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ABSTRACT

MEASUREMENT OF AIR EXCHANGE RATE OF RESIDENTIAL HOUSES,
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Distribution of air infiltration rates and their determinant factors were sought. The air infiltration rate were measured in 501 house units selected from Greater Boston area using standard area probability sampling method in winter 1985. Perfluorocarbon tracer-gas sources (PFT) and passive charcoal collectors (CAT) were used. The air infiltration rates ranged from 114 m^3/hr to 1456 m^3/hr with the mean and standard deviation being 347 (m^3/hr) and 205 (m^3/hr). The mean and standard deviation of air exchange rates calculated from the air infiltration rate and house volume were 1.57 (1/hr) and 1.27 (1/hr) respectively. The air infiltration rates were explained by house volume, and percentages of implementation with window caulking, interior storm window and/or of floor covering with wood.

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MEASUREMENT OF AIR EXCHANGE RATE OF RESIDENTIAL HOUSES

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INTRODUCTION

Reduction of infiltration rates or air exchange rates is useful to save energy consumption for heating or cooling in homes. From the perspective of maintaining indoor air quality, however, too much reduction of the infiltration rate may cause adverse health effects by increasing exposures to certain air pollutants. Keeping moderate temperature in homes with less energy consumption while concurrently achieving lower levels of indoor air pollution has become a social demand. The distribution of the infiltration rate or the air exchange rate of residential houses is not well known.

The tracer-gas method is one of the techniques to measure the infiltration rate. By knowing the amount of tracer-gas discharged in a house and the difference of tracer-gas concentrations inside and outside of the house, the infiltration rate can be calculated from mass balance equations. The validity of the calculation is dependent upon uniformity of the tracer-gas concentrations indoors and outdoors. If this is not so, the house can be divided into several zones such that the uniformity requirement is satisfied in each. The infiltration rate is obtained differentially or integrally in this technique. In the differential method, sometimes called the decay method, the tracer-gas is discharged within a short period and its decay rate is measured. The time constant of the change in tracer-gas concentrations gives the air exchange rate. When the tracer-gas is continuously discharged into the house at a constant rate, an mean infiltration rate is calculated from the tracer-gas concentrations and the emission rate. The air exchange rate is then obtained by dividing the infiltration rate by the house volume. The advantage of the tracer-gas method is that the infiltration rate is measured under activity conditions which are typical for the occupants. A disadvantage is the requirement for uniformity of tracer-gas concentration or complete mixing of the tracer-gas within a defined "mixing volume".

The residential air infiltration rate is determined primarily by several physical parameters: wind velocity and direction, an opening of the building envelop and the indoor/outdoor temperature difference across the building envelop. These factors are modified by house structure and human activities, such as closing and opening of windows and doors, and use of combustion appliances and vents. Therefore, the air infiltration rate will vary among homes, as well as within a home, with time. The mean air infiltration rate over a period of weeks to months is the most representative of long term conditions when considering energy consumption and impacts of indoor air pollution.

This paper presents the results of the infiltration measurements carried out in winter in greater Boston area. Perfluorocarbon tracer-gas sources (PFT) and passive charcoal collectors developed by Dietz et. al. (1) were used. The relationship of the infiltration rate with the house characteristics is also reported.

METHODS AND MATERIALS

The subject houses were selected from Greater Boston area using standard area probability sampling to allow extrapolations of survey sample results to the larger population. Details of the sample selection procedures are described elsewhere (2). Measurements of the air infiltration were carried out in January 1985 through May 1985.

Two types of tracer-gases, perfluoro-monomethyl-cyclohexane (PMCH) and perfluoro-dimethyl-cyclohexane (PDCH), were used in this study. These gases were released in a house through permeation tube capsules whose emission rates were gravimetrically measured prior to the study. Several capsules of PMCH emission source were placed in a kitchen and several PDCH capsules were set in various locations in the house. The number of the capsules used in each house was determined according to the house volume. Tracer-gases were passively sampled by activated charcoal (Ambersorb 347) in capillary absorption tubes (CAT) placed in kitchen, living room and bedrooms. After exposing CATs to indoor air for two weeks, the amount of the adsorbed tracer-gas was analyzed with a GC/ECD following the procedure reported by Dietz et al. (1). The tracer-gas concentrations were calculated from the amount of the adsorbed gas and the tracer-gas sampling rate of CAT.

