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Modeling Contaminant Transport from Garage to Living Space in Residential Buildings Based on Single Tracer Gas Decay Measurements

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ABSTRACT

Attached garages can pose a threat to a home's indoor air quality because the garage air, which often contains some contaminants such as particulate matter, carbon monoxide, and volatile organic compounds, can migrate into living spaces. In this paper, a model is developed to characterize the transport of contaminants from a garage to a living space based on a measurement of single tracer gas decays without limiting the numbers of zones in the building. Unlike conventional multi-tracer gas methods, this model considers time delays of contaminant transport, and is much simpler, less costly and less time-consuming. It interprets the test results with clear physical meanings of the coefficients in the model equations, and is helpful for understanding the transport process of contaminants. An example of the model's applications shows the goodness of fit of the model to test data and its effectiveness at interpreting results of tracer gas decay expirements.

INTRODUCTION

Attached garages can pose a threat to the indoor air quality in a house. Internal combustion vehicles and other frequently garaged items such as fuels, pesticides, and paints, produce contaminants including particulate matter, carbon monoxide, and volatile organic compounds. These contaminants and their byproducts can migrate across garage-house interfaces and into living spaces through openings and bypasses in the structure, or via ductwork. To characterize the transport of the contaminants from an attached garage to the living spaces in a house, some research has been conducted with in field direct contaminant measurements (Merrin et al. 2017; Zielinska et al. 2011; Graham et al. 2004; Emmerich et al. 2003) or model simulations (Nirvan et al. 2012; Duci et al. 2004; Lansari et al. 1996). The direct measurement methods usually need intentional generation of the contaminant or a tracer in an attached garage, such as vehicle starts (Graham et al. 2004), evaporation of fuels/chemicals (Zielinska et al. 2011; Lansari et al. 1996), or controlled sulfur hexafluoride (SF6) releases (Merrin et al. 2017). Then the contaminant concentrations in the garage and in living spaces can be directly measured and compared. Field measurements usually are costly and time consuming. Accuracy of the results for the contaminant transport may be undermined by possible contaminant sources or sinks in the living spaces. In addition, the contaminants generated during the tests may compromise the air quality both in the garages and in the living spaces. Although direct measurement test results are usually more reliable than simulations for a specific house,

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they do not reveal more general information about the mechanisms of contaminant transports without supplemental modeling analysis.

The conventional approach for investigating garage air transport through simulation methods is to estimate the airflow rates between the garage and the house, and the airflow rates between the different zones inside the house. With the simulated air changes among different zones, the contaminant transport from the garage to the living space zones can be calculated. In addition to the requirements for geometric and boundary conditions, a simulation also needs to be calibrated or validated with field experimental data (Emmerich et al. 2004; Sextro et al. 1999). The field experimental data usually include the airflow rates among different zones inside the simulation geometric domain indirectly measured with tracer gas tests. A house cannot typically be considered as a single zone, or even as two zones; to fully determine the flow rates simultaneously among all the zones, including the garage and outdoor, multi-gas techniques are necessary (Sherman 1989; Sherman and Dlckerhoff 1989; Miller et al. 1997), requiring a complex simulation method to achieve reliable predictions. In addition, simulation results are often not easily interpreted by people, making it difficult to understand the specifics of the contaminant transport and the physical meanings of coefficients in the simulation models.

A well-mixed tracer gas injected into a garage migrating to indoor living spaces can be assumed to mimic the transport of a contaminatn, which can be considered as a gas without sink, adhesion, or reaction during its migration from the garage to living spaces. Thus, single tracer gas measurements have also been used to investigate contaminant mitigation. Compared with the direct field measurements of contaminants, single tracer gas method is simple. However, similar to the direct contaminant measurements, single tracer gas studies usually present their results in the form of ratios or comparisons of the maximum concentrations in a garage to a living place, and do not reveal much information about contaminant transport mechanisms. This paper presents a model based on single tracer gas decay measurements to characterize contaminant transports from an attached garage to a living space in residential buildings. This model is relatively simple and can interpret meaningful contaminant transport mechanisms from test results.

