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Shaw, C. Y.

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THE EFFECT OF MECHANICAL VENTILATION ON THE AIR LEAKAGE CHARACTERISTIC OF A TWO-STOREY DETACHED HOUSE

by

C.Y. Shaw

Division of Building Research, National Research Council Canada

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ABSTRACT

Air change rates were measured in a two-storey detached house with operation of various types of mechanical fresh-air ventilation systems. Four systems were studied, including two balanced systems (supply = exhaust) and two exhaust-only systems. The forced ventilation rate (supply or exhaust) was controlled at 0.15, 0.25, 0.4 or 0.5 air changes per hour. Expressions were developed for the test house relating the house air change rate under winter conditions to the forced ventilation rate and the infiltration rate due to wind and temperature difference.

Key Words: Air Leakage, Mechanical Ventilation, Residential, Measurement, Weather, Pressure

INTRODUCTION

The air change rate in a house has a major influence on energy consumption, indoor air quality and moisture problems. To investigate the effect of weather, airtightness, heating and ventilation systems on air change and air pressure distribution, a series of studies has been undertaken on the four detached two-storey houses of the Mark XI Energy Research Project co-sponsored by the Division of Building Research and the Housing and Urban Development Association of Canada (HUDAC)[1]. The air change rates and airtightness values measured for the four houses and a discussion on the effects of airtightness, wind and stack action on house air change have been reported[2,3]. The increase in house air change resulting from the operation of a natural-draft gas furnace has also been reported[4]. This paper discusses the interaction between house air change and the operation of mechanical ventilation systems.

Mechanical or forced ventilation systems are coming into increasing use in tight houses to provide outdoor air for controlling indoor humidity and improving indoor air quality. The ventilation systems can be classified as either balanced systems or exhaust-only systems. A balanced system consists of both a supply fan, which draws air into the house from the outdoors, and an exhaust fan, which exhausts an equal amount of indoor air to the outside. An exhaust system consists of only an exhaust fan.

In sizing a mechanical ventilation system, air infiltration or natural ventilation is often neglected. As a result, the house air change rate under the combined action of mechanical ventilation and weather often exceeds the design fresh air requirement, causing an unnecessary increase in energy consumption[5]. The objectives of the current study are to promote better understanding of the influence of mechanical ventilation on the house air leakage characteristic, and to develop an expression for estimating the house air change rate under winter conditions.

TEST HOUSE AND MECHANICAL VENTILATION SYSTEMS

The test house (H2) is a two-storey detached house with a full basement, located in a developed residential area in the city of Gloucester, Ontario. The house has a forced-air heat distribution system with an electric furnace. The volume of the house, including basement, is 386 m^3 (13,633 ft^3). The airtightness value of this house was 79.7 L/s at 10 Pa (169 cfm at 0.04 in. of water) or 0.033 m^2 (0.355 ft^2) in terms of equivalent leakage area[1,2].

One supply and two exhaust systems were installed in the house. The supply fan brought outdoor air into the house through an intake located in the south wall of the basement and discharged it into the return duct of the forced-air heating system. The two exhaust fans both drew air from the basement: one discharged it through a duct in the south wall of the basement and the other discharged it through a duct projecting through the roof. The flow rate of the fans could be controlled with a manual damper from 0 to 55 L/s (0 to 116 cfm) or 0 to 0.5 air changes per hour (ac/h). The damper was installed in the air duct downstream of the fan.

The three fans were used in the four system configurations shown in Figure 1.

Balanced Systems

System I—supply through basement wall and exhaust through roof

System II—supply and exhaust both through basement wall

Exhaust-Only Systems

System III—exhaust through roof

System IV—exhaust through basement wall

The four configurations were selected to determine the difference in performance of balanced and exhaust-only systems; and to illustrate the possible effect of exhaust opening location on the ventilation characteristic.

MEASUREMENT METHODS

The air change rate of the house was measured using the tracer gas decay method with N_2O (nitrous oxide) as the tracer gas. The gas was injected into the forced-air heat distribution system, and air samples were collected from the same system. The furnace fan was operated continuously during a test to mix the tracer gas with the indoor air. N_2O concentrations were measured with an infrared gas analyzer which was located inside the test house. A sample N_2O concentration versus time curve, for relatively high wind conditions, is given in Figure 2. The result indicates a straight line relationship between the logarithms of N_2O concentration and time. This suggests that adequate mixing has been achieved during the test. (The N_2O detector has been periodically calibrated using certified calibration gas. The calibration is linear within experimental error.)

The flow rate of the mechanical ventilation system was controlled at 0.15, 0.25, 0.4 or 0.5 ac/h during each test. Both the supply and exhaust flow rates were measured with a vane anemometer installed in the ductwork. The difference between the two flow rates during balanced operation was controlled within 5% of the set flow rate. The vane anemometer and duct assembly were calibrated against a laminar air-flow meter (Merian LFE Element, accuracy of 3% of measured flow rate) in the laboratory. No attempt was made to correct the flow rate of the supply air for outdoor air temperature, because such a correction is not normally made for actual installations. When an exhaust system was tested, the supply system was shut down and a metal cap sealed over the fan intake.

Inside and outside air temperatures, wind speed, and wind direction were recorded on a computer-based data logging system. Wind speed and direction were measured approximately 18 m (60 ft) above ground and about 10 m (33 ft) south of the house.

The indoor-outdoor pressure difference under calm conditions was measured across the north wall at four levels with a diaphragm-type pressure transducer (static error band of 5% full scale). The pressure probes were located at the head and sill of a ground floor window and of a second floor window directly above the first. Pressure readings were taken with and without mechanical ventilation, and with the vent openings sealed and unsealed while the mechanical ventilation was off.

TESTS AND RESULTS

The air change rates of the house were measured with and without mechanical ventilation. The four ventilation systems were tested in this manner during the 1981-82 heating season under a variety of weather conditions, with indoor to outdoor temperature differences ranging from 18 to 46 K (32 to 83 R) and with wind speeds up to 25 km/h (16 mph). Detailed house air change results are given in tables 1-5.

House Air Change Rate and Weather, No Mechanical Ventilation

The effect of indoor to outdoor temperature difference (stack action) and wind on house air change rate is shown in Figures 3a and 3b, respectively, under representative winter conditions. These results are similar to those obtained for two practically identical houses located on adjacent lots[3]. For these houses, the air infiltration rates were found not to vary significantly with temperature difference and wind during the cold winter months. The infiltration rate (I_o) of the test house under winter conditions was, therefore, assumed to be constant at a value of 0.26 ac/h.

House Air Change Rate and Weather, With Mechanical Ventilation

The effect of temperature difference and wind speed on house air change rate for System I (basement supply and roof exhaust) with a nominal forced ventilation rate of 0.5 ac/h is shown in Figures 4a and 4b, respectively. Figure 4 shows that the house air change rate increases with temperature difference for wind speeds up to 25 km/h (16 mph). It also shows that at moderate temperature differences, the house air change rate increases with wind speed. Figure 4b, however, shows that the influence of wind is considerably diminished in the presence of a large temperature difference. For comparison, a line representing the sum of the assumed constant infiltration rate and the imposed forced ventilation rate is shown in both figures. The measured air change rate is less than the sum.