Home characteristics, such as home type, heating system and fuel, cooking and water heating fuels, ventilation, and occupants activities, were asked using the home characteristics questionnaire.

RESULTS AND DISCUSSION

Among 501 house units visited by technicians, the tracer gas concentrations were monitored for two weeks in 424 house units. PMCH and PDCH concentrations were successfully measured in 352 and 390 houses respectively. In 346 houses both of PMCH and PDCH concentrations could be measured. The mean PMCH concentration of 352 houses and its standard deviation were 23.0 ppt and 12.3 ppt with minimum and maximum concentrations of 2.7 ppt and 58.9 ppt. The mean and the standard deviation for PDCH were 16.4 ppt and 10.7 ppt with the minimum and maximum concentrations of 2.5 ppt and 67.7 ppt. When the sum of PMCH and PDCH concentrations was considered as one tracer-gas, the average of PMCH plus PDCH was 37.7 ppt with the standard deviation, minimum and maximum concentrations being 18.0 ppt, 6.6 ppt and 105.9 ppt respectively. All raw concentration data were used for further analysis in this paper, although some low concentration data were below the reliable detection limit.

The air infiltration rates were calculated based upon a mass balance model as follows:

$$F\ (m^3/hr) = \frac{S\ (nl/hr)}{C_{av}\ (nl/m^3 \text{ or ppt})}$$

Here, F (m^3/hr), S (nl/hr) and C_{av} (nl/m^3 or ppt) are the air infiltration rate, tracer-gas discharging rate and average tracer-gas concentration, respectively. The physical meaning of this equation was discussed in elsewhere (3).

As shown in Table 1, the air infiltration rate measured by the PMCH tracer-gas ranged from 126 m^3/hr to 1717 m^3/hr with the mean and standard deviation being 396 m^3/hr and 265 m^3/hr. When the PDCH tracer-gas was used, the air infiltration was distributed from 41 m^3/hr to 2175 m^3/hr with the mean and standard deviation of 299 m^3/hr and 235 m^3/hr. The air infiltration rate obtained from the sum of PMCH and PDCH concentrations ranged from 114 m^3/hr to 1456 m^3/hr as shown in Figure 1 and displayed a heavy tail. Their mean and standard deviation were 346 m^3/hr and 205 m^3/hr, respectively.

The air exchange rates were calculated from the air infiltration rates by dividing by the house volume. The means of the air exchange rates were 1.79, 1.36 and 1.57 for PMCH, PDCH and PMCH plus PDCH tracer-gases as shown in Table 2. The frequency distribution of the air exchange rates calculated from the sum of PMCH and PDCH tracer-gas concentrations is shown in Figure 2. The distribution of the air exchange rate was skewed toward high exchange rate.

The air infiltration and exchange rates determined by PMCH tracer-gas were higher than those obtained with PDCH tracer-gas. The air infiltration and exchange rates given by the sum of PMCH and PDCH concentrations were between those by PMCH and PDCH. This came from the fact that the concentration gradient of the PMCH plus PDCH tracer-gases within the house unit was the smallest. The sum of PMCH and PDCH is considered to give the better estimate of the air infiltration and exchange rates (3). For further analysis, the air infiltration rates based upon the sum of PMCH and PDCH were used.

The characteristics of the subject house unit were investigated with the house characteristics questionnaire having 154 questions. These questions were categorized into 5 groups; 1) setting and home type; 2)heating system and fuels; 3)cooking and water heating fuels; 4) ventilation; and 5) participants.

Determinant factors of the air infiltration rates were sought by using stepwise multiple regression analysis. Among the 154 questions, several factors were selected as potential determinant factors from the preliminary analysis. These factors were house volume, implementation of permanent and seasonal energy conservation measures and floor covering materials. For example, the extent of these device implementation was asked by following questions:

> Check off which of the following permanent or seasonal energy conservation devices are present? How extensively have they been implemented? (For example, of all the places they could be installed, what percentage of the place have them?)

Percentages of implementation with interior storm window, vestibule, window caulking, door caulking, exterior storm door, and of floor coverings with wood as well as house volume were used as potential independent variables for the step wise regression analysis.