OVERALL ASSUMPTIONS

It is assumed that the tracer gas is uniformly mixed within each individual zone, including the garage. During the tracer gas decay process, no additional tracer gas is released, there is no sink, no adhesion, and no reaction inside the garage or the house interior spaces. The diffusion effect of the tracer gas is equivalent to gas flow. The house configuration, the airflows within the house, and the air exchange between the house and outdoors are steady during the tracer gas test. The contaminants in the garage air perform similarly to the tracer gas in terms of their migration to living spaces in the house. The air temperature is uniform across each living space inside the house. There is no tracer gas present in the ambient outdoor air.

Figure 1 shows an imaginary residential house with an attached garage. It also shows the hypothetical air flows, containing the tracer gas, flowing into and out of the garage and a living space room during a tracer gas decay measurement.

TRACER GAS CONCENTRATION IN GARAGE

For a garage with a volume of $\mathrm{V_g}$ during the period of measurement with the tracer gas decay, the mass-balance equation of the tracer gas takes the following form:

$$w\rho_{\mathrm{g}}\mathrm{V_g}\frac{dC_{\mathrm{g},t}}{dt} = \sum_j\left(w\rho_j Q_{\mathrm{hg}j}C_{\mathrm{h}j,t}\right) - \sum_j\left(w\rho_{\mathrm{g}}Q_{\mathrm{gh}j}C_{\mathrm{g},t}\right) + w\rho_{\mathrm{o}}Q_{\mathrm{og}}C_{\mathrm{o}} - w\rho_{\mathrm{g}}Q_{\mathrm{go}}C_{\mathrm{g},t} \qquad (1)$$

where w is the ratio of the molar mass of the tracer gas to that of air; $C_{\mathrm{g},t}$ is the tracer gas concentration in the garage at time t; $Q_{\mathrm{hg}j}$ is the air flow rate with the tracer gas concentration $C_{\mathrm{h}j,t}$ from house space j into the garage; $Q_{\mathrm{gh}j}$ is the air flow rate with the tracer gas concentration $C_{\mathrm{g},t}$ from the garage into house space j; Q_{og} is the air flow rate with the

tracer gas concentration C_{o} from outdoor into the garage; Q_{go} is the air flow rate with the tracer gas concentration $C_{\mathrm{g},t}$ from the garage to outside; ρ_{g} is the average density of the air in the garage; ρ_{o} is the density of outdoor air; and ρ_j is the average density of the air in house space j. We assume that the ρ_j is similar for all the interior zones of the house, i.e. $\rho_j \approx \rho_{\mathrm{h}}$. All the concentrations in Equation (1) are volume based. From the air mass balance, we have:

$$\rho_{\mathrm{g}} \sum_j Q_{\mathrm{gh}j} + \rho_{\mathrm{g}} Q_{\mathrm{go}} = \rho_{\mathrm{h}} \sum_j Q_{\mathrm{hg}j} + \rho_{\mathrm{o}} Q_{\mathrm{og}} \tag{2}$$

It is assumed that the tracer gas concentration in outdoor air is negligible, i.e. $C_{\mathrm{o}} = 0$. We may split the total airflow from house spaces to the garage, $\rho_{\mathrm{h}} \sum_j Q_{\mathrm{hg}j}$, into two virtual parts, one part with the tracer gas concentration $w\rho_{\mathrm{g}} C_{\mathrm{g},t}$, the same as the air in the garage, and the second part with 0 tracer gas concentration, the same as the outdoor air:

$$Q_{\mathrm{hg}}^{(1)} = \frac{\rho_{\mathrm{h}} \sum_j (Q_{\mathrm{hg}j} C_{\mathrm{h}j,t})}{\rho_{\mathrm{g}} C_{\mathrm{g},t}} \tag{3}$$

$$Q_{\mathrm{hg}}^{(2)} = \frac{\rho_{\mathrm{h}}}{\rho_{\mathrm{g}}} \sum_j Q_{\mathrm{hg}j} - Q_{\mathrm{hg}}^{(1)} \tag{4}$$

$Q_{\mathrm{hg}}^{(1)}$ should always be positive, while $Q_{\mathrm{hg}}^{(2)}$ could be negative in certain cases. With the definitions of (3) and (4), Equations (1) and (2) can be rewritten as:

