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VENTILATION EFFECTIVENESS IN MULTIZONE BUILDINGS

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ABSTRACT

Increased awareness of the potential health risks associated with indoor air pollutants and growing attentions on energy efficiency have stimulated studies of the performance of ventilation systems. Air exchange efficiency and ventilation effectiveness examine two aspects of ventilation performance: to supply fresh air to and to remove contaminants from the zones of occupancy. This paper describe the theoretical derivation process for a relative contaminant removal effectiveness term and its relation to other concepts and definitions that are used in ventilation performance studies. The term is applied to a set of experiments conducted in a naturally ventilated apartment building.

KEYWORDS: Ventilation effectiveness, removal effectiveness, age of air, trace gas techniques.

INTRODUCTION

Knowledge of ventilation performance is important in the development of control strategies for indoor air quality in an energy-efficient manner. Traditionally, ventilation systems have been designed based on the assumption that the supply air and the pollutant are well mixed throughout the ventilated space. It has also been assumed that the air flow is distributed uniformly within a building. However, recent studies have shown that the overall ventilation rate within a building can be up to 50% of the ventilation rate in certain parts of that building [1]. This low air exchange rate may cause slow removal of the indoor contaminants in these parts of the building.

Ventilation performance is usually measured in terms of: the ability to supply fresh air to the room and the ability to remove contaminants from the room [2-3]. Conventionally, these two aspects are referred to as air exchange efficiency and ventilation effectiveness respectively. The rationale for this separate treatment is that the behaviour of air and contaminants are usually different, especially when pollutants are not uniformly distributed.

When pollutants are introduced in a space, they generally are not well-mixed immediately with room air. The consequent contamination migration and distribution are affected by room air movement patterns and the diffusion processes, and are usually different from those of the room air. Therefore, the air-exchange efficiency could not indicate the ability of the ventilation system to evacuate the contaminant originating from a source in the room. The term ventilation effectiveness is used to express the degree to which pollutants are removed and prevented from spreading to specific zones. There are various definitions associated with these two terms. Most of the definitions are based on the performance of mechanically supplied air to remove the uniformly distributed indoor contaminants, that is the efficiency of the air distribution. In the case of non-uniform contaminant distribution, the definitions and/or the measurements of the ventilation effectiveness are limited mostly to mechanical ventilation dominated systems. Thus, no appropriate techniques exist for the evaluation of contaminant removal capability in situations where natural ventilation dominates and uniform contaminant distribution cannot be assumed, or when there are too many supply and return diffusers for convenient measurements.

A procedure for measuring ventilation effectiveness in above situations was proposed in a previous paper [4], in which a new term called relativeness contaminant removal effectiveness was defined. The emphasis of this paper is to present the theoretical aspect of the new term and to show the relations of this term with some other concepts and definitions employed in studying air-exchange efficiency and ventilation effectiveness.

THEORETICAL DERIVATION OF THE RELATIVE REMOVAL EFFECTIVENESS

Consider the following generic situation, a building of a volume V (m^3) has a ventilation rate of Q (m^3/s), which may not be easily measurable. The generation rate of the contaminant inside the building is F (m^3/s). Let $\langle\tau\rangle$ be the average age of the air, defined as the average time that has elapsed since the air entered the buildings, and $\langle\tau_c\rangle$ the average age of the contaminant, defined as the average time that has elapsed since the contaminant is emitted at the source. These two terms indicate the ability of the ventilation system (whether natural or mechanical) to supply fresh air and to remove contaminants. Relative contaminant removal effectiveness term is defined as the ratio between these two average ages, i.e.:

$$\mu = \frac{\langle \tau \rangle}{\langle \tau_c \rangle} \tag{1}$$

In order to measure this effectiveness term, two tests are to be performed in the above mentioned building: a tracer gas decay test to measure the effective ventilation rate due imperfect mixing of fresh air with the room air, and a constant tracer gas injection test to simulate the behaviour of contaminant migration and removal. Let $\langle b \rangle$ be the average decay exponent (which equals to the air exchange rate of the building) obtained from the decay test, and $\langle C^r \rangle$ be the average steady-state (tracer gas) concentration during the constant injection test. Then, the average age of the air can be expressed as the reciprocal of $\langle b \rangle$:

$$\langle \tau \rangle = \frac{1}{\langle b \rangle} \tag{2}$$

The average age of the contaminant can also be obtained from the experimental data as:

$$\langle \tau_c \rangle = \frac{F}{V \langle C^r \rangle} \tag{3}$$

where F is the tracer gas generation rate.

Therefore, the relative removal effectiveness, μ, can be expressed in the measurement results from the two-part experiment, as:

$$\mu = \frac{F}{V \langle b \rangle \langle C^r \rangle} \tag{4}$$

This expression is the same as that of [4]. The difference is that the previous derivation [4] starts from the experimental data, while the above derivation (equations 1-4) begins with a theoretical definition for a generic building.

The "relativeness" of the μ term can be shown more directly if it is expressed in relation with another two popularly employed term: the average ventilation effectiveness defined by Skaret [2], $\langle \varepsilon_c \rangle$, and the air exchange efficiency defined by Sandberg [3], η_a. The Skaret's term is defined as the ratio between exhaust and the average room contaminant concentration at the steady-state, i.e.:

$$\langle \varepsilon_c \rangle = \frac{F/Q}{\langle C^r \rangle} = \frac{F/Q}{\frac{F}{V \langle \tau_c \rangle}} = \frac{V}{Q} \times \frac{1}{\langle \tau_c \rangle} \tag{5}$$

The air exchange efficiency is the ratio between the nominal time constant, $\tau_n = V/Q$, and the average age of the air, as:

$$\eta_a = \frac{V/Q}{2\langle\tau\rangle} \qquad (6)$$

The relation between μ and these terms can be written in:

$$\mu = \frac{\langle e\rangle}{2\eta_a} \qquad (7)$$

The relative removal effectiveness integrates the concepts of air-exchange efficiency and ventilation effectiveness. It can be understood as the relative effectiveness of removing the contaminant from the space with respect to a given air exchange efficiency. When the contaminant is removed from the space faster than the room air, the relative removal effectiveness is greater than unity. Otherwise, when the contaminant is removed more slowly than the room air being replaced by the fresh air, the μ value would be less than unity.

EXPERIMENTAL PROCEDURE AND RESULTS

Experiments were carried out in an apartment building in Montreal. Each experiment consisted of a constant tracer gas injection test and a tracer gas decay test. During the injection period, tracer gas CH_4 was injected at a constant rate for three to four hours to permit the CH_4 concentration levels to reach the steady state. Once the injection stopped, measurement of the decay was continued for another 2 to 3 hours. No mixing fan was used during both injection and decay.

Twelve tests were conducted during the winter season of 1988 to 1989 for combinations of the following test conditions: (1) hood Off/On, (2) forced air system Off/On, (3) interior door Closed/Open, and (4) exhaust fan Off/On.

Figure 1 show the tracer gas concentrations of the test #1. The lines on the figure have a general pattern of rise and decay. During the time of constant emission, the tracer gas concentration increase, more or less, for all 12 sampling locations. During decay, the concentrations decrease. Both rise and decay exhibit an exponential behaviour. The steady-state concentrations during the rise period were different for the 12 sampling locations. The differences in the results were due to the contaminant (tracer gas) migration, which depends upon the airflow field in the apartment. The conditions of the range hood, the forced air system, the interior doors, the exhaust fan, and the indoor/outdoor climate affect the contaminant dispersion patterns.

Table 1 shows the results for the 12 tests together with the climatic parameters. The μ values vary with test conditions. The greatest influence on the μ values are the operations of the range hood, which removes a large amount of contaminants (simulated by the tracer gas). The higher μ values for tests with hood in operation indicate the hood being an effective source removal device. When the hood is not in operation, the μ values are less than unity, which indicates that the contaminant (tracer gas during injection) are removed from the apartment slower than the room air being replaced. The other three test conditions (the forced-air system, the interior door and the exhaust fun) also influence the relative removal effectiveness, but to a lesser degree.

CONCLUSION

The theoretical analysis of the relative contaminant removal effectiveness term which describes the ability of a ventilation system to remove contaminants under given air exchange efficiency is presented. The derivations show that the term is well defined and is closely related with other concepts and definitions used in studying ventilation performance in buildings.

The experiment results show the effects of the operation of local exhausts, forced air system, interior partitions and exhaust fans on the pollutant migration and removal.

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Table 1. Relative Contaminant Removal Effectiveness

Hood	Off						On					
Forced Air	Off				On		Off				On	
Door	Closed		Open		Closed	Open	Closed		Open		Closed	Open
Fan	Off	On	Off	On	Off	On	Off	On	Off	On	Off	On
Test #	1	2	3	4	5	6	7	8	9	10	11	12
μ	0.74	0.63	0.90	0.87	0.83	0.92	3.68	3.61	4.70	1.98	3.68	3.26
$T_i - T_o$	29.7	29.9	33.5	24.0	25.7	17.8	31.0	36.9	18.7	28.6	30.5	29.3
V	8.39	22.2	11.9	25.5	14.5	10.6	18.8	14.6	15.3	17.1	10.6	4.9
D	W	W	NNE	WSW	N	W	ENE	W	ESE	NE	NNE	NNW

Note: V is the wind speed in mph, and D is the wind direction.

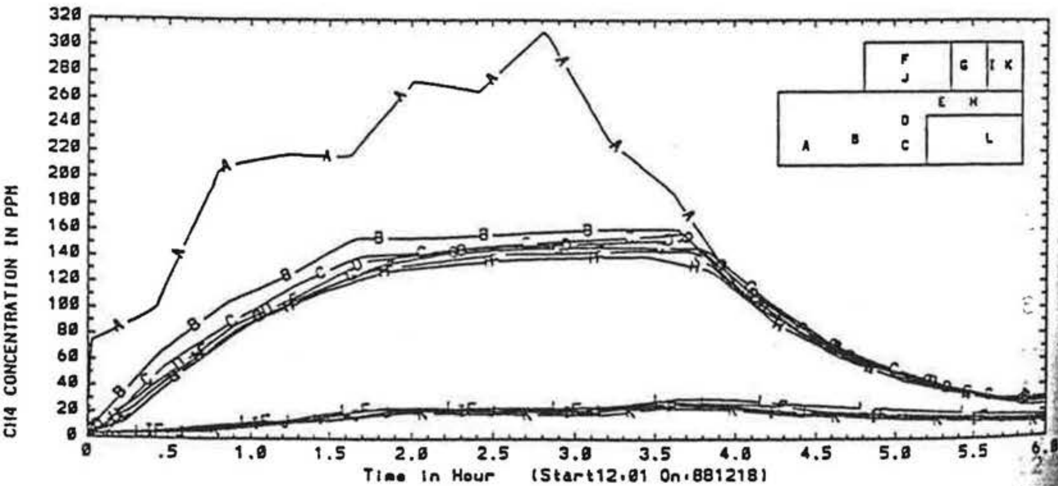

Figure 1: Forced Air-Off, Door-Closed, Hood-Off and Fan-Off