Building and Environment, Vol. 25, No. 2, pp. 163-172, 1990.
Printed in Great Britain.

0360-1323/90
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A Procedure for Measurement of Ventilation Effectiveness in Residential Buildings

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Ventilation effectiveness is expressed by two newly defined terms: relative contaminant removal effectiveness and removal efficiency. The relative removal effectiveness is defined as the relative ratio between the rate of contaminant removal and rate of room air replacement. The removal efficiency is the percentage of the total generated contaminant removed by purpose-provided openings. A series of tracer gas tests was performed to simulate the contaminant migration and the removal of the contaminant generated by a point source in a residential building. The values of relative removal effectiveness are calculated from test results. The removal efficiency is then obtained from the values of relative removal effectiveness for two concerned tests. The new terms can be used to assess the air quality related building problems and help in the design stage in decisions among alternative schemes.

INTRODUCTION

STUDY OF ventilation performance is very important to develop energy conservation measures and to diagnose indoor air quality related problems. For a ventilated room, the ventilation performance can be expressed in terms of: the ability to supply fresh air to the room and the ability to remove pollutants from the room. 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 pollutants are usually different, especially when the pollutants are not uniformly distributed [1].

The precise analysis of the airflow and contaminant migration fields requires sophisticated measurements and/or complicated, time consuming numerical simulations, and thus, is rarely used in practical situations. Instead, the tracer gas technique is being used to study the pattern of airflow and contaminant migration in order to measure the air-exchange efficiency and ventilation effectiveness, to identify and diagnose building problems related to air quality and ventilation, to develop control strategies, and to support the development of a ventilation model.

A large amount of research has concentrated on definitions and measurements of ventilation performance. Liddament and Skaret [2, 3] have provided comprehensive and up-to-date reviews of these definitions. Anderson [4] has classified the definitions into three categories: (1) the physical meanings attached to the definitions (air-exchange efficiency and ventilation effectiveness); (2) the building subsystem that the definition is applied to (building, room or occupied zone); (3) the measurement approaches (laboratory measurement, field measurement or numerical calculations). A fourth important category that should be added is the type of ventilation technique employed in the building (natural or forced). These four categories divide the ventilation performance into 36 cells, as shown in Fig. 1. A definition may apply to one or more of these cells. Figure 1 shows the application areas of the terms defined by references [5, 7]. Depending on what the desirable requirements for

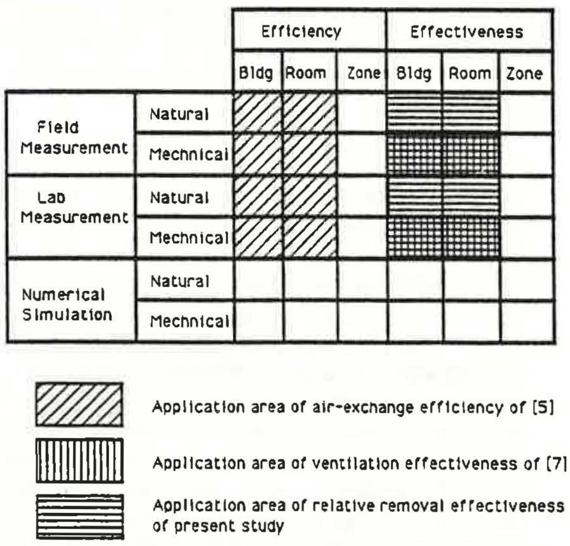

Fig. 1. Classification of air-exchange efficiency and ventilation effectiveness.

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the ventilation system are, suitable definitions can be chosen according to their positions in the cell-map.

Sandberg [5] considered the air-exchange efficiency as the degree to which the old air in the zone/room is replaced by the fresh air for a given ventilation rate. The expression is:

$$\varepsilon_a = \frac{\tau}{2\langle\tau\rangle}, \quad (1)$$

where $\tau = V/Q$ indicates the fresh air supply (usually defined as the nominal time constant). The term $\langle\tau\rangle$ represents the average age of room air, it can be measured by the tracer gas decay technique. If the concept of effective ventilation rate, Q_{eff}, is employed to represent the actual amount of old air being removed due to fresh air supply Q, then $\langle\tau\rangle = V/Q_{eff}$. So that ε_a can be manipulated as:

$$\varepsilon_a = \frac{\frac{V}{Q}}{2\frac{V}{Q_{eff}}} = \frac{1}{2}\frac{Q_{eff}}{Q} \propto \frac{Q_{eff}}{Q}. \quad (2)$$

That is, the air-exchange efficiency can be indicated as the ratio between the effective ventilation rate and the actual ventilation rate.