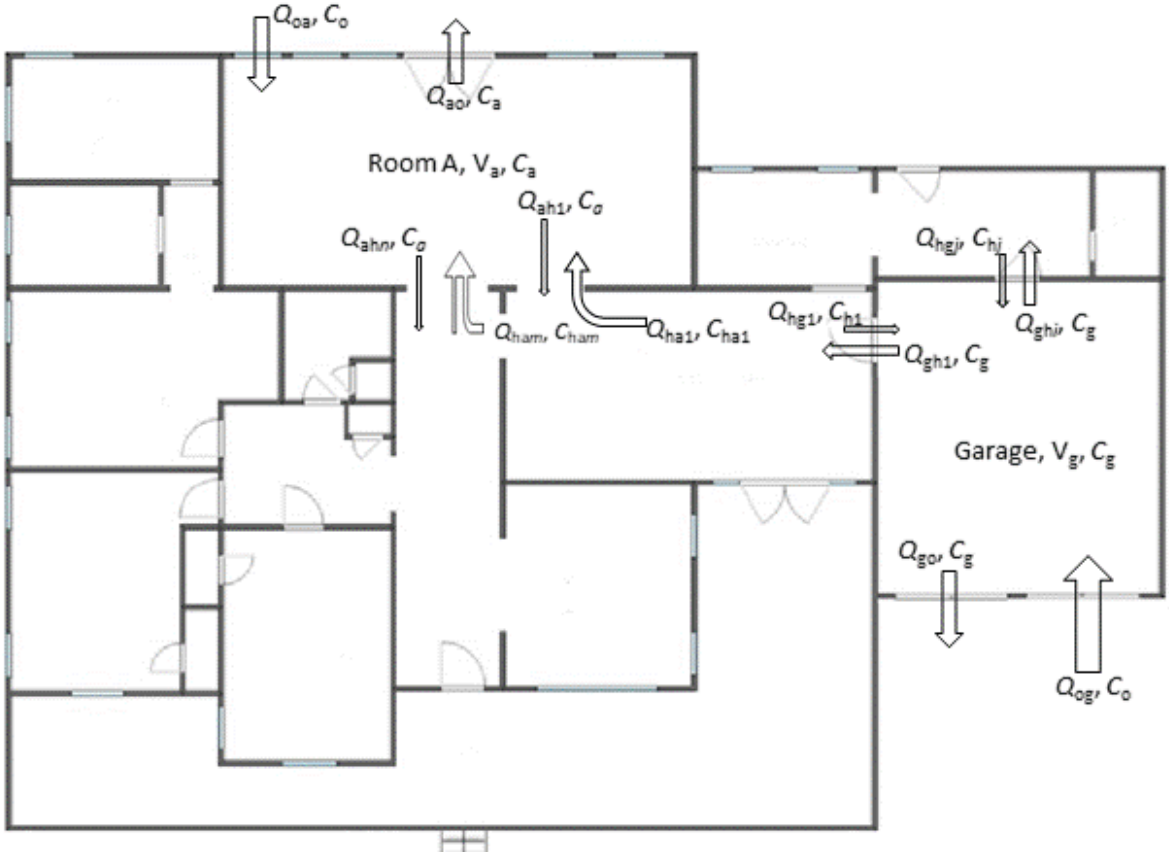

Figure 1 Hypothetical airflows in the garage and a general room in a house during tracer gas decay.

$$\mathrm{V_g}\frac{dC_{\mathrm{g},t}}{dt} = -\left(\sum_j Q_{\mathrm{gh}j} - Q_{\mathrm{hg}}^{(1)} + Q_{\mathrm{go}}\right)C_{\mathrm{g},t} \tag{5}$$

$$\rho_{\mathrm{g}}\left(\sum_j Q_{\mathrm{gh}j} - Q_{\mathrm{hg}}^{(1)} + Q_{\mathrm{go}}\right) = \rho_{\mathrm{g}}Q_{\mathrm{hg}}^{(2)} + \rho_{\mathrm{o}}Q_{\mathrm{og}} \tag{6}$$

The left-hand side of Equation (6) is the virtual net flow rate of the garage air exiting the garage. Being considered as a part of $\sum_j Q_{\mathrm{gh}j}$, $Q_{\mathrm{hg}}^{(1)}$ makes a round trip to house interior spaces and back to the garage, and can still be considered a part of the garage air at time *t*. The right-hand side of Equation (6) is the total flow rate of air, which does not contain the tracer gas, entering the garage. $\rho_{\mathrm{g}}Q_{\mathrm{hg}}^{(2)}$ can be considered as outdoor air entering the garage through the house interior spaces, i.e. $\rho_{\mathrm{g}}Q_{\mathrm{hg}}^{(2)}$, which infiltrates into house interior spaces from outside, and then travels to the garage. In a scenario of $Q_{\mathrm{hg}}^{(2)} < 0$, $\left(-Q_{\mathrm{hg}}^{(2)}\right)$ can be considered as a part of outdoor air passing through the garage in an imaginary pipe into the house interior space.