The effect of temperature difference and wind on house air change rate for System II (basement supply and exhaust) is shown in Figures 5a and 5b, respectively. The results again indicate a stronger influence of temperature difference than wind on house air change rate. Figure 5 also shows the air change rates of System I for comparison. The two sets of house air change data are almost identical.

The house air change rates for Systems III and IV are plotted against temperature difference and wind in Figure 6a-d for two forced ventilation rates, 0.5 and 0.25 ac/h. The results show that at Q = 0.5 ac/h (Fig. 6a, b), the house air change rates under various weather conditions are nearly equal to the imposed forced ventilation rate. At the lower forced ventilation rates, however, Figures 6c and d indicate that the house air change rates are greater than the forced ventilation rate, but still less than the sum of I_o and Q.

In comparison with the results of the balanced systems, the house air change rate for the exhaust-only systems was relatively insensitive to both temperature difference and wind. This was especially true for the higher exhaust rates. Figures 6a and b also show that some of the measured air change rates were lower than the imposed forced ventilation rate because of the inaccuracy in tracer gas measurements, which was estimated to be about 10% of measured value[6] (Fig. 2).

<u>House Air Change Rate and Forced Ventilation Rate (Balanced Systems I and II)</u>

The air change rates measured under similar temperature differences are plotted against forced ventilation rates in Figure 7a and b for the two balanced systems. The simplest model relating the two parameters would be a linear relationship,

$$I = I_o + RQ$$

or

$$R = (I - I_o)/Q \tag{1}$$

where

I = house air change rate with mechanical ventilation, ac/h

I_o = house air change rate without mechanical ventilation, ac/h, assumed constant for cold winter months

Q = ventilation rate, ac/h

R = proportionality constant.

For comparison, the boundaries, $I = Q$ and $I = I_o + Q$, are shown in Figures 7a and b.

The values of R corresponding to various forced ventilation rates are plotted against temperature difference in Figure 7c, assuming a constant I_o. Because the two balanced systems produced almost identical house air change rates, their R values are plotted on the same graph. The figure shows that R and Δt can be represented by an equation of the general form

$$R = a\ (\Delta t)^b. \tag{2}$$

The constants a and b were determined by the method of least squares, which yields

$$R = 0.13\ (\Delta t)^{\frac{1}{2}} \tag{2a}$$

where Δt is in degrees Kelvin. (The constant 0.13 in Equation 2a should be replaced by 0.1 if Δt is in degrees Rankine.)

House Air Change Rate and Forced Ventilation Rate (Exhaust Systems III and IV)

Figure 8a and b shows the relationship between house air change rate and forced ventilation rate for the two exhaust-only systems. For comparison, the boundaries $I = Q$ and $I = I_o + Q$ are also shown. The figures indicate that for low forced ventilation rates, the house air change rate is greater than the corresponding forced ventilation rate but that the difference decreases as the forced ventilation rate increases. This suggests that as the forced ventilation rate increases, the area of building envelope undergoing air exfiltration due to weather factors, decreases. Beyond some forced ventilation rate (Q_c) only infiltration occurs across the envelope and, hence, the house air change is affected by the exhaust system only.

For $Q < Q_c$, the semi-logarithmic plots of I/I_o against Q in Figure 8c and d, and the boundary condition, $I = I_o$ at $Q = 0$, suggest that the house air change rate increases with forced ventilation rate according to the expression

$$I/I_o = \exp(a \cdot Q^b). \quad (3)$$

Using the least square curve fitting technique, the following equations were obtained:

$$I/I_o = \exp(1.31\ Q) \quad \text{for System III} \quad (3a)$$

$$I/I_o = \exp(2.61\ Q^2) \quad \text{for System IV.} \quad (3b)$$

For $Q > Q_c$, the house air change rate is equal to the imposed forced ventilation rate.

Pressure Difference Caused by Ventilation

The pressure difference across the north wall was measured at four levels on several calm days to gain a better understanding of the effect of the ventilation system on house pressure. These data were fitted to a straight line to determine the neutral pressure level (NPL). Figure 9a shows the measurements with Systems I and III for an indoor to outdoor temperature difference of 43 K (77 R); Figure 9b shows the measurements with Systems II and IV for a temperature difference of 30 K (54 R).

Curve 1 on Figure 9a and b shows that the neutral pressure level of the house before installation of the mechanical ventilation system was at about 3.4 m (11.2 ft) above grade. It also shows that operation of the balanced systems produced no major shift in NPL even though the house air change resulting from the combined action of mechanical ventilation and stack effect increased.

Curve 2 in Figure 9a and b, however, shows that the operation of the exhaust systems at a flow rate of 0.5 ac/h raised the NPL to about 5.5 m (18 ft) which is almost at the second storey ceiling level. As a result, air exfiltration across the house envelope almost ceased and the house air change rate equalled the exhaust rate.

The maximum pressure differential induced by the operation of the exhaust systems was about 10 Pa (0.04 in. of water) which is only slightly greater than the pressure differential acting on the house without mechanical ventilation. If the house were tighter, a greater pressure differential would be required to maintain the same exhaust rate, or the exhaust rate would be reduced. Therefore, the exhaust-only system may not be appropriate for tight houses unless a make-up air inlet is provided in the building envelope.

SUMMARY

1. The house air change rate with the balanced systems increases with forced ventilation rate and indoor-to-outdoor temperature difference; the house air change rate with the exhaust-only systems is controlled by the forced ventilation rate.

2. To provide the desired air change rate of 0.5 ac/h for the test house, an exhaust-only system would require a forced ventilation rate of 0.5 ac/h, whereas a balanced system would only require a forced ventilation rate of 0.3 to 0.4 ac/h.

3. For this house, the location of the exhaust outlets has less effect on the house air change rate with balanced systems than with exhaust-only systems.

4. If an exhaust-only system is to be installed in a tight house, it is desirable to provide a suitably sized air intake in the house envelope.

5. Under calm conditions, the house pressure distribution is unaffected by the operation of the balanced systems but is affected by the exhaust-only systems.

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TABLE 1 House air change rate - No mechanical ventilation

Date	ΔT (K)	V (km/h)	Θ	Supply (ac/h)	Exhaust (ac/h)	I (ac/h)
Jan 19	38.8	5.6	SSE	0	0	0.237
Jan 21	35.1	10.4	NW	0	0	0.275
Jan 26	42.5	9.4	WSW	0	0	0.278
Feb 24	32.8	13.3	WNW	0	0	0.243
Feb 25	32.9	17.9	WNW	0	0	0.264

ΔT = indoor air temperature - outdoor air temperature
V = wind speed
θ = wind direction
I = house air change rate with mechanical ventilation