When the pollutants are introduced in a room, they generally are not well-mixed immediately with the room air. The consequent contaminant migration and distribution are affected by room air movement patterns and the diffusion processes [6], 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 thus introduced. Most ventilation effectiveness definitions are defined for buildings with mechanical ventilation systems, and their measurements rely on the contaminant concentrations in the supply or return ducts. Skaret [7] defined an average effectiveness term, ε_v^c, as the ratio between the steady state contaminant concentration in the exhaust air (or the volumetric average concentration), $C_e(\infty)$, and the steady state average concentration of the contaminant in the room, $\langle C_i(\infty)\rangle$, i.e.

$$\varepsilon_v^c = \frac{C_e(\infty)}{\langle C_i(\infty)\rangle}. \quad (3)$$

Most of the existing definitions on air-exchange efficiency and ventilation effectiveness are inappropriate when they are applied in certain situations, such as residential buildings where natural ventilation (due to wind induced pressures and temperature stratification) dominates. If the pollutant is not uniformly distributed, the concentrations through adventitious openings vary and cannot be easily measured. Skaret's [7] and others' definitions of ventilation effectiveness, which depend on the concentrations at return ducts, have little meaning and cannot be applied in these cases. Also, when purpose-provided openings are placed near the sources of contaminant generation, some of the contaminant is directly removed. The definition of overall pollutant removal would tend to be too general for the situation, and it does not well represent the effect of the direct removal mechanism. Furthermore, there is no attempt to connect the two concepts. After all, the efficiency and effectiveness are just two aspects of the performance of the ventilation systems (whether natural or forced).

In this paper, the emphasis is placed on the pollutant removal in residential buildings where natural ventilation dominates and the contaminant is not uniformly distributed. The ventilation effectiveness is viewed from two aspects; a relative measure as an overall indicator for contaminant removal, and a term as an indicator of the efficiency of local exhausts. In the following, we will discuss a series of field tests in an attempt to advance the understanding of contaminant distribution caused by a point source in a residential building, and to derive new terms to describe the effectiveness for the natural ventilation, the mechanical ventilation and the local exhaust in removing the contaminant. A constant tracer gas emission technique is used to simulate the pollutant generation by a point source. The formulation of the two concepts and the calculations based on the conducted tests are presented in detail.

TEST FACILITY AND PROCEDURE

The facility is located in an unoccupied, attached, three-storey apartment building on St. Denis street in Montreal. Each apartment in the building is completely furnished to simulate real living conditions. A forced-air mechanical system with total circulation air is in operation. At least one pair of air supply and return ducts is placed in each room on the floor level.

The CH4 monitoring system includes the sampling system, a hydrocarbon gas analyser, the micro-computer based data collection system, a personal computer (PC) and a VAX/785 computer. The sampling system has twelve channels which are connected to tubes reaching different sampling points in the house (Fig. 2). Each sampling tube inlet is placed at a height of 1.6 m above the floor. The sampling system skips along twelve channels every two minutes, therefore data for each channel is collected every 24 min. The analyser continuously pumps in the air through the tube selected by the sampling system. The output as voltage is transferred to digital signals and recorded by the data collection system. The data recording sequence is pre-programmed into the built-in microcomputer on the data logger through the PC. Once the program starts and relevant parameters are set, it automatically performs the necessary tasks. Indoor and outdoor temperature, relative humidity, wind speed and direction are also measured periodically using thermal couples, a hygrometer and an anemometer. Data recorded on the data logger are then transmitted via a telephone line to the VAX machine for later analysis. The system diagram is illustrated in Fig. 3.

A constant emission rate tracer gas method is used to simulate the operation of a stove. Tracer gas CH4 is injected at a constant rate at the location of the stove. The injection continues for three to four hours to permit the CH4 concentration levels at all sampling locations to reach the steady state values. After the injection stops, measurement of the decay is continued for another 2–3 h. No mixing fan is used during both injection and decay.

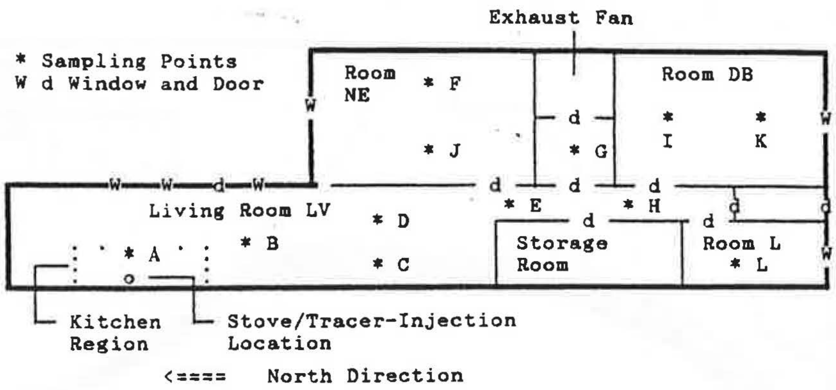

Fig. 2. Testing floor plan.

Several tests have been conducted under the following conditions:

- forced air system operation conditions: on/off
- interior door conditions: open/closed
- range hood operation conditions: on/off.

There are eight cases for the combination of the above three conditions; tests for all of them were conducted during the winter season of 1988–1989.

TEST RESULTS

Figures 4–11 show the concentration of CH4 as a function of time for each location in the building. The lines on each graph have a general pattern of rise and decay. During the time of constant emission, contaminant concentration levels increase, more or less, for all locations; while during decay, the concentration levels decrease. Both of the processes exhibit an exponential behaviour. During the rise, the concentration level for each channel has large fluctuations. This is due to the high turbulence of the contaminant field [8].

The steady state concentration levels are different for the 12 channels. The concentration levels near the source are much higher and have larger fluctuations. The locations away from the source have more uniform concentrations, though there are still differences in the level of pollutant concentrations. The differences in the results are due to the contaminant migration, which depends upon the airflow field in the house. The conditions of the forced air system, the interior doors and the hood, and the conditions of the indoor/outdoor climate affect the airflow. Detailed analyses of the concentration level differences and their implications on the air movement and contaminant migration patterns were presented [1].