If we denote $\left(\sum_i Q_{\mathrm{gh}i} - Q_{\mathrm{hg}}^{(1)} + Q_{\mathrm{go}}\right)$ or $\left(Q_{\mathrm{hg}}^{(2)} + \frac{\rho_{\mathrm{o}}}{\rho_{\mathrm{g}}}Q_{\mathrm{og}}\right)$ as $Q_{\mathrm{g}e}$, which can be considered as the total flowrate of outdoor air into the garage and is assumed constant under the steady conditions, Equation (5) can be written as:

$$\frac{dC_{\mathrm{g},t}}{dt} = -\frac{Q_{\mathrm{g}e}}{\mathrm{V_g}}C_{\mathrm{g},t} \tag{7}$$

We denote the air change rate or air turnover rate of the garage as

$$\mathrm{ACR_g} = \frac{Q_{\mathrm{g}e}}{\mathrm{V_g}} \tag{8}$$

The solution of Equation (7) is:

$$C_{\mathrm{g},t} = C_{\mathrm{g0}}e^{-\mathrm{ACR_g}\left(t - t_{\mathrm{g0}}\right)} \tag{9}$$

In Equation (9) C_{g0} is the tracer gas concentration in the garage at time t_{g0}, which can be set as the start time of the tracer gas decay process. To simplify the equations let the start point of the decay, $t_{\mathrm{g0}} = 0$. We are not interested in the historical garage concentrations of the tracer gas when $t < 0$. In other words, Equation (9) with $t_{\mathrm{g0}} = 0$ describes the tracer gas concentration with time in the garage, and is only valid when $t \geq 0$. The air change rate, $\mathrm{ACR_g}$, can be estimated through an exponential regression with the measured data of the tracer gas concentration in the garage during a decay test.

TRACER GAS CONCENTRATION IN A HOUSE ROOM

For a living space in the house, Room A, with a volume of $\mathrm{V_a}$, we have the mass-balance equation of the tracer gas as follows:

$$w\rho_{\mathrm{h}}\mathrm{V_a}\frac{dC_{\mathrm{a},t}}{dt} = w\rho_{\mathrm{h}}\sum_m\left(Q_{\mathrm{ha}m}C_{\mathrm{ha}m,t}\right) - w\rho_{\mathrm{h}}C_{\mathrm{a},t}\sum_n Q_{\mathrm{ah}n} - w\rho_{\mathrm{h}}Q_{\mathrm{ao}}C_{\mathrm{a},t} + w\rho_{\mathrm{o}}Q_{\mathrm{oa}}C_{\mathrm{o}} \tag{10}$$

where $C_{\mathrm{a},t}$ is the tracer gas concentration in Room A at time *t*; $Q_{\mathrm{ha}m}$ is the air flow rate from neighbor space *m* to Room A with the tracer gas concentration of $C_{\mathrm{ha}m,t}$; $Q_{\mathrm{ah}n}$ is the airflow rate from Room A to neighbor space *n*; Q_{ao} is the air flow rate from Room A to outdoors; and Q_{oa} is the air infiltration from outdoor to Room A with the tracer gas

concentration of $C_{\mathrm{o}} = 0$.