TABLE 2 House air change rate with mechanical ventilation - System I

ΔT (K)	V (km/h)	Θ	Supply (ac/h)	Exhaust (ac/h)	I (ac/h)	R
38.4	11.6	ENE	0.150	0.146	0.367	0.730
42.0	13.9	WSW	0.150	0.150	0.405	0.973
37.3	22.5	WSW	0.257	0.250	0.447	0.743
31.1	13.4	WSW	0.248	0.252	0.451	0.768
38.9	13.9	WSW	0.249	0.248	0.487	.918
40.8	11.3	SW	0.255	0.256	0.497	0.932
28.0	5.0	S	0.252	0.249	0.415	0.622
39.1	2.5	S	0.246	0.251	0.492	0.936
40.7	10.4	NW	0.247	0.249	0.487	0.919
34.9	13.2	W	0.244	0.246	0.436	0.722
39.7	10.2	SSW	0.399	0.399	0.575	0.792
48.3	5.6	SSE	0.398	0.399	0.655	0.992
41.1	7.3	WNW	0.399	0.399	0.634	0.940
26.1	14	W	0.497	0.493	0.596	0.681
45.6	2.5	S	0.496	0.499	0.704	0.894
44.1	10.4	NW	0.499	0.499	0.716	0.916
23.9	14.3	NE	0.499	0.499	0.570	0.623
20.9	14.3	NE	0.499	0.499	0.589	0.661
20.5	14.3	NE	0.499	0.499	0.541	0.565
22.3	7.8	E	0.499	0.499	0.542	0.567
24.5	21.3	WNW	0.499	0.499	0.644	0.771
21.6	21.9	WNW	0.504	0.500	0.571	0.624
21.8	21.9	WNW	0.503	0.499	0.597	.673
26.5	24.0	E	0.499	0.499	0.622	0.727
26.3	24.0	E	0.499	0.499	0.645	0.774
29.4	14.0	W	0.493	0.493	0.630	0.752
37.4	11.6	ENE	0.505	0.505	0.632	0.739
26.5	18.2	W	0.499	0.499	0.630	0.743
28.4	14.2	E	0.491	0.495	0.656	0.805
43.1	5.6	SSE	0.499	0.499	0.696	0.876
29.0	17.2	WSW	0.499	0.499	0.586	0.655
28.5	12.9	ESE	0.503	0.505	0.578	0.632
24.7	11.8	E	0.499	0.505	0.611	0.700

ΔT = indoor air temperature - outdoor air temperature
V = wind speed
θ = wind direction
I = house air change rate with mechanical ventilation
R = $(I - I_o)/Q$ (forced ventilation rate)

TABLE 3 House air change rate with mechanical ventilation - System II

ΔT (K)	V (km/h)	Θ	Supply (ac/h)	Exhaust (ac/h)	I (ac/h)	R
25.1	13.9	S	0.152	0.150	0.336	0.510
30.0	11.8	E	0.150	0.151	0.334	0.500
27.8	13.9	S	0.246	0.246	0.413	0.626
34.2	13.2	W	0.250	0.250	0.456	0.788
33.3	12.9	ESE	0.252	0.252	0.428	0.671
28.6	13.9	S	0.401	0.401	0.568	0.771
34.9	14.7	E	0.394	0.394	0.620	0.916
27.5	18.2	W	0.394	0.394	0.550	0.739
29.0	14.2	E	0.399	0.399	0.54	0.704
24.1	9.1	SW	0.491	0.491	0.581	0.656
32.4	9.1	SW	0.491	0.491	0.627	0.749
35.1	13.2	W	0.499	0.499	0.677	0.838
32.2	14.2	E	0.499	0.499	0.683	0.850
30.2	17.2	WSW	0.499	0.499	0.589	0.661
31.7	12.9	ESE	0.499	0.503	0.606	0.693
29.7	12.9	ESE	0.499	0.503	0.599	0.679
28.8	12.9	ESE	0.499	0.503	0.570	0.620
27.0	11.8	E	0.499	0.503	0.575	0.629
25.4	11.8	E	0.499	0.503	0.561	0.602
24.3	11.8	E	0.499	0.503	0.581	0.643
30.8	13.3	WNW	0.499	0.499	0.595	0.673
30.8	13.3	WNW	0.499	0.499	0.601	0.685

ΔT = indoor air temperature - outdoor air temperature
V = wind speed
θ = wind direction
I = house air change rate with mechanical ventilation
R = $(I - I_o)/Q$ (forced ventilation rate)

TABLE 4 House air change rate with mechanical ventilation - System III

ΔT (K)	V (km/h)	Θ	Supply (ac/h)	Exhaust (ac/h)	I (ac/h)
39.6	22.5	WSW	0	0.152	0.348
35.5	13.4	WSW	0	0.150	0.264
39.6	22.5	WSW	0	0.247	0.358
40.3	2.5	S	0	0.249	0.371
38.8	7.3	WNW	0	0.249	0.361
26.3	5.0	S	0	0.396	0.384
38.8	5.6	SSE	0	0.399	0.419
39.1	10.4	NW	0	0.395	0.432
42.5	11.6	ENE	0	0.499	0.463
32.5	12.5	WSW	0	0.495	0.477
52.5	2.5	S	0	0.499	0.556
37.4	9.4	WSW	0	0.497	0.477
20.9	14.3	WSW	0	0.499	0.480

ΔT = indoor air temperature - outdoor air temperature
V = wind speed
θ = wind direction
I = house air change rate with mechanical ventilation

TABLE 5 House air change rate with mechanical ventilation - System IV

ΔT (K)	V (km/h)	Θ	Supply (ac/h)	Exhaust (ac/h)	I (ac/h)
20.7	7.8	S	0	0.156	0.229
25.9	18.3	WSW	0	0.153	0.270
26.7	5.9	S	0	0.146	0.239
26.8	7.2	SSW	0	0.145	0.293
29.1	7.5	E	0	0.252	0.297
28.7	14.0	W	0	0.244	0.300
24.5	5.9	S	0	0.246	0.294
30.8	20.0	WSW	0	0.244	0.309
27.8	20.3	SW	0	0.251	0.338
20.5	8.1	SE	0	0.246	0.267
26.8	7.5	E	0	0.253	0.291
26.8	7.5	E	0	0.242	0.289
31.0	14.0	W	0	0.244	0.325
22.1	7.8	S	0	0.399	0.377
31.6	14.0	W	0	0.399	0.393
25.3	8.1	SE	0	0.394	0.401
24.0	7.8	S	0	0.491	0.478
32.8	14.0	W	0	0.495	0.495
26.2	5.9	S	0	0.491	0.474
32.5	20.3	SW	0	0.491	0.508
28.8	8.1	SE	0	0.495	0.484
33.4	13.3	WNW	0	0.499	0.545
29.2	17.3	SE	0	0.491	0.537
26.3	5.9	S	0	0.491	0.447

ΔT = indoor air temperature - outdoor air temperature
V = wind speed
θ = wind direction
I = house air change rate with mechanical ventilation

