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A Novel Approach to Near-Real Time Monitoring of Ventilation Rate and Indoor Air Quality in Residential Houses

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ABSTRACT

Physics-based infiltration models, like Lawrence Berkeley Laboratory (LBL) and Alberta Infiltration Model (AIM-2), have been used to predict infiltration rate in near-real time. These models are derived from the driving forces of wind and temperature difference across the building enclosure system, both of which cause pressure differences across the enclosure system for infiltration. The model incorporates other major factors like building leakage characteristics, distributions of openings, microenvironment conditions around the building enclosure as affected by building shields, topography and building shape. The accuracy of the models dependents on getting these factors right. However, these factors are specific for individual buildings and measuring these factors in occupied buildings is difficult. In theory, these can be determined by using generalized table and blower door test but it requires heavy equipment and skilled work force, which is difficult to implement in occupied houses.

In this paper, a methodology is developed to determine the air change rate (ACH) and Indoor air quality (IAQ) in near-real time by combining a physics-based infiltration model with a tracer gas decay test method. The methodology is applicable to naturally ventilated houses. Existing infiltration models are modified explicitly to include the impact of the wind direction. The input data for the models also include indoor air temperature and weather data. Tracer gas method is used to determine the infiltration model parameters using multi variable nonlinear regression. Once these parameters are obtained, it is able to predict the ACH with 10% and 16% error for AIM-2 and LBL models, respectively

KEYWORDS

Infiltration, ACH, AIM2 model, LBL Model, Tracer