In Equation (10), $w\rho_{\mathrm{h}} \sum_m (Q_{\mathrm{ham}} C_{\mathrm{ham},t})$ is the tracer gas mass transported from the garage to Room A, and can be considered virtually to be equal to $w\rho_{\mathrm{g}} \sum_m (Q_{\mathrm{gam}} C_{\mathrm{gm},t-t_m})$, where Q_{gam} is the flow rate of the air from the garage to Room A through pathway m, and $C_{gm,t-t_m}$ is the tracer gas concentration in the garage at the moment when the air flow of Q_{gam} exits the garage. Here we assume that it takes an amount of time, t_m, for the garage air to travel to Room A through pathway m. We can also let $Q_{\mathrm{ga}} C_{\mathrm{g},t-t_{\mathrm{lag}}}$ be equivalent to $\sum_m (Q_{\mathrm{gam}} C_{\mathrm{gm},t-t_m})$ and $Q_{\mathrm{ga}} = \sum_m Q_{\mathrm{gam}}$, i.e.:

$$Q_{\mathrm{ga}} C_{\mathrm{g},t-t_{\mathrm{lag}}} = \sum_m (Q_{\mathrm{gam}} C_{\mathrm{gm},t-t_m}) = \frac{\rho_{\mathrm{h}}}{\rho_{\mathrm{g}}} \sum_m (Q_{\mathrm{ham}} C_{\mathrm{ham},t}) \tag{11}$$

We define the lag factor of the air transport from the garage to Room A as:

$$f_{\mathrm{lag}} = e^{\mathrm{ACR_g} t_{\mathrm{lag}}} \tag{12}$$

the air transport rate from the garage to Room A is defined as:

$$\mathrm{ATR_{g-A}} = \frac{\rho_{\mathrm{g}} Q_{\mathrm{ga}}}{\rho_{\mathrm{h}} \mathrm{V_a}} \tag{13}$$

and the air change rate of Room A is defined as:

$$\mathrm{ACR_a} = \frac{1}{V_a} (Q_{\mathrm{ao}} + \sum_n Q_{\mathrm{ah}n}) \tag{14}$$

Then during the decay process and when $t > \max(t_m)$, Equation (10) can be rewritten as

$$\frac{dC_{\mathrm{a},t}}{dt} + \mathrm{ACR_a} C_{\mathrm{a},t} = \mathrm{ATR_{g-A}} C_{\mathrm{g},t-t_{\mathrm{lag}}} \tag{15}$$

After substituting Equations (9) and (12) into (15), a solution to Equation (15) is:

$$C_{\mathrm{a},t} = \frac{\mathrm{ATR_{g-A}} f_{\mathrm{lag}} C_{\mathrm{g0}}}{\mathrm{ACR_a} - \mathrm{ACR_g}} e^{-\mathrm{ACR_g} t} - \left(\frac{\mathrm{ATR_{g-A}} f_{\mathrm{lag}} C_{\mathrm{g1}}}{\mathrm{ACR_a} - \mathrm{ACR_g}} - C_{\mathrm{a1}} \right) e^{-\mathrm{ACR_a}(t-t_1)}$$
$$\text{when } \mathrm{ACR_a} \neq \mathrm{ACR_g} \text{ and } t > \max(t_m) \tag{16}$$

where C_{a1} and C_{g1} are the tracer gas concentrations in Room A and in the garage at time t_1 [$>\max(t_m)$], respectively. When $\mathrm{ACR_a} = \mathrm{ACR_g}$, which is unusual, Solution (16) is not valid, and the solution to Equation (15) will be:

$$C_{\mathrm{a},t} = \mathrm{ATR_{g-A}} f_{\mathrm{lag}} C_{\mathrm{g0}} t e^{-\mathrm{ACR_g} t} \quad \text{when } \mathrm{ACR_a} = \mathrm{ACR_g} \text{ and } t > \max(t_m) \tag{17}$$

We are interested in $\mathrm{ATR_{g-A}}$ and t_{lag} (or f_{lag}), the overall transport rate and transport time of the garage air to Room A. However, $\mathrm{ATR_{g-A}}$ and f_{lag} stick together in Equation (16) or (17), and we cannot uniquely determine their individual values by regressing the equations with test data. Another issue of Equation (16) or (17) is that they are only valid when $t > \max(t_m)$, but t_m is unknown. These two issues will be addressed later in an example of the model applications.