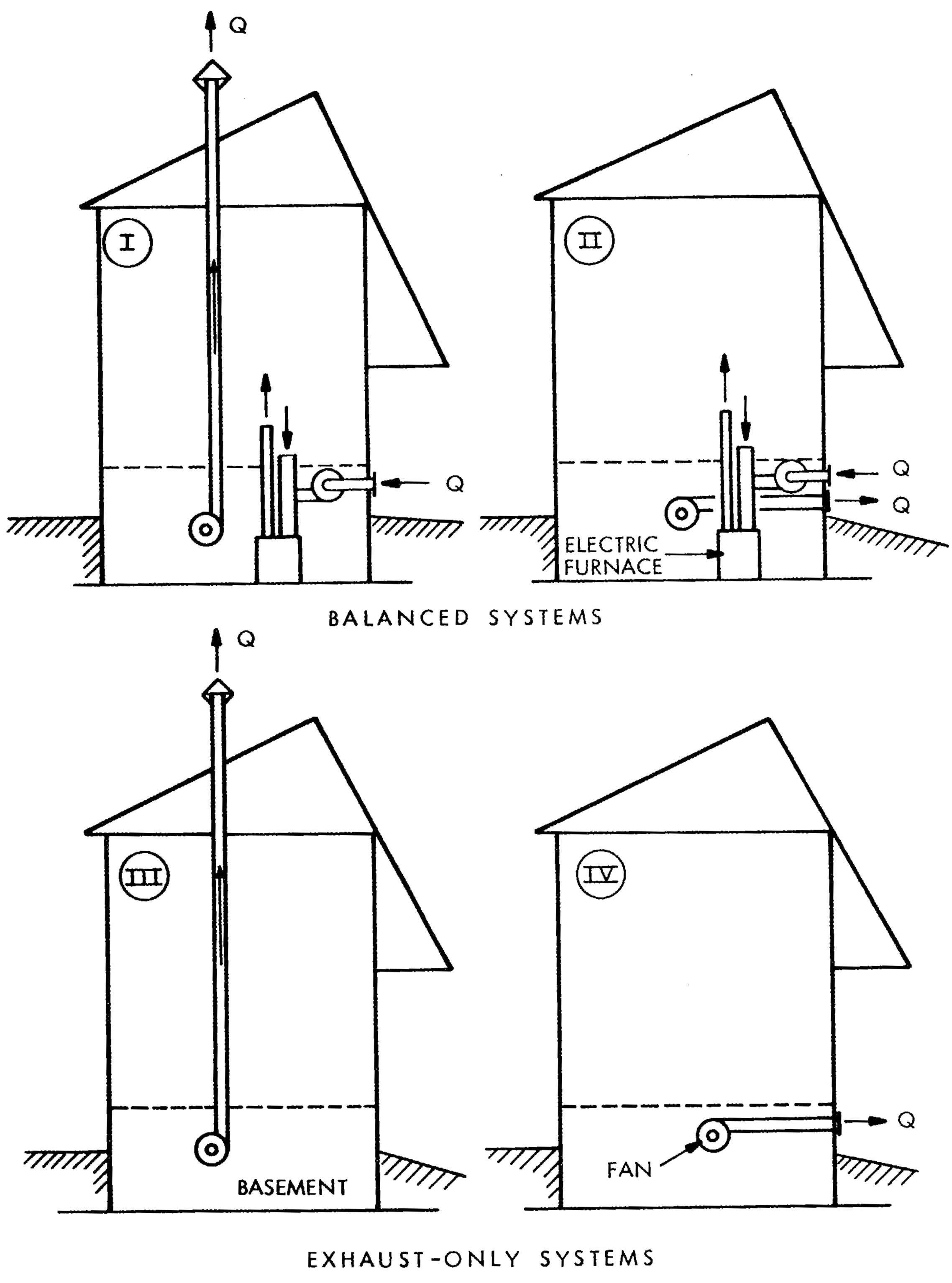

FIGURE 1

TEST VENTILATION SYSTEMS

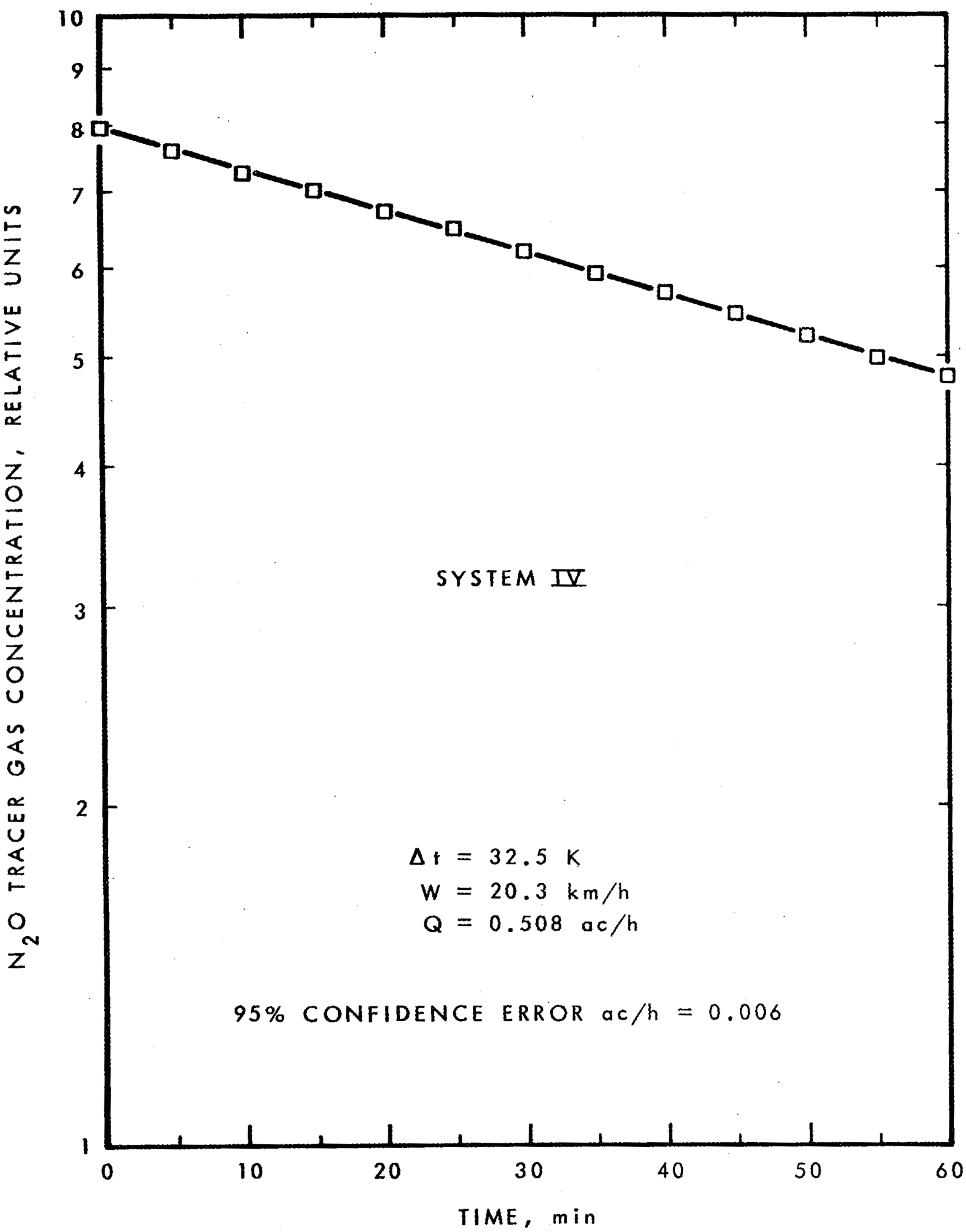

FIGURE 2

SAMPLE PLOT OF N_2O CONCENTRATION VERSUS TIME

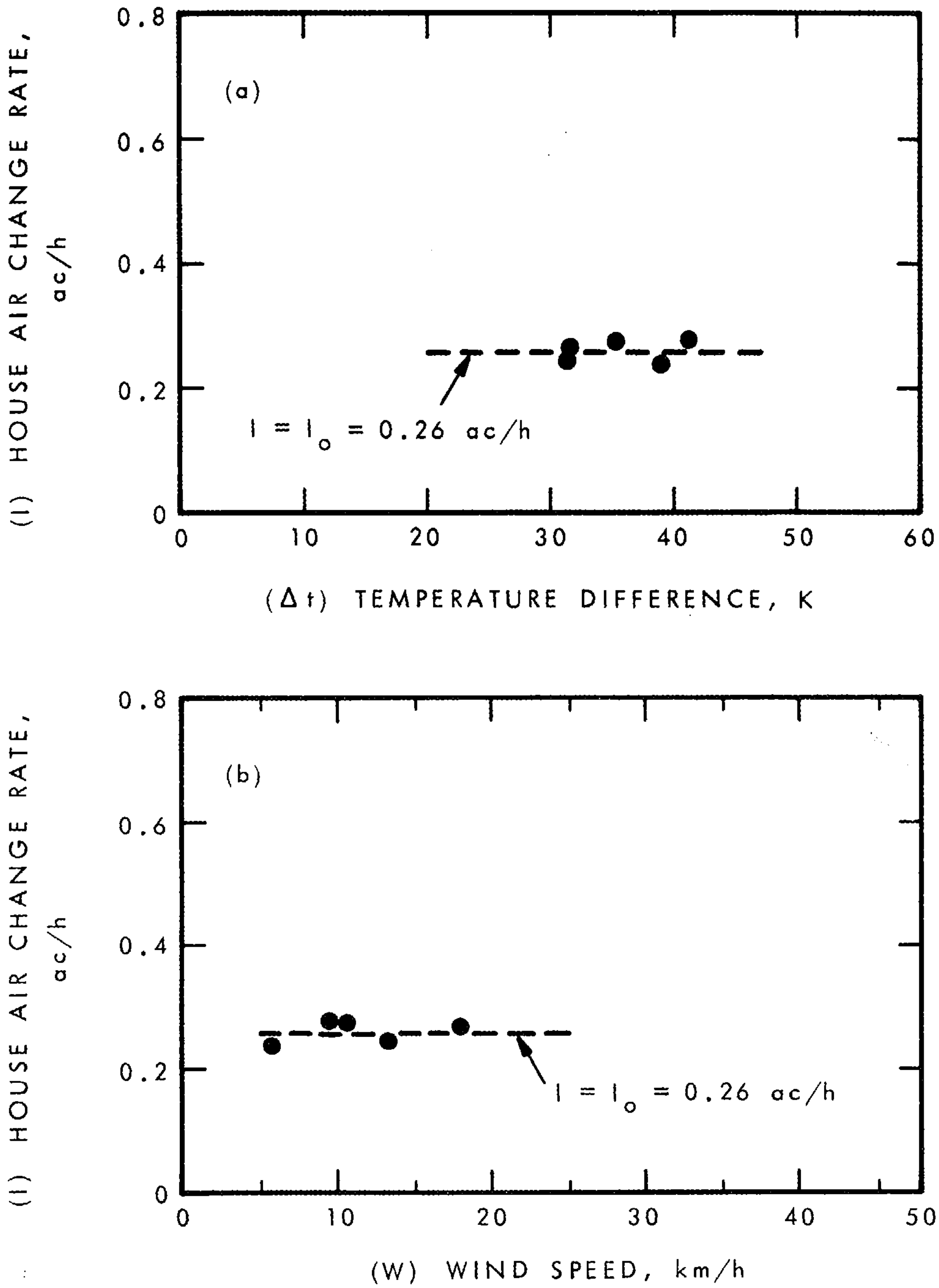

