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Predicted and Measured Air Exchange Rates

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As part of an ongoing indoor air quality (IAQ) modeling study, air exchange rates of ten Kuwait residential buildings were measured according to the American Society for Testing and Materials (ASTM) E741-83 standard which is a tracer gas decay technique. In this study, SF_6 was used as the tracer gas. Air exchange rates were predicted based on the characteristics of the HVAC system, openings (such as windows), leakage areas, pertaining average wind speed, average indoor/outdoor temperature difference and wind and stack coefficients.

When the coefficients recommended in the literature were used, predicted air exchange rates consistently were higher by about 34% than those obtained from tracer measurements. Therefore, a modified procedure has been proposed to accurately predict the air exchange rate of tightly controlled residential buildings of this region.

Normally, IAQ models are based on a mass balance equation involving outdoor and indoor concentrations, sink, source and air exchange rate terms. An important element of these models is the air change rate, which is defined as the ratio of the net volumetric flow rate entering (or leaving) the volume of the building. Therefore, it is equivalent to the reciprocal of the mean residence time (or space velocity), which is the usual concept used in traditional chemical reactor theory.

The air exchange rate (also called the air change rate) is normally symbolized by ACH and is a measurement of how much fresh outdoor air replaces indoor air in a given time period. It is measured in units of air changes per hour and equals the ratio of the hourly indoor air volume replaced by outdoor air to the total indoor volume. Therefore, a high ACH means a large volume of outdoor air comes in and replaces the indoor air over time.

In an accompanying detailed study, indoor and outdoor concentrations of certain volatile organic compounds (VOCs) have been measured in the residential areas of Kuwait with the ultimate aim of developing a mathematical IAQ model.[1] The model requires, among other factors, an accurate estimate of air exchange rate (ACH). The air exchange rate of a building cannot be estimated based on the building's construction or age or from a simple visual inspection. It is possible only when a detailed quantification of the leakage sites and their magnitude area are made. Then the air exchange rate of a building can be calculated in a straightforward manner, given the location and leakage functions for every opening in the building enve the wind and stack coefficients over the building envelope. any mechanical ventilation airflow rates.

Although these inputs are normally available, the stu involving experimental verifications are scarce. This means the reliability of these calculations is unknown. Further, also uncertain whether these techniques can be used co dently for buildings that may have different physical nature such as those in Kuwait and the Arabian Peninsula. The bu ings in these locations are relatively new and are designe cope with harsh conditions, such as extreme temperature dust storms. The aim of this work is to measure air excha rates for some typical Kuwaiti residential buildings and co pare them with the predictions. The ultimate goal is to obta modified predictive technique.

Experimental Method

A tracer gas method is used to determine the ACH in Kuwaiti residential buildings. An appropriate tracer gas sho not be a normal constituent of air and has to be measurable a technique that is free of interference by substances that normally present in ambient air. Here SF_6 (sulphur hexafluori was chosen as a tracer gas because it is chemically inert wl pure and is also non-toxic.

The maximum allowable concentration of SF_6 in air (vol./v was 1000 ppm and the minimum detectable concentration gas chromatography was 0.000002 ppm. On the other hand, average tropospheric background concentration of SF_6 is 1 ppm and the typical indoor and urban ambient concentratio around 10^{-5} ppm. The volume of SF_6 that was released throu out the entire house was adjusted depending on the ind volume. It was then allowed to mix with the indoor air for ab 30 minutes.

A series of air samples were collected intermittently at t sampling site (the living room). A sequential air sampler w tedlar bags automatically collected air samples into six 1 L (0.