As mentioned previously, $\mathrm{ACR_g}$ can be estimated by exponentially regressing Equation (9) with the measured tracer gas garage concentration data during a decay test. After $\mathrm{ACR_g}$ is evaluated, we can estimate the values of $\mathrm{ACR_a}$ and

$\frac{\mathrm{ATR_{g-A}} f_{\mathrm{lag}}}{\mathrm{ACR_a}-\mathrm{ACR_g}}$ by regressing Equation (16) with the measured tracer gas concentration data from the garage and in Room A during a tracer gas decay test. If the measured tracer gas concentration curve with time in Room A is too flat, to obtain a better estimation of $\mathrm{ACR_a}$, we may add another tracer gas decay test in Room A, i.e. to inject the tracer gas only in Room A and do the decay test for Room A independently. Thus, we can regress an equation similar to Equation (9) with the test data in Room A. Then with the estimated $\mathrm{ACR_g}$ and $\mathrm{ACR_a}$, we can estimate $\mathrm{ATR_{g-A}} f_{\mathrm{lag}}$ by regressing Equation (16) or (17) if $\mathrm{ACR_a}$ is very close to $\mathrm{ACR_g}$. A method of the nonlinear least-squares minimization can be used to regress Equation (16), which is not discussed here due to space limitations. It is necessary to point out that only the measured data after the time where the tracer gas concentration in Room A is near its highest should be used for the regression of Equation (16) or (17).

AN EXAMPLE

Figure 2 shows an example decay and the regressed equations from one of a series of tracer gas tests conducted at an occupied house with an attached garage (Merrin et al. 2017). The tracer gas was pulse-injected into the garage once every six hours. Only those data points after 2.5 hours in the distant room were used to conduct the regression. The $\mathrm{R^2}$ values of the two nonlinear regressions in Figure 2 were calculated with $\mathrm{R^2} = 1 - \frac{\Sigma(\mathrm{y_i}-\mathrm{f_i})^2}{\Sigma(\mathrm{y_i}-\bar{\mathrm{y}})^2}$, not $\mathrm{R^2} = \frac{\Sigma(\mathrm{f_i}-\bar{\mathrm{y}})^2}{\Sigma(\mathrm{y_i}-\bar{\mathrm{y}})^2}$ which would result in $\mathrm{R^2} > 1$ (Kvalseth 1983). Even though the trend of the measured concentration data in the distant room was relativly flat and the concentrations were low, the regressed equation still fit fairly well, confirming the effectiveness of the model described with Equations (9) and (16) for characterizing the air transport from one zone to another in the same building. The regression of Equation (16) would have been more accurate if there was no tracer gas residue in the indoor and outdoor air from a prior injection.

We predict Equation (16) or (17) should have a good fit to measured data only after $\max(t_m)$ since those equations do not take into consideration any tracer gas concentration history in the garage when $t < 0$. From the graph of the