As shown in Table 3, house volume and percentages of window caulking and wood floor coverings were selected as explanatory variables for the air infiltration rates. Regression coefficient of the house volume was a positive number. The house volume may indicate area of a house envelop, such as wall and roof. The percentage of window caulking had a negative regression coefficient of -0.92. This implies that reduction of the air infiltration rate by 92 (m^3/hr) is expected if all of the windows are caulked. Floor covering with wood increases the air infiltration rate. This may be due to narrow gap of wood floor. The regression equation was statistically significant but the multiple correlation coefficient was relatively small (R=0.352).

When the subject houses were divided in single-family and multi-family houses, the same statistical procedure was applied to each group separately. The air infiltration rate of the single-family houses was related to the house volume and the percentages of window caulking and interior storm window. The multiple correlation coefficient was improved to R=0.446. The regression coefficients of the house volume and percentage of window caulking were similar to the previous equation. The percentage of floor covering with wood was not selected in single-family houses, while the percentage of storm window was selected with a negative regression coefficient. The negative coefficient implies that the more storm windows are installed, the larger air infiltration rates are expected. This is conflict with physical effect of the storm window. There may be some confounding factors.

For the multi-family house, explanatory power of the regression model was small (R=0.193). The house volume was selected as only one independent variable. This may be due to variety of house unit settings.

CONCLUSION

The air infiltration rates measured with PMCH and PDCH tracer-gases ranged from 114 m^3/hr to 1456 m^3/hr with the mean and standard deviation being 347 (m^3/hr) and 205 (m^3/hr). The mean and standard deviation of air exchange rates were 1.57 (1/hr) and 1.27 (1/hr) respectively. The air infiltration rates were explained by house volume, and percentages of implementation with window caulking, interior storm window and/or of floor covering with wood. The air infiltration rates of a single-family house could be predicted with several parameters of the house characteristics, while prediction power for multi-family house was low.

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2) P. B. Ryan, M. L. Soczek, J. D. Spengler and I. H. Billick, "The Boston residential NO_2 characterization study: I. Preliminary evaluation of the survey methodology", JAPCA. 38:22 (1988)
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Table 1 Air infiltration rate

Type of gas	Number of data	Mean (m^3/hr)	Standard deviation (m^3/hr)	Minimum (m^3/hr)	Maximum (m^3/hr)
PMCH	327	396.0	264.9	125.6	1716.9
PDCH	356	299.7	235.2	41.1	2175.2
PMCH + PDCH	310	346.6	205.1	114.0	1455.7

Table 2 Air exchange rate

Type of gas	Number of data	Mean (1/hr)	Standard deviation (1/hr)	Minimum (1/hr)	Maximum (1/hr)
PMCH	292	1.79	1.69	0.27	13.14
PDCH	315	1.36	1.16	0.11	9.83
PMCH + PDCH	276	1.57	1.27	0.19	8.69

Table 3 Regression model for air infiltration rate

ALL HOUSES

Independent variables		Regression coefficients	
HOUSE VOLUME	(m^3)	0.35821	p=0.0000
WINDOW CAULKING	(%)	-0.92383	p=0.0015
WOOD FLOOR	(%)	0.82131	p=0.0398
(Constant)	(m^3/hr)	246.31670	p=0.0000
(Number of data = 259, R = 0.352)			

SINGLE FAMILY HOUSES

Independent variables		Regression coefficients	
INTERIOR STORM WINDOW	(%)	7.81567	p=0.0006
HOUSE VOLUME	(m^3)	0.29063	p=0.0091
WINDOW CAULKING	(%)	-0.98170	p=0.0227
(Constant)	(m^3/hr)	285.52952	p=0.0000
(Number of data = 127, R = 0.446)			

MULTI-FAMILY HOUSES

Independent variables		Regression coefficients	
HOUSE VOLUME	(m^3)	0.31251	p=0.0268
(Constant)	(m^3/hr)	253.73383	p=0.0000
(Number of data = 132, R = 0.193)			