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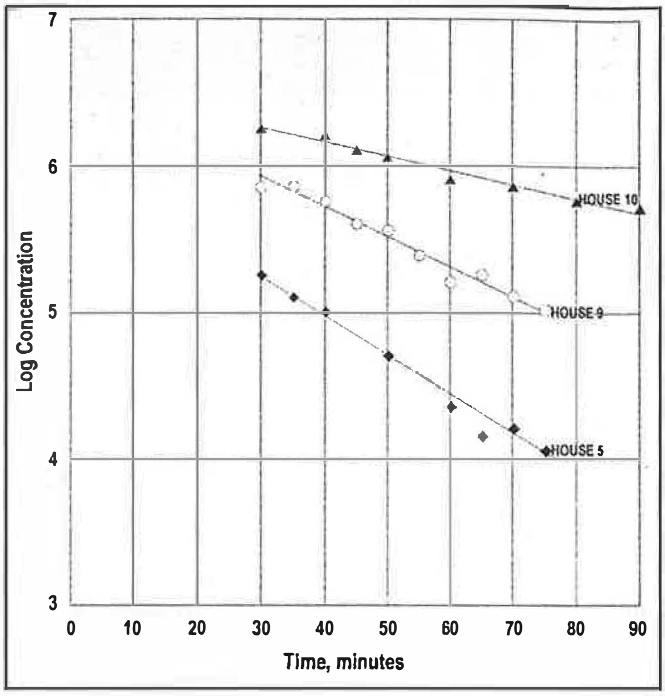

Figure 1: Measured tracer gas concentration for three typical houses.

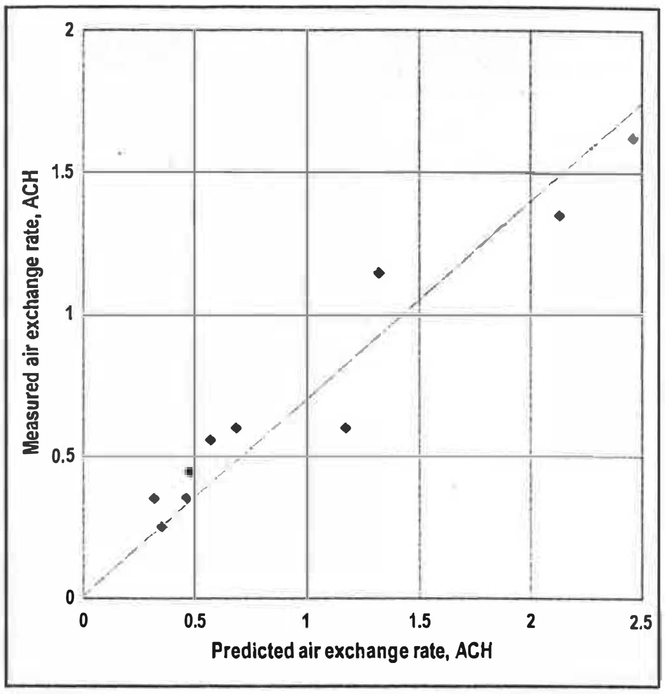

Figure 2: The predicted versus the measured air exchange rates (ACH).

ft^3) bags. Precise low flow rates were maintained using a critical orifice and applying a constant vacuum to the chamber.

The contents of the filled tedlar sampling bags were then analyzed for SF_6 content using a gas chromatograph with a 1.5-m (5 ft) long and 4 mm (0.16 in.) diameter propack column and a thermal conductivity detector.

Other pertinent details were performed according to the procedure outlined in "ASTM E741-83: Standard Test Method for Determining Air Leakage Rate by Tracer Dilution" and the National Institute of Standards and Technology protocol developed for the Washington State Energy Office (WSEO), "Instructions for Tracer Gas Test."[2]

Background

Air exchange between indoors and outdoors consists of two groups: ventilation (controlled) and infiltration (uncontrolled). Ventilation can be natural and forced. Natural ventilation is non-powered airflow through open windows, doors and other intentional openings in the building envelope. Forced ventilation is intentional and consists of powered air exchange by a fan or a blower and intake and/or exhaust vents specifically designed and installed for ventilation.