FIGURE 3

HOUSE AIR CHANGE RATE VERSUS TEMPERATURE DIFFERENCE AND WIND SPEED -- NO MECHANICAL VENTILATION

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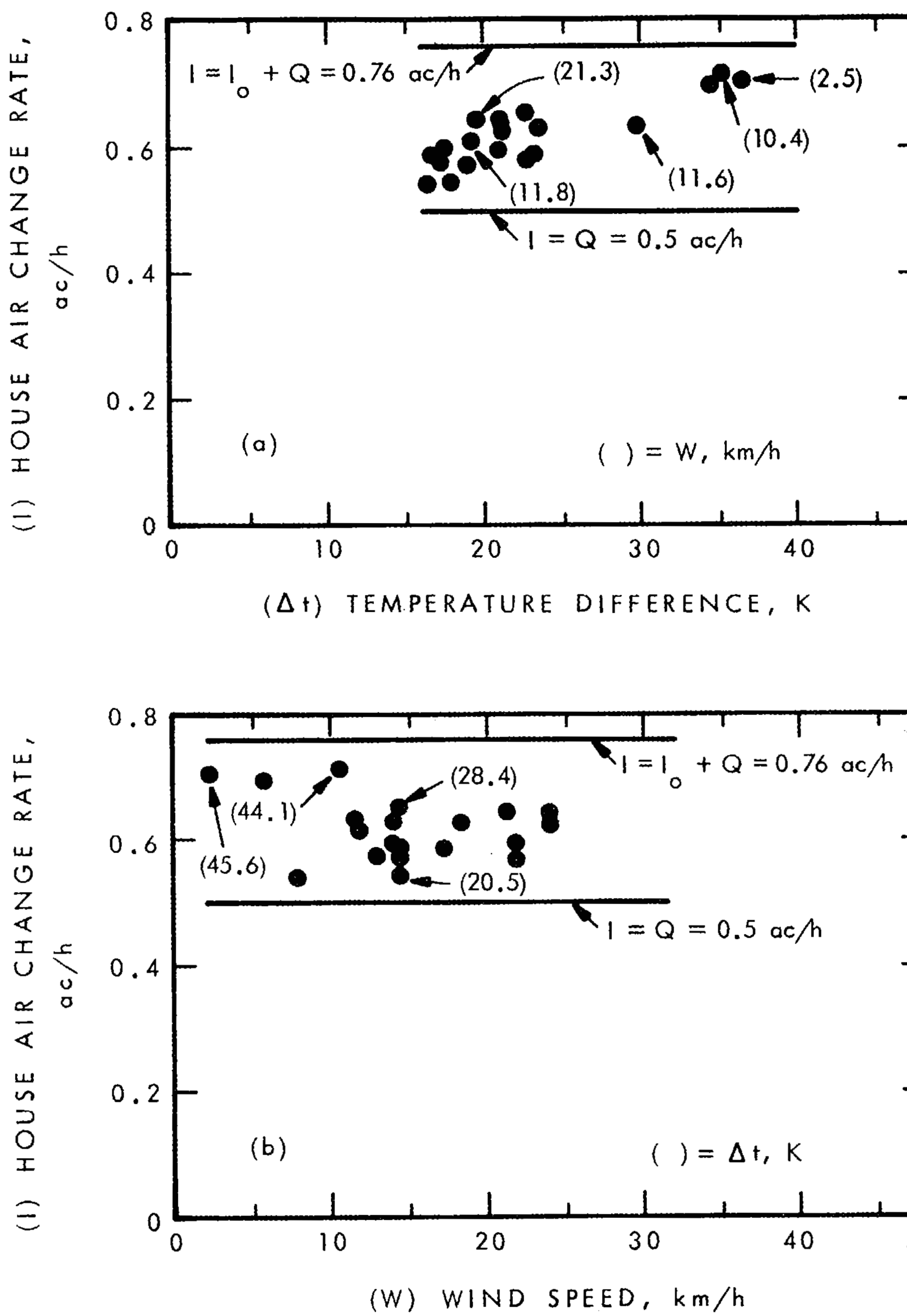