The contaminant concentration level in a room is a statistical variable [9, 10], and is influenced by microscopic fluctuations as well as macroscopic variables, such as sudden airflow pattern changes due to fluctuations in outdoor conditions. The concentration curve for each location can be considered as two segments: the rise during emission and the decay after emission was shut off. The rise part can be fitted by:

$$C_i^r(t) = C_i^r(1-e^{-a_i t})+B, \qquad (4)$$

where: C_i^r = the steady state concentrations during injection; a_i = the exponents; B = the background or outdoor concentration level; t = the time passage, $t = 0$ when injection starts.

The room average steady state concentration (total CH4 over the room volume) depends on the CH4 generation rate and the total effective ventilation rate. The local $C_i^r(t)$, however, might differ from each other. The exponent a_i indicates how fast the steady state value is reached, that is, how quickly the emitted CH4 reaches a location. Since the distances from the sampling points to the source are different, the rate of increase of $C_i^r(t)$ is generally different. The airflow pattern, which is affected by outdoor conditions and local exhausts and partitions, influences the value of exponent a_i.

The concentration of CH4 during the decay period can be represented as:

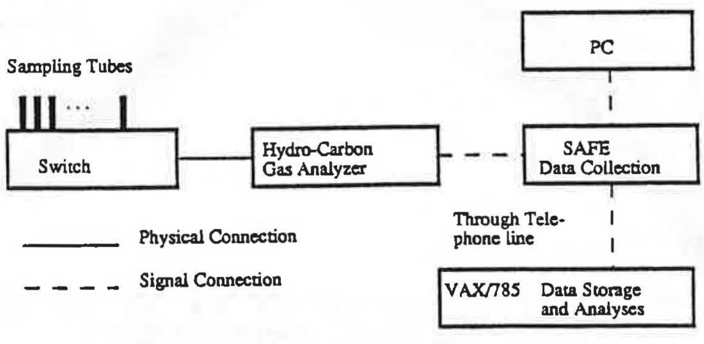

Fig. 3. Monitoring system diagram.

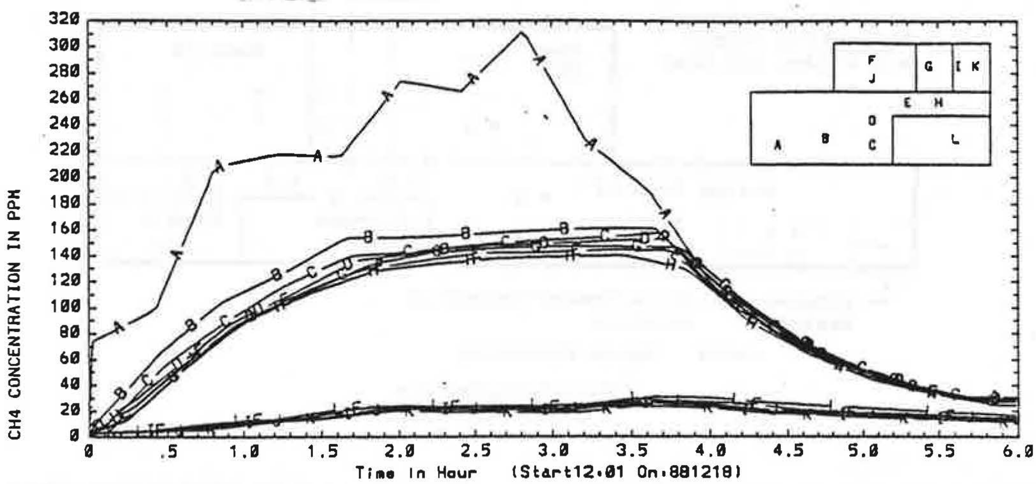

Fig. 4. Forced air off, door closed and hood off.

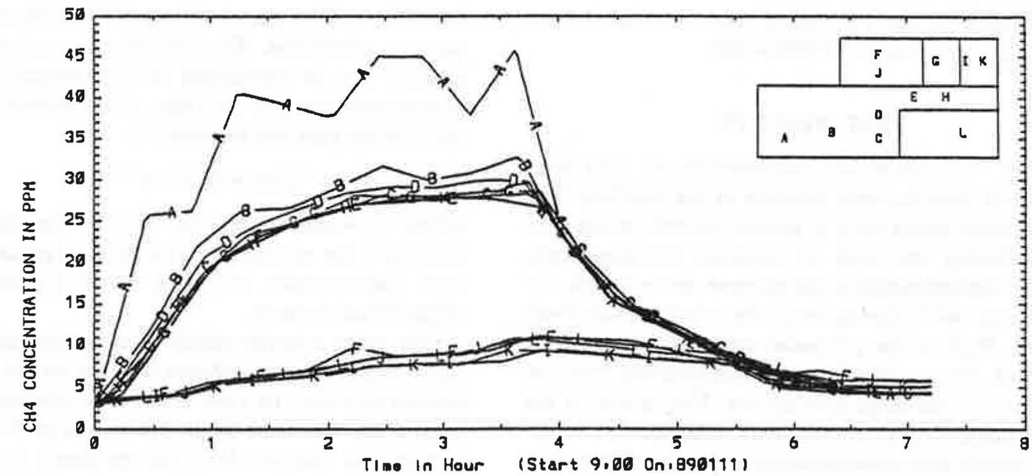

Fig. 5. Forced air off, door closed and hood on.