Infiltration is uncontrolled airflow through cracks, interstices and other unintentional openings. Infiltration, exfiltration and natural ventilation airflows are caused by pressure difference due to wind and indoor-outdoor temperature difference.[3]

The relationship between the airflow through an opening in the building envelope Q_N and the pressure difference across it is called the leakage function of the opening. The form of the leakage function depends on the geometry of the opening. Airflow can also depend on wind. Factors that affect the ventilation rate due to wind forces include average speed and prevailing direction. *Equation 1* shows the quantity of air forced through ventilation inlet openings by wind.[4]

$$Q_N = C_V A_R V \qquad (1)$$

where

Q_N = airflow rate m^3/s
A_R = free area of inlet opening, m^2
V = wind speed, m/s
C_V = effectiveness of openings (C_V is assumed to be 0.5 to 0.6 for perpendicular winds and 0.25 to 0.35 for diagonal winds)

For the HVAC system, duct measurements involving usual anemometry techniques were used to determine the value of total airflow rate Q_F from both duct makeup and recirculated air. Usually when the HVAC is on, the air exchange rate will be constant due to the airflow rate through the HVAC system without any flow through openings (i.e., windows or doors). However, infiltration through leakage will always be present.[5]

Air leakage is a physical property of a building and is determined by its design, construction, seasonal effects and deterioration over time. Both interior and exterior walls contribute to the leakage of the structure. Leakage occurs between the sill plate and the foundation, at cracks below the bottom of the gypsum wall board, at electrical outlets and at plumbing penetrations. Leaks into the attic at the top plates of walls also occur.

Leakage across the top ceiling of the heated space is particularly insidious because it reduces the effectiveness of insulation on the attic floor and contributes to infiltration heat loss. More variation is seen in window leakage among window types.

House No.	Volume (m^3)	ACH
1	1400	0.445
2	1500	0.558
3	600	0.250
4	626	0.350
5	900	1.725
6	1600	0.600
7	1100	0.350
8	1400	1.350
9	1500	1.147
10	750	0.601

Table 1: Measured air exchange rate (ACH).

House No.	Air Condition	Building Leakage	Openings	Total
1	0.485	–	**	0.485
2	0.566	–	**	0.566
3	0.350	–	**	0.350
4	0.320	–	**	0.320
5	*	0.097	2.362	2.459
6	*	0.284	0.886	1.170
7	0.463	–	**	0.463
8	*	0.275	1.856	2.131
9	*	0.172	1.417	1.319
10	0.680	–	**	0.680

**Air conditioner not working. **No openings while a/c was working.*

Table 2: Calculated air exchange terms (ACH).

Windows that seal by compressing the weather strip show significantly lower leakage than windows with sliding seals. A full table of the effective leakage areas for a variety of residential building components is listed in the *1993 ASHRAE Handbook—Fundamentals*.

To obtain the building's total leakage area, multiply the overall dimensions or number of occurrences of each building component by the appropriate table entry. The sum of the resulting products is the total building leakage area.

Using the effective leakage area, the airflow rate due to infiltration is calculated by the following equation:[4]

$$Q_I = L(A\Delta T + BV^2)^{0.5} \times 10^{-3} \qquad (2)$$

where

Q_I = airflow rate, m^3/s
L = effective leakage area, cm^2
A = stack coefficient
ΔT = average indoor-outdoor temperature difference, °C
B = wind coefficient
V = average wind speed, m/s

A and B are listed for different house heights and surrounding terrain in the *1993 ASHRAE Handbook—Fundamentals*. The sum of Q_N, Q_F and Q_I divided by the indoor volume results in the air exchange rate.

To estimate the measured air exchange rate from the tracer experiments, the following equation was used from ASTM E741-83, 1990.

$$C = C_o \exp(-60 \text{ ACH } t) \qquad (3)$$

where

C = tracer gas concentration at time t, ppm
C_o = tracer gas concentration at time $t = 0$, ppm
ACH = air exchange rate, hour^{-1}
t = time, min.

Obviously *Equation 3* is derived from an unsteady state mass balance equation where the indoor air is completely mixed.

Results and Discussion

Ten houses with different volumes, configurations and occupant activities were studied. The data were analyzed according to *Equation 3* and three typical plots of the tracer gas concentration against time are shown in *Figure 1* for some of the houses. The air exchange rates calculated using *Equation 3* for all houses were listed in *Table 1* along with house volume.

Five of the houses were investigated in summer and the other five were studied in winter. In the first five, the air-conditioning system (cooling) was affecting the air exchange rate. In the other five, two used the air-conditioning system (heating) and the rest opened windows during the sampling time. *Table 2* lists the three airflow rates that affect the air exchange rate, namely air conditioning, building leakage (*Equation 2*) and openings (*Equation 1*) for each house studied.