FIGURE 4

HOUSE AIR CHANGE RATE VERSUS TEMPERATURE DIFFERENCE AND WIND SPEED -- SYSTEM I

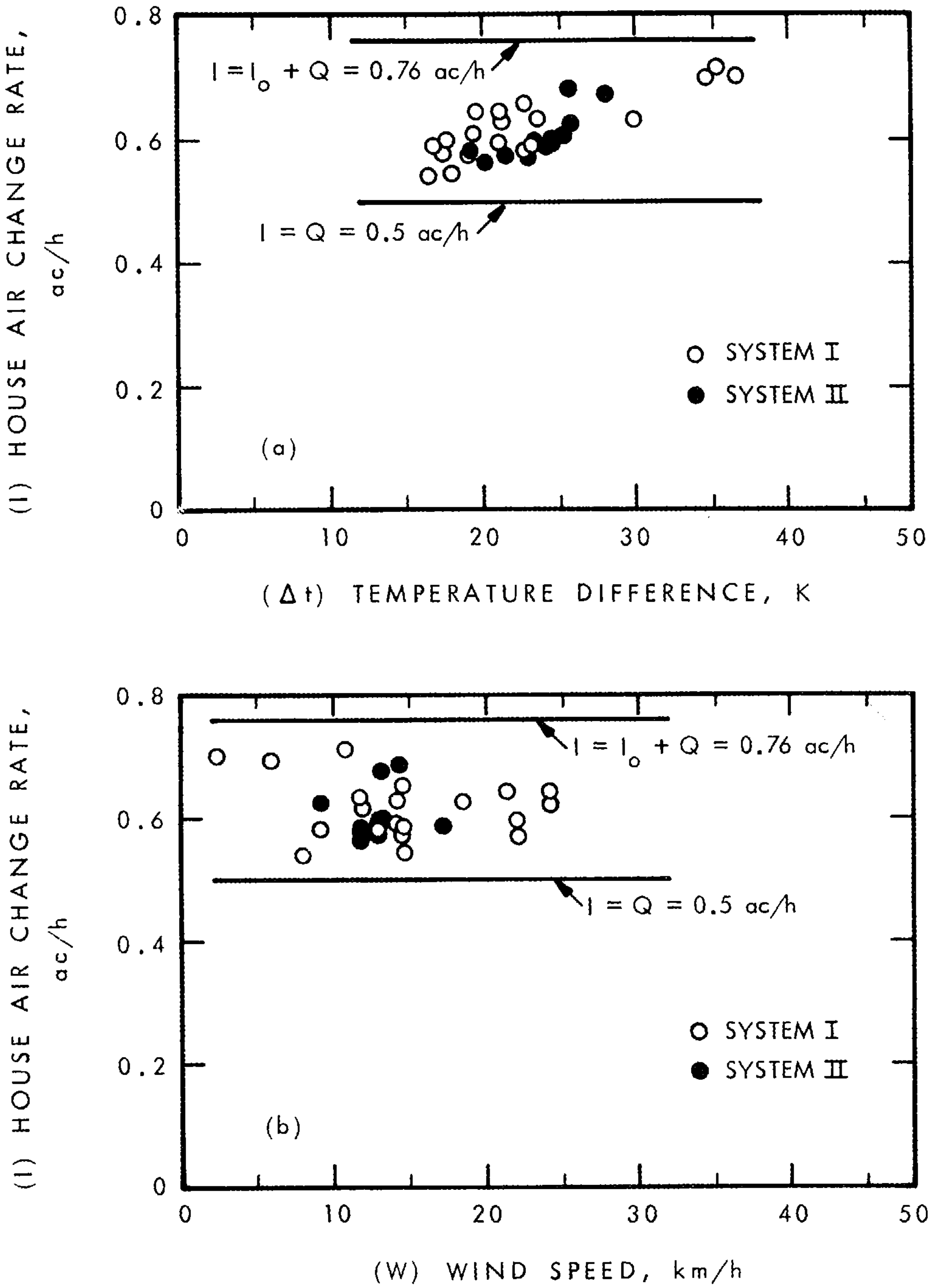

FIGURE 5

HOUSE AIR CHANGE RATE VERSUS TEMPERATURE DIFFERENCE AND WIND -- SYSTEM II