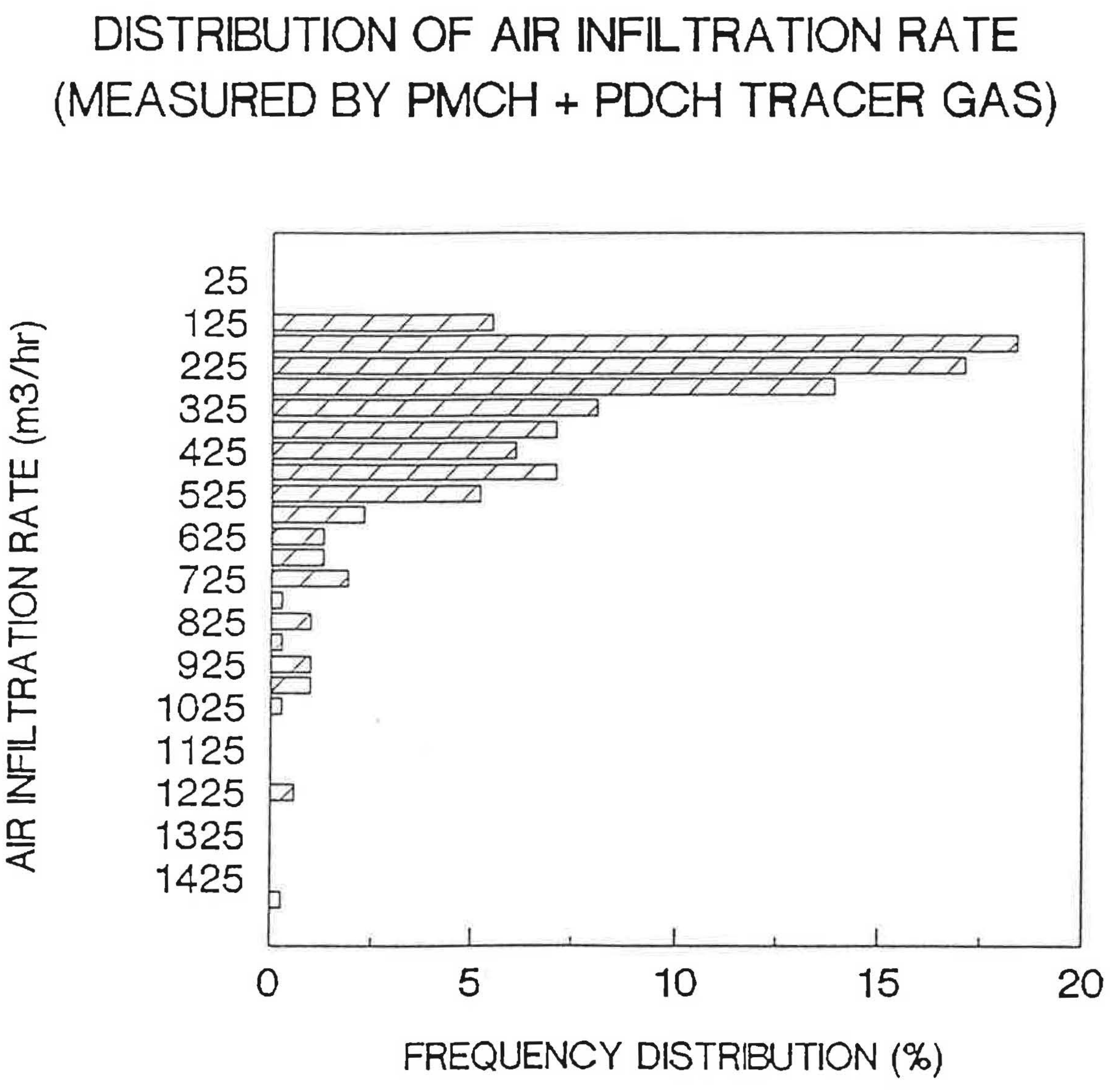
DISTRIBUTION OF AIR INFILTRATION RATE
(MEASURED BY PMCH + PDCH TRACER GAS)
AIR INFILTRATION RATE (m3/hr)
25
125
225
325
425
525
625
725
825
925
1025
1125
1225
1325
1425
0
5
10
15
20
FREQUENCY DISTRIBUTION (%)