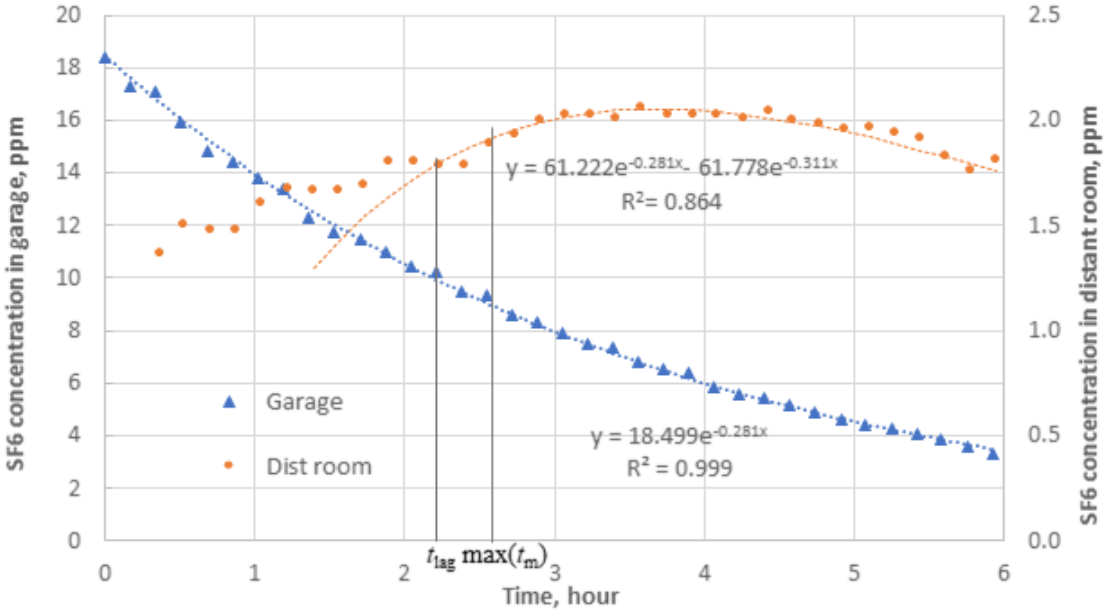

Figure 2 Estimation of air travel time from garage to a distant room from tracer gas decay test and model prediction graphs. (The tracer gas concentration in the distant room at the beginning of the decay test was caused partially by the tracer gas residue from the previous decay test. The tracer gas was pulse-injected into the garage once every six hours. The injection of the example occurred around 3:10 am on March 24, 2014.)

tracer gas concentration in the distant room, we can estimate $\max(t_m)$ to be around 2.6 hours. If we assume the fitting is relatively accurate after t_{lag}, then we can estimate the t_{lag} in the example is about 2.2 hours. The values of $\max(t_m)$ and t_{lag} can also be estimated based on outlier detections of three consecutive data points instead of subjective judgments. In the example, we can obtain the following values from the regressed equations with the test data: $C_{\text{g0}} = 18.499$ ppm, $\text{ACR}_{\text{g}} = 0.281$/hour, $\text{ACR}_{\text{a}} = 0.311$/hour, and $\frac{\text{ATR}_{\text{g-A}} f_{\text{lag}} C_{\text{g0}}}{\text{ACR}_{\text{a}} - \text{ACR}_{\text{g}}} = 61.222$ ppm. We then get

$$f_{\text{lag}} = e^{\text{ACR}_{\text{g}} t_{\text{lag}}} = e^{0.281 \times 2.2} = 1.856$$

and the garage air transport rate to the distant room is

$$\text{ATR}_{\text{g-A}} = \frac{61.222\left(\text{ACR}_{\text{a}} - \text{ACR}_{\text{g}}\right)}{f_{\text{lag}} C_{\text{g0}}} = \frac{61.222 \times (0.311 - 0.281)}{1.856 \times 18.499} = 0.053/\text{hour}$$

This means that the total air volume transported hourly from the garage into the distant room is ~5.3% of the distant room's volume.

The fraction of the garage air in the total air volume flowing into the distant room is estimated as

$$\frac{\text{ATR}_{\text{g-A}}}{\text{ACR}_{\text{a}}} = \frac{0.053}{0.311} = 17.0\%$$

That means that under the steady conditions, if the garage has a consistent contaminant concentration of 10 ppm, the transport of garage air will contribute 1.7 ppm of the contaminant to the air in the distant room. When the concentration of a contaminant in the garage is not consistent and changes arbitrarily with time, we can numerically solve Equation (15) to estimate the contaminant concentration in Room A after t_{lag}.

In fact, the model described by Equations (9) and (16) or (17) can be used to interpret any single tracer gas decay test with one tracer gas injection zone and another target zone in the same building, no matter how many zones there are in the building, and how far away the target zone is from the injection zone, as long as accurate tracer gas concentration data in the target zone can be obtained.

The model can be further applied to estimate the contribution of a local contaminant source or sink in an air space zone (not presented here due to space limitations).

CONCLUSION

It is a difficult task to characterize airflows between zones in a multizone building because those flows are highly correlated and hard to measure, making it difficulty to estimate the garage contaminant transport by analyzing those flows. Directly measuring and comparing the concentrations of contaminants in a house and in its attached garage is usually costly, and the accuracy of the measured results for the contaminant transports may be undermined by possible sources or sinks of the contaminants inside the house living spaces. The interpretations of measurement or simulation results are usually not much beyond ratios or direct comparisons of the maximum concentrations of contaminants or tracer gas in a garage to a living place, and contaminant transport mechanisms are not revealed clearly.

The model developed in this paper demands only a single tracer gas decay test, and has no limitation to the number of living space zones into which a test building is subdivided. It quantifies multiple characteristics of contaminant transport, such as the transport rate and overall transport time defined in this paper. The coefficients contained in the model have clear physical meanings, and are helpful to interpret and understand measured results. The model's goodness of fit in the presented example shows its effectiveness at characterizing the air transport from a zone to another and interpret measured data from tracer gas decay tests.

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