With air conditioning, the indoor air pressure should be slightly higher than the atmospheric pressure, and therefore infiltration may not exist. The average wind speed used in *Equations 1* and *2*, for the batch of houses studied in winter was 3.5 m/s (11.5 fps) and in summer was 6 m/s (19.7 fps). The temperature difference used in *Equation 2* for summer was in a range of 20° to 25°C (68° to 77°F) while in winter it was –2° to –5°C (28° to 23°F).

The average airflow rate for air-conditioning ducts varied between 500 and 850 m^3/h (290 and 500 cfm) for central units and between 350 and 650 m^3/h (210 and 380 cfm)for split and wall units. The total airflow rate was divided by the house's total volume to arrive at the air exchange rate. In general, the air

Component	L_i*	D_i**	D_iL_i
Doors, weather stripped	20 cm²/each	2	40
Door Frames, general	12 cm²/each	2	24
Windows, weather stripped, slider	0.72 cm²/m	18.4	13.25
Ceiling	1.8 cm²/m²	250.5	450.9
Electrical Sockets	2.5 cm²/each	14	35
Vents	40 cm²/each	2	80
Low Density Brick	1.1 cm²/m²	380.4	418.4

*Leakage. **Dimensions (areas, perimeter or units).

Table 3: Effective leakage area based on component leakage.

exchange rate through the air-conditioning system was found to be lower than the air exchange rate through openings. No large difference existed between the cooling and heating systems in terms of flow rates.

Table 3 shows the details of effective leakage area pertinent to House 9, which is a two-story building. This leads to a total effective leakage area of 1061.55 cm². Using a stack coefficient A of 0.00029 (L/s)² cm⁻⁴ (°C)⁻¹ (0.030 cfm² in⁻⁴ °F⁻¹) and the wind coefficient B of 0.000137 (L/s)² cm⁻⁴ (m/s)⁻² (0.0024 cfm² in.⁻⁴ fps⁻²) as given in the *1993 ASHRAE Handbook* and an average indoor-outdoor temperature difference of 10°C (50°F), Q_l was calculated by *Equation 1* to be 258.58 m³/h. Taking an effectiveness of opening of 0.25, the flow rate air due to a window opening was calculated by *Equation 2* to be 2126 m³/h. During that sampling period, there was no mechanical ventilation so that $Q_F = 0$. Summing Q_l and Q_v and dividing by the indoor volume of 1500 m³, the predicted air exchange rate was found to be 1.5894 hr⁻¹. Similar calculations were also carried for other houses. The results are summarized in *Table 2*.

A plot of measured air exchange rate versus predicted ones is shown in *Figure 2*, which gives a simple linear relationship. As a result, the following modified air exchange model can be proposed:

$$\mathrm{ACH} = \frac{0.7}{\mathrm{Volume}}\left[C_V A_R V + Q_F + L\left(A\Delta T + BV^2\right)^{0.5}\right] \tag{4}$$

In this model, *Equation 1* and *Equation 2* were summed up along with the air-conditioning system flow rate.

Table 4 shows both the measured ACH and the predicted ACH produced by using the modified equation, *Equation 4*. The normalized mean square error (NMSE) and the fractional bias (FB) were found to be 0.00337 and 0.05803 respectively indicating that the use of *Equation 4* is acceptable.

The study's findings clearly show that the predictions based on the coefficients of the *1993 ASHRAE Handbook—Fundamentals* consistently overestimates by about 30% of the measured ACH values of the Kuwaiti residential buildings. Therefore, exercise care when using the coefficients in the *1993 ASHRAE Handbook—Fundamentals* for buildings, such as those in Kuwait, which may differ in configuration and openings as necessitated by local weather conditions.

House No.	$ACH_{meas.}$	$ACH_{calc.}$
1	0.445	0.340
2	0.558	0.396
3	0.250	0.245
4	0.350	0.224
5	1.725	1.721
6	0.600	0.819
7	0.350	0.324
8	1.350	1.492
9	1.147	0.923
10	0.601	0.476

Table 4: Comparison between measured air exchange rate and calculated rate based on Equation 4.

Acknowledgments

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