Figure 1

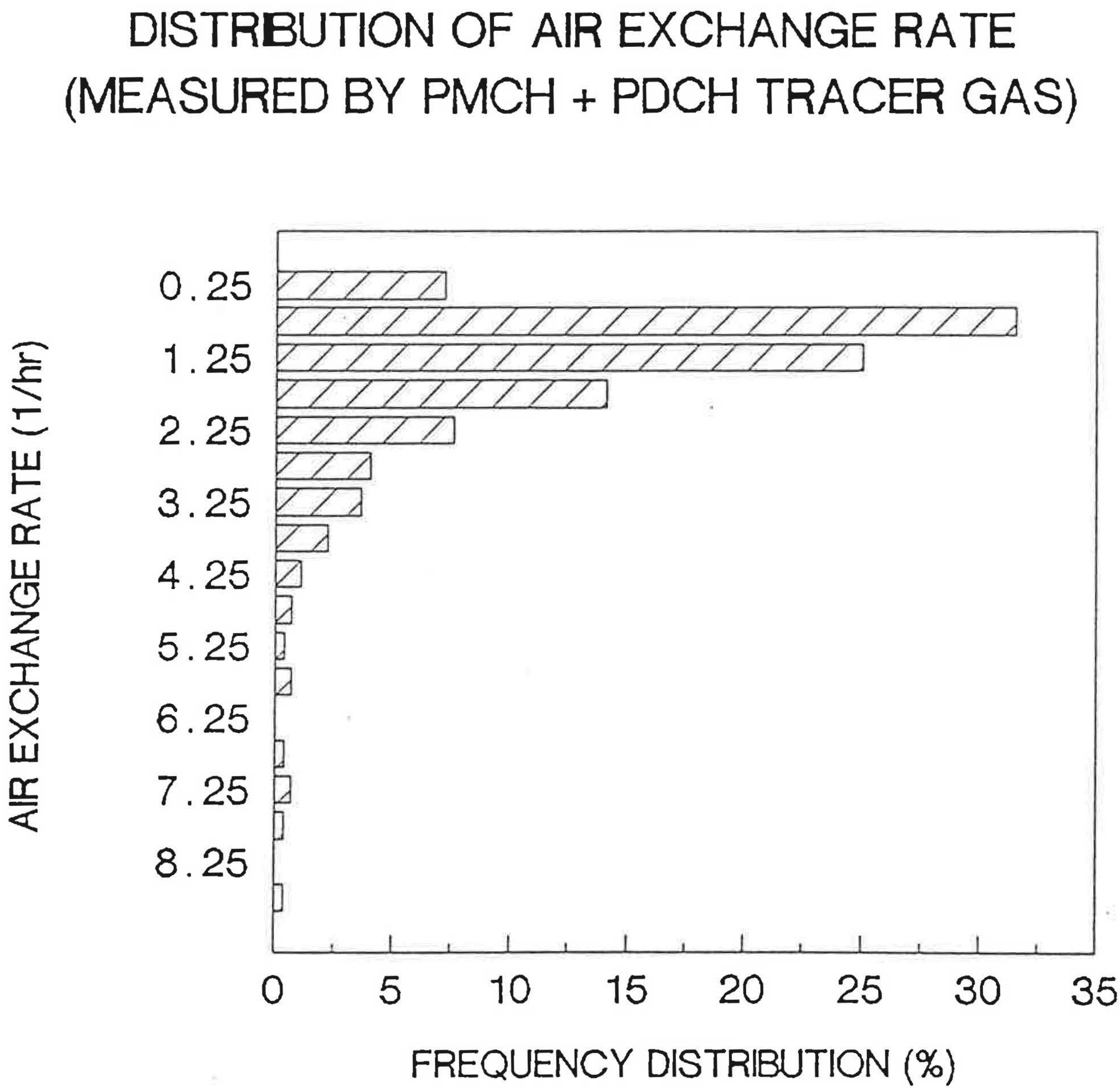
DISTRIBUTION OF AIR EXCHANGE RATE
(MEASURED BY PMCH + PDCH TRACER GAS)
AIR EXCHANGE RATE (1/hr)
0.25
1.25
2.25
3.25
4.25
5.25
6.25
7.25
8.25
0
5
10
15
20
25
30
35
FREQUENCY DISTRIBUTION (%)

Figure 2