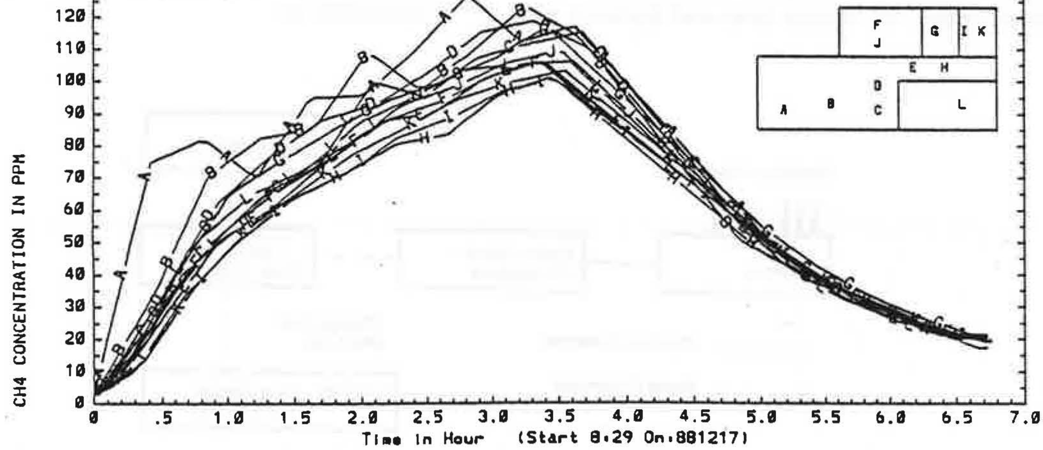

Fig. 6. Forced air off, door open and hood off.

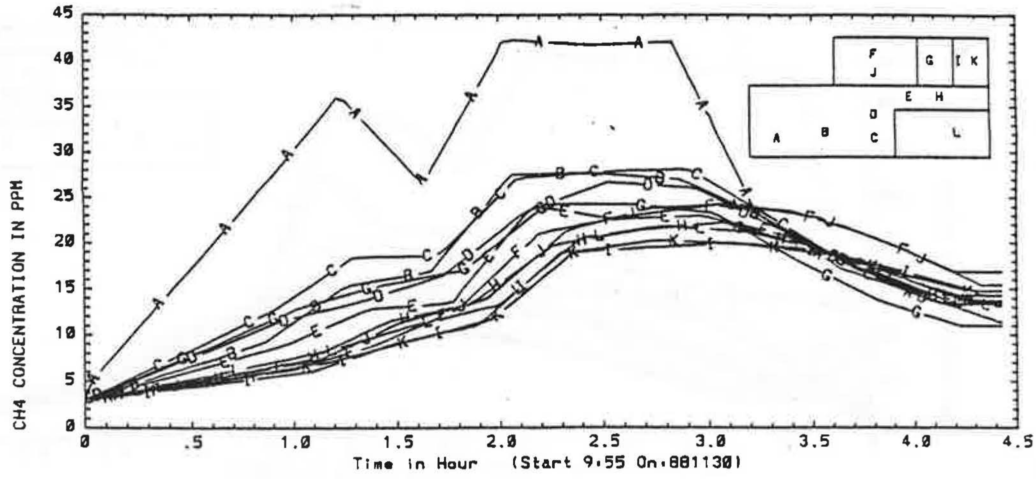

Fig. 7. Forced air off, door open and hood on.

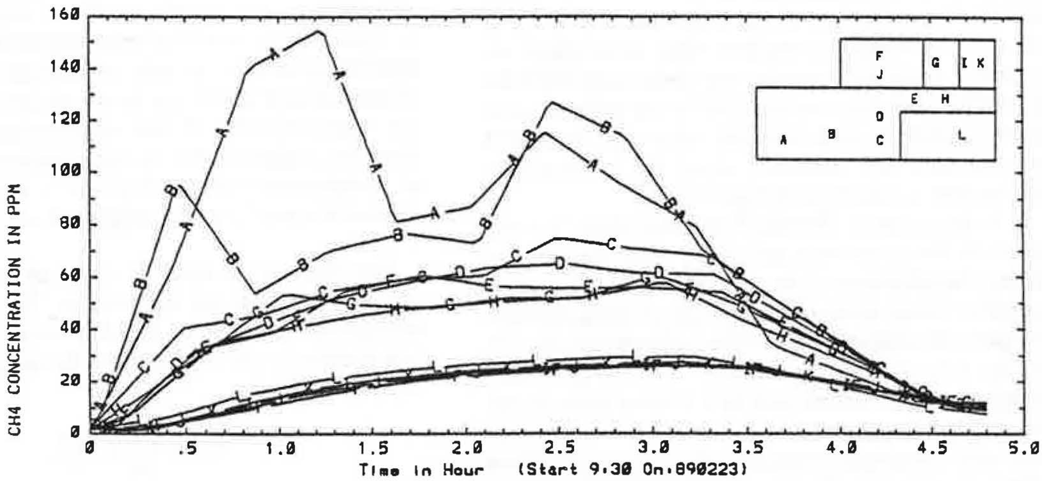

Fig. 8. Forced air on, door closed and hood off.