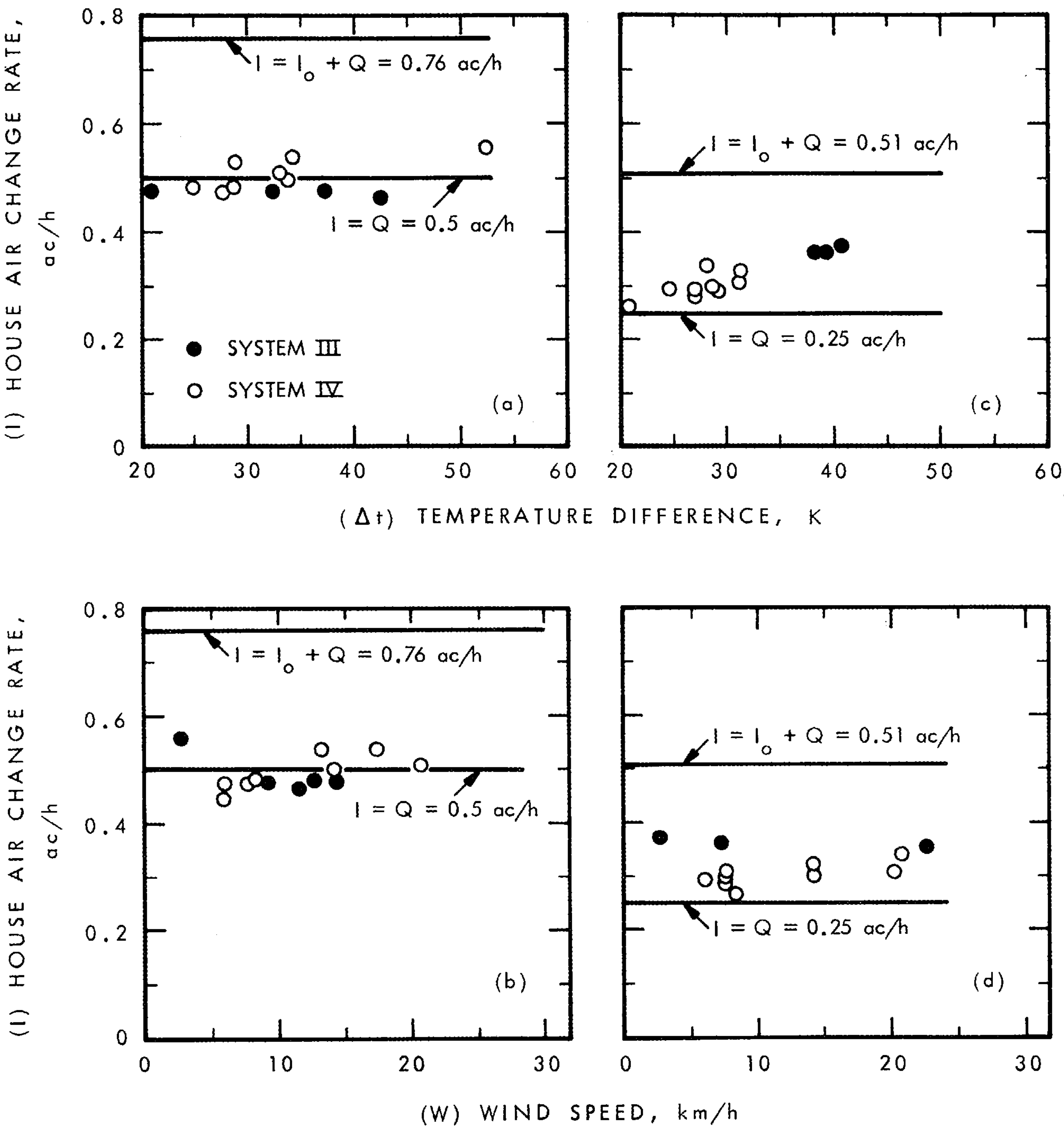

FIGURE 6

HOUSE AIR CHANGE RATE VERSUS TEMPERATURE DIFFERENCE AND WIND SPEED -- EXHAUST SYSTEMS III AND IV

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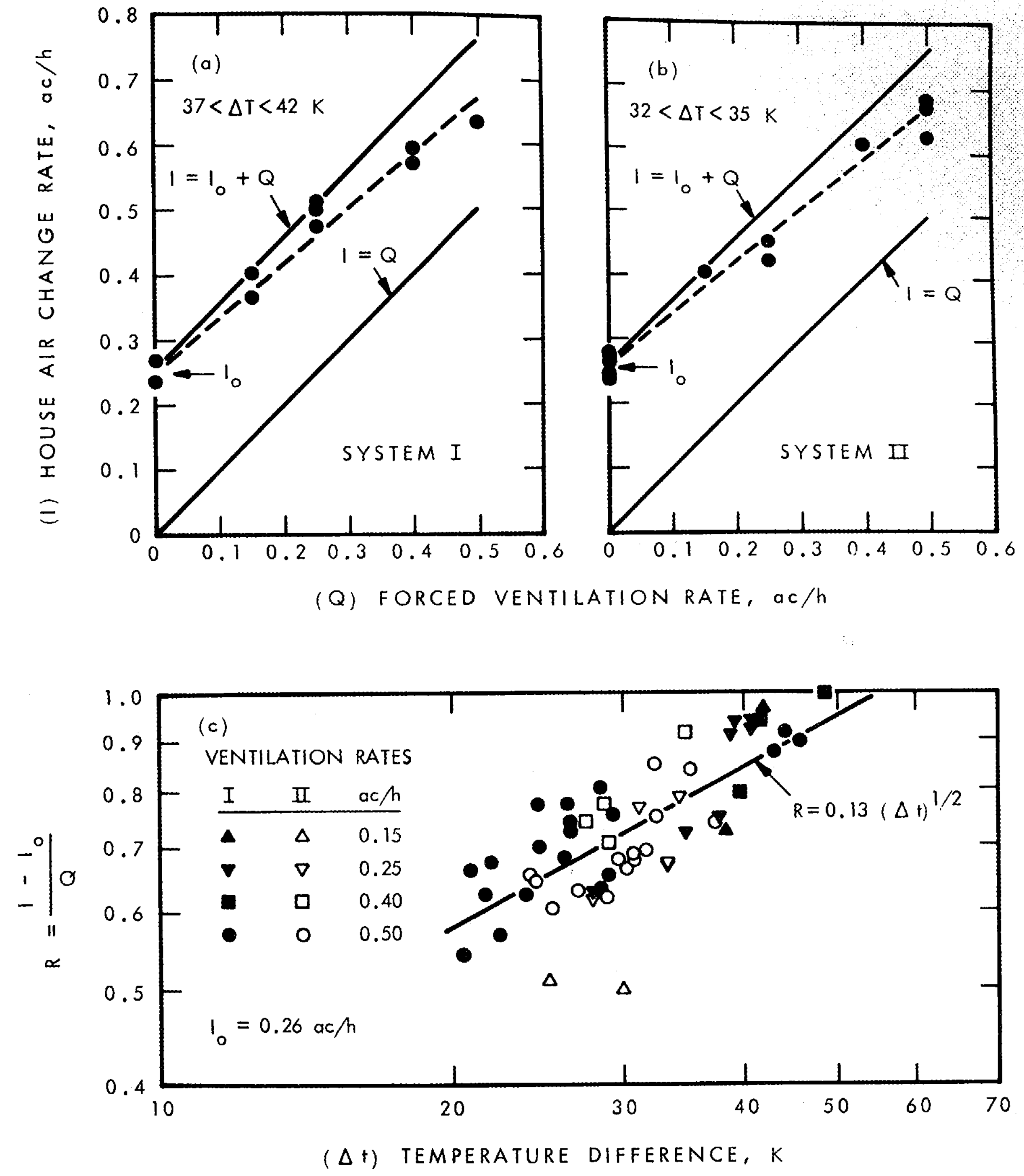

