case 1, Case 2 and Case 3.

(3) The ventilation effectiveness in the mechanical inlet/natural extract system is found to be better than in the mechanical inlet/extract system and the natural inlet/mechanical extract system.

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