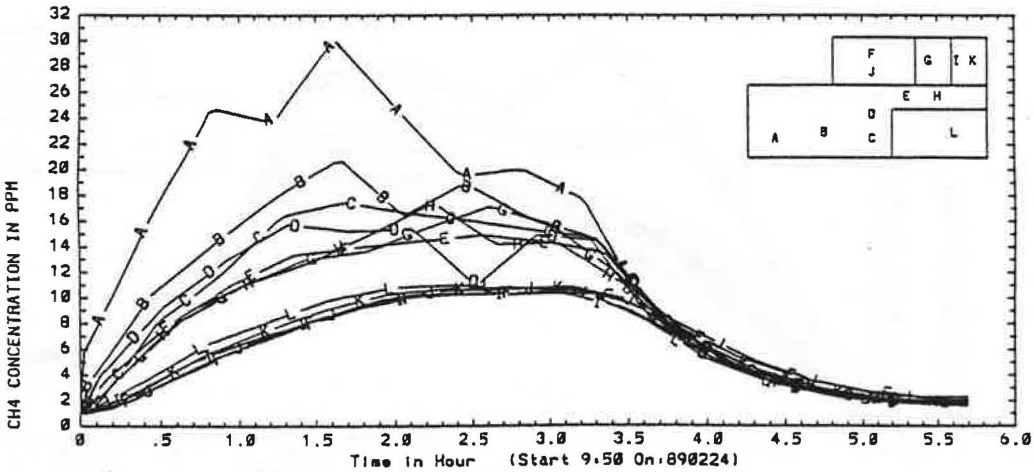

Fig. 9. Forced air on, door closed and hood on.

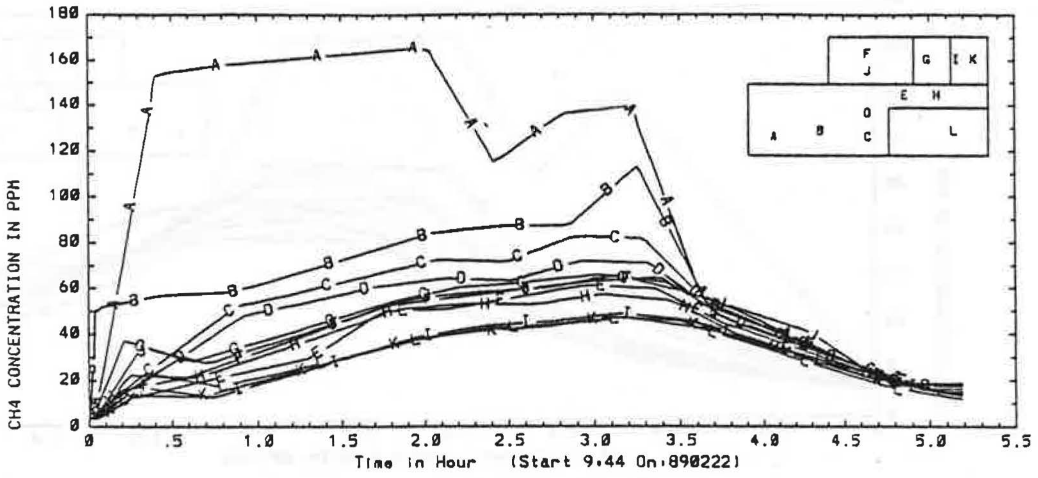

Fig. 10. Forced air on, door open and hood off.

$$C_i^d(t) = C_i^d e^{-b_i(t-t_s)} + B, \quad (5)$$

where: C_i^d = the magnitude of decay; b_i = the decay exponent; t_s = the time when emission source was shut off. C_i^d is the concentration level when decay starts, i.e. at time t_s. Since the concentration levels in the room are different at that time and the CH4 in the room tends to be mixed after emission stops, the value of C_i^d for a given location does not necessarily equal the concentration level at time t_s calculated by equation (4).

It is important to distinguish between these two segments of the curve—rise and decay. The rise part represents the behaviour of the contaminant field caused by the point source, hence the parameters of fitting equation (4) show the characteristics of the build-up and dilution of the non-uniform contaminant. During the decay period, since the contaminant field is more uniform and follows the air movement in the space, the contaminant removal is the same as room air replacement. In addition, equations (4) and (5) have different interpretations. Equation (4) is only a fitting of the rise of concentration during the emission period. It does not assert that the behaviour of the concentration during the rise is exponential. This can be justified by the analytical solution of two-compartment models [5, 8] in which one room is considered to consist of two compartments, and the concentration levels in both compartments, as a result of contaminant generation in one of the compartments, are superpositions of two exponential constituents. However, equation (5) is a representation of the decay of concentration whose behaviour is exponential. The values for a_i and b_i of all the eight tests are listed in Table 1.