FIGURE 7

HOUSE AIR CHANGE RATE AS A FUNCTION OF FORCED VENTILATION RATE AND TEMPERATURE DIFFERENCE -- BALANCED SYSTEMS I AND II

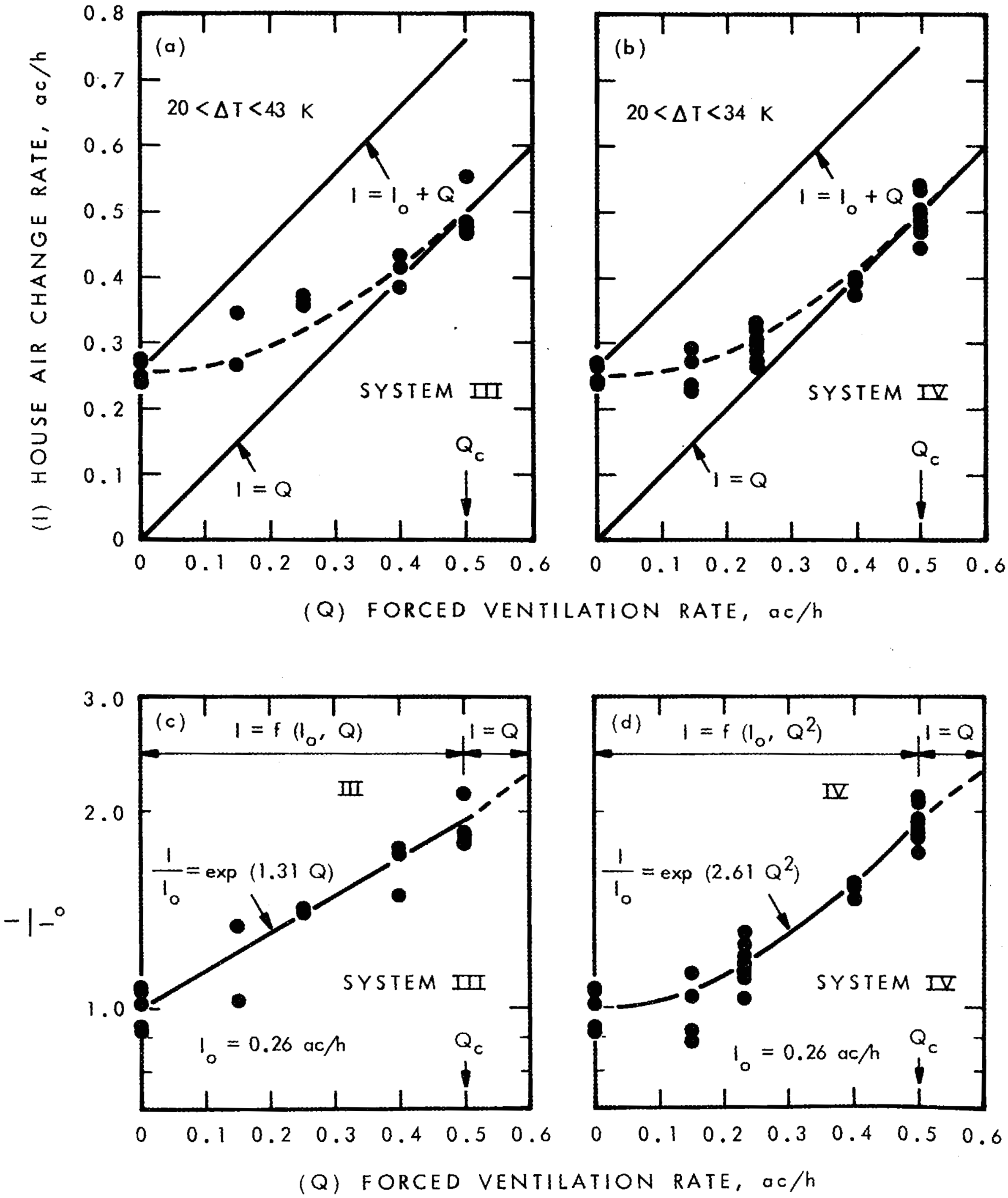

FIGURE 8

RELATIONSHIP BETWEEN HOUSE AIR CHANGE RATE AND FORCED VENTILATION RATE -- EXHAUST-ONLY SYSTEMS III AND IV

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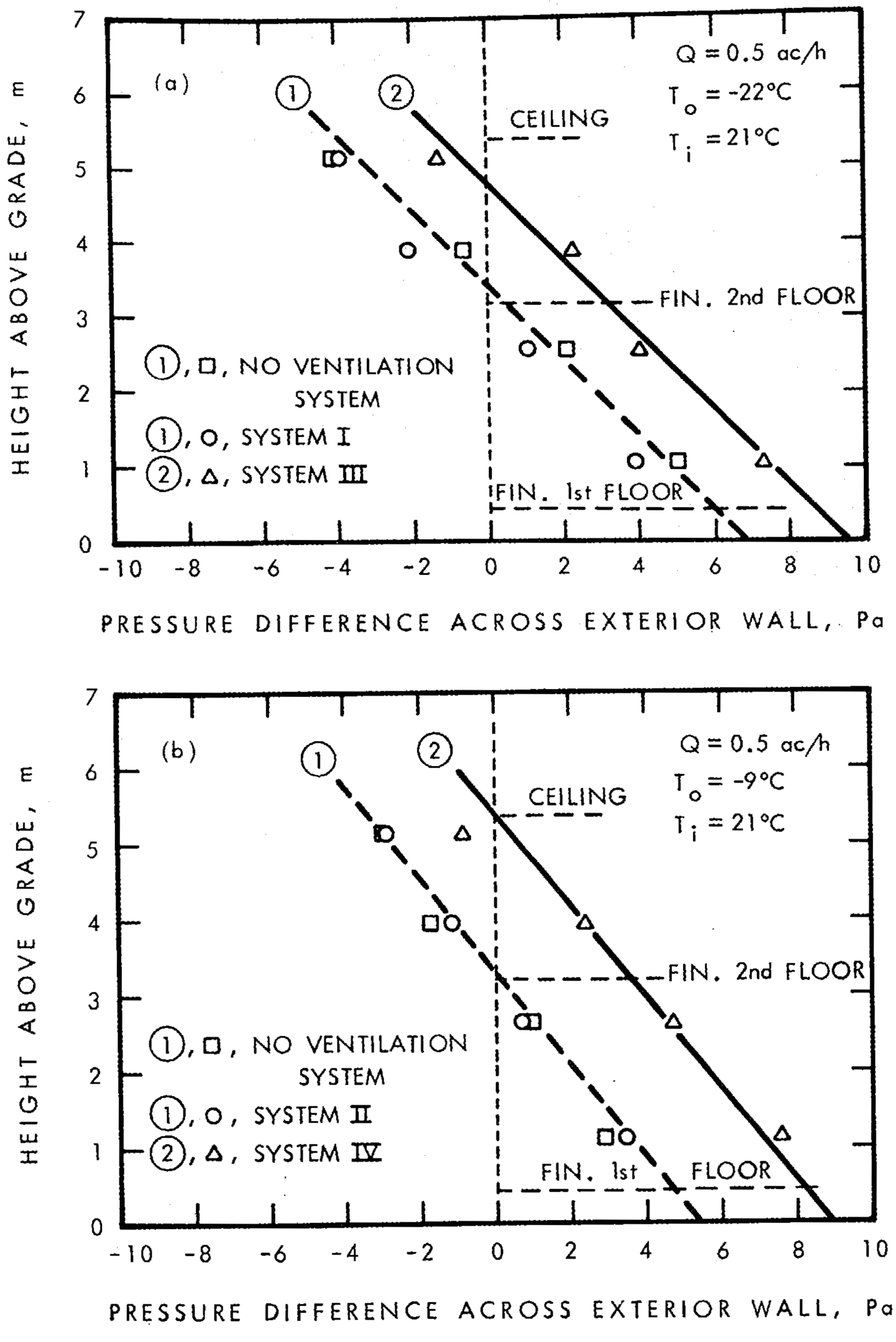

FIGURE 9

PRESSURE DIFFERENCE ACROSS EXTERIOR WALL WITH AND WITHOUT VENTILATION SYSTEMS UNDER LOW WIND CONDITIONS