The exponent of equation (5) is an indicator of the efficiency of room air replacement. The aggregate, or average value, represents the effective air exchange rate and is equal to the reciprocal of the average age of the room air. That is:

$$\langle b \rangle = \frac{1}{\langle \tau \rangle} = \frac{Q_{\text{eff}}}{V}, \quad (6)$$

and:

$$Q_{\text{eff}} = \langle b \rangle V, \quad (7)$$

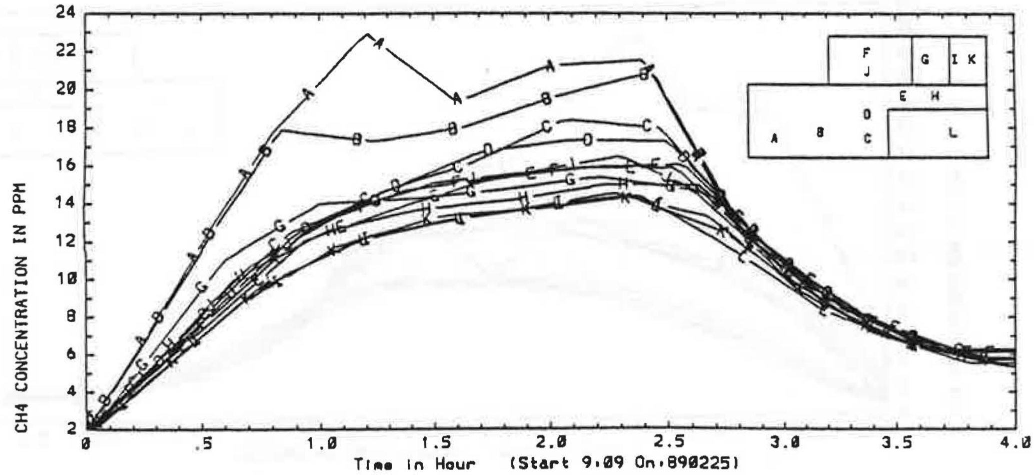

Fig. 11. Forced air on, door open and hood on.

Table 1. Value for a_i and b_i

ForceAir		Off				On			
Door		Close		Open		Close		Open	
Hood		Off	On	Off	On	Off	On	Off	On
Date		D18	J11	D17	N30	F23	F24	F22	F25
Test #		1	2	3	4	5	6	7	8
	A	0.99	1.36	0.98	1.14	0.89	1.42	3.66	1.80
	B	1.26	1.13	0.84	0.83	0.71	1.40	0.96	1.74
	C	1.05	1.12	0.77	0.87	1.13	1.41	0.99	1.31
	D	1.00	1.17	0.80	0.80	1.20	1.81	1.05	1.51
	E	1.02	1.15	0.77	0.78	1.33	1.45	0.80	1.49
	F	0.87	0.86	0.77	0.55	0.83	1.05	0.95	1.70
a_i	G	1.00	1.12	0.78	0.85	1.18	0.99	1.17	2.12
	H	1.05	1.14	0.76	0.62	1.12	0.96	0.99	1.70
	I	0.65	1.01	0.76	0.59	0.88	1.09	0.77	1.47
	J	0.50	0.70	0.77	0.55	0.84	1.06	1.00	1.54
	K	0.63	0.70	0.77	0.54	0.87	1.07	0.76	1.55
	L	0.66	0.66	0.84	0.56	1.06	0.89	0.93	1.49
	A	0.85	1.04	0.63	0.89	1.49	1.08	1.10	1.29
	B	0.83	0.99	0.61	0.57	1.56	1.02	1.05	1.22
	C	0.84	0.95	0.62	0.66	1.51	1.12	0.92	1.13
	D	0.84	0.98	0.63	0.61	1.45	1.12	0.88	1.10
	E	0.83	0.96	0.58	0.49	1.38	1.12	0.85	1.07
	F	0.36	0.36	0.59	0.33	0.72	1.14	0.88	1.07
b_i	G	0.86	0.99	0.60	0.73	1.40	1.08	0.87	1.16
	H	0.85	0.98	0.61	0.44	1.32	1.05	0.84	1.14
	I	0.40	0.43	0.59	0.27	0.80	0.98	0.78	1.01
	J	0.35	0.36	0.62	0.38	0.73	1.16	0.94	1.09
	K	0.39	0.41	0.60	0.30	0.87	1.02	0.75	1.03
	L	0.32	0.44	0.60	0.42	1.14	0.88	0.85	1.04
		0.84	0.98	0.61	0.51	1.20	1.06	0.89	1.11

where Q_{eff} is the effective ventilation rate, that is, the ventilation rate that actually participates in removing the uniform contaminant from the space of volume V. When complete mixing occurs, it is equal to the ventilation rate—air volume entering or leaving the space per unit time.

REMOVAL EFFECTIVENESS AND EFFICIENCY

Equation (5) has different parameters from those of equation (4), due to non-uniformity of the contaminant in the first part of the test and the uniformity in the second part. In order to examine this difference, the steady state concentration of the first part is considered in the following discussion.

Assuming the generation rate of CH4 is uniform in the space, then the concentration in the space represents the room air replacement and has the same exponent as the decay part. Thus, the hypothetical CH4 concentration is uniform in the space and can be expressed as a function of time:

$$C^*(t) = C^*(1-e^{-\langle b \rangle t})+B, \tag{8}$$

where: C^* = the steady state concentration; $\langle b \rangle$ = the aggregate exponent in decay; B = the background (outdoor) concentration. The steady state concentration can be expressed as:

$$C^* = \frac{F}{Q_{eff}} = \frac{F}{\langle b \rangle \cdot V}, \tag{9}$$

where F is the total generation rate of CH4.

The steady state concentration of equation (9) is obtained by assuming a uniform generation and distribution of the contaminant, it is generally different from the values calculated by equation (4). The ratio:

$$\mu_i = \frac{C^*}{C_i^r} = \frac{F/\langle b \rangle V}{C_i^r}, \tag{10}$$

indicates the difference due to non-uniformity of contaminant concentration and the effects of local removal. When the average steady state concentration from the test is used, the aggregate value can be obtained as:

$$\mu = \frac{C^*}{\langle C^r \rangle} = \frac{F/\langle b \rangle V}{\langle C^r \rangle} = \frac{F}{V\langle b \rangle \langle C^r \rangle}, \tag{11}$$

where $\langle C^r \rangle$ is the volumetrically weighted average concentration in the space at steady state, during the rise period.

For a given contaminant generation rate, the value $1/\langle C^r \rangle$ indicates how effectively the non-uniform contaminant is removed, while the value $1/C^*$ is an indication of the air distribution efficiency in the building. The ratio $\mu = \{1/\langle C^r \rangle\}/\{1/C^*\} = C^*/\langle C^r \rangle$ is thus the relative effectiveness of the non-uniform contaminant removal with respect to the given room air replacement rate. Therefore, this ratio given by equation (11) is called "relative removal effectiveness". It can be understood as the relative effectiveness of removing the contaminant to the removal of room air in the building, if the room air is considered as a contaminant. 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

Table 2. Contaminant removal effectiveness

ForceAir	Off				On			
Door	Close		Open		Close		Open	
Hood	On	Off	On	Off	On	Off	On	Off
Date	D18	J11	D17	N30	F23	F24	F22	F25
Test #	1	2	3	4	5	6	7	8
μ	0.74	3.68	0.90	4.70	0.83	3.68	0.92	3.26
β	80%		81%		76%		72%	
Ti–To	29.7	31.0	33.5	18.7	25.7	30.5	17.8	29.3
V	8.39	18.8	11.9	15.3	14.5	10.6	10.6	4.9
D	W	ENE	NNE	ESE	N	NNE	W	NNW

Note: V is the wind speed (mph); D is the wind direction.

slowly than the old air is being replaced by fresh air, the μ value would be less than unity.

The μ values for eight tests are listed in Table 2. They vary considerably from test to test. The calculations were carried out according to equation (11). Derivation of the μ value for test 1 is presented here to show the calculation procedure. In this test, the forced-air system and range hood are not in operation and the interior doors are closed. The values for $\langle b \rangle$ and $\langle C_r \rangle$ are based on the fitting results [equations (4) and (5)] of the sampling locations in the living room (locations A, B, C, D, E, G and H of Fig. 2); $\langle b \rangle = 0.84\ \text{h}^{-1}$ and $\langle C^r \rangle = 177.8$ ppm. The volume of relevant space V is 165 m^3, and the emission rate F is 304 cm^3 min^{-1}. Substituting these values in equation (11) yields:

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

$$= \frac{(304\,\text{cm}^3\,\text{min}^{-1})}{(165\,\text{m}^3) \times (0.84\,\text{h}^{-1}) \times (177.8\,\text{ppm})}$$

$$= \frac{(304 \times 10^{-6}/60\,\text{m}^3\,\text{s}^{-1})}{(165\,\text{m}^3) \times (0.84 \times 1/3600\,\text{s}^{-1}) \times (177.8 \times 10^{-6})}$$

$$= 0.74.$$

From Table 2, it can be seen that the μ values for all tests without the hood in operation are less than unity. The contaminant, which is not uniformly mixed with the room air, is removed at a rate less than that of the room air. Also, the μ values for tests with the hood in operation are much higher than when it is not. Since the hood removes the contaminant directly from the source before mixing takes place, the rate of overall removal is very high. This indicates that the range hood as a direct removal device is a very effective means for contaminant control. Furthermore, the forced air system operation affects the μ value to some extent. Since the forced air is circulating the air in all four rooms (LV, DB, NE and L), it tends to make the mixing faster and more complete. Thus, when the hood is not in operation, the contaminant is removed in a manner like the room air, and the μ values are closer to unity (tests 5 and 7 comparing to 1 and 3). While the hood is in operation, the better-mixing (due to the forced air system) results in less contaminant being directly removed by hood, and consequently decreases the μ values (tests 6 and 8 as compared to 2 and 4).

The relative effectiveness gives an overall measure of contaminant removal in the room, and the effect of local exhaust is implicitly accounted for by μ. However, when the efficiency of the local exhaust is to be known, one is interested in the percentage of the total generated contaminant which is removed by the exhaust before it is mixed with the room air. This percentage is defined as the "removal efficiency". In Fig. 12, of the total contaminant generated F, an amount of F_e is directly removed by the local exhaust before mixing, and only an amount of F_m migrates to the room and mixes with the room air ($F = F_e + F_m$). The removal efficiency in this case is defined as:

$$\beta = F_e/F \times 100\% = (1 - F_m/F) \times 100\%. \quad (12)$$

The physical meaning of this removal efficiency is obvious. In the following, the relationship between β and the previously defined μ is presented.

Two features of μ are important for deriving β from μ. First, the μ value indicates the relative rate of contaminant being removed with respect to the rate of the room air replacement. It depends on the airflow patterns in the room, rather than the absolute amount of the airflow. Thus, the value of μ does not change significantly when other parameters remain unchanged. Second, the hood causes a suction of air and directly removes a large portion of the generated contaminant. The suction may also change, to some extent, the airflow patterns in its vicinity. However, considering the relatively low flow rate of the hood as compared to the (natural) ventilation rate, the change is minimized. Therefore, the hood operation can only result in the direct removal of the β percentage of contaminant F_e, it does not affect the dispersion of the mixing part of the contaminant F_m in the space, thus the relative removal effectiveness of the F_m remains the same as that without the hood in operation.

Let us consider two tests, A and B, with same con-

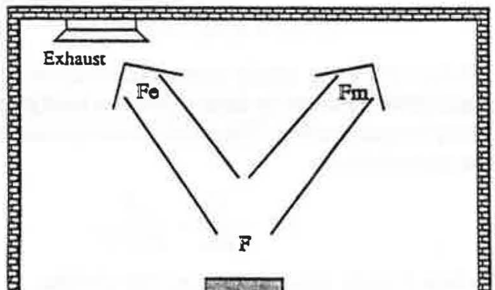

Fig. 12. Generation of contaminant in a room.

ditions except that one test is conducted without the hood in operation and the other with the hood in operation (the climatic conditions might differ). The μ values for the two tests are μ_A and μ_B, respectively. For the second test (with hood in operation), the process of contaminant removal can be considered as consisting of two separate steps. One step is the direct removal of the F_e amount of the contaminant through the hood; the other step is that the F_m part of the contaminant is mixed with the room air and is eventually carried away with the natural ventilation.

From equation (11), the μ value of the overall contaminant removal in test B can be written as:

$$\mu_B = F/(V\langle b\rangle_B\langle C^r\rangle_B), \tag{13}$$

where the subscripts indicate the corresponding test. The μ value for the removal of the mixed part of the generated contaminant in test B is equal to:

$$\mu'_B = F_m/(V\langle b\rangle_B\langle C^r\rangle_B). \tag{14}$$

According to the two features of the μ term, μ'_B should be the same as the μ value for test A. Therefore:

$$\mu'_B = \mu_A. \tag{15}$$

The contaminant generation can now be deduced from equation (14) and (15) as:

$$F = \mu_B V\langle b\rangle_B\langle C^r\rangle_B, \tag{16}$$

and:

$$F_m = \mu'_B V\langle b\rangle_B\langle C^r\rangle_B = \mu_A V\langle b\rangle_B\langle C^r\rangle_B. \tag{17}$$

By applying equation (12), the removal efficiency can be derived as:

$$\beta = 1-\mu_A/\mu_B. \tag{18}$$

The β term indicates the percentage of contaminant removed by the local exhaust. It has been shown that β can be calculated from the results of two tests; with the hood in operation and without it. The four values of β for the eight tests are listed in Table 2. These indicate that the range hood is very effective in removing the contaminant; as in all cases almost three-quarters of the generated contaminant is removed by the hood prior to mixing, which explains the high values of μ for the test with the hood in operation. It is also noticed that the operation of the forced air system increases mixing in the room and decreases the direct removal by the hood, thus the values of β are smaller when the forced air system is in operation.

CONCLUSIONS

In this paper, two new terms have been defined to analyse the ability of the ventilation system to remove a contaminant generated from a point source in a building. The relative contaminant removal effectiveness shows the relative amount and rate of contaminant removal compared to the replacement of the room air. The definition of μ integrates the air-exchange efficiency and ventilation effectiveness. The removal efficiency is simply defined as the percentage of the contaminant removed by a local direct exhaust device near the source; and it can be obtained from the μ values for two test conditions. Both terms indicate the contaminant removal in the room/building of interests, when dealing with a point source. The μ term is an overall indicator, whereas the β term has a direct physical meaning. Although these two terms were used for the field measurements in a naturally ventilated building, they can be applied to both naturally and mechanically ventilated buildings to represent the ventilation effectiveness (see Fig. 1 for the application areas of the μ term).

Results of eight field tracer gas tests for combinations of three conditions are shown. The obtained μ and β values well explained the test situations.

Since these tests were originally designed for the understanding of the behaviour of room air movement and contaminant migration, they provide more information than what is required for the sole measurement of the terms μ and β. A simplified version of the test set-up could use a manifold to obtain the average concentrations. This new set-up will lead to a less complicated sampling system and fewer computational efforts. For mechanically ventilated buildings/rooms, fresh air supply may be chosen as the basis for the definition of μ. Thus, in equation (11), the $\langle b\rangle$ term can be replaced by the reciprocal of the nominal time constant $1/\tau = Q/V$. In this way, the μ value indicates the relative effectiveness of contaminant removal for a given air supply.

In the proposed procedure, it was assumed that the ventilation rates remain constant during the period of the test (rise and decay). However, in naturally ventilated buildings, the ventilation rate is a function of indoor and outdoor environments. Therefore, to improve the accuracy of the results, it is recommended that two tracer gases be used simultaneously.

Acknowledgement—We wish to express out thanks to the National Research Council of Canada and "Fonds pour la Formation de Chercheurs et l'Aide a la Recherche" which funded this study through the NSERC and FACAR grants, and to Gaz Metropolitain inc. of Montreal for provinding the house (MEGA). Thanks are also due to Mr. J Payer for his help in the installation and the calibration of measurement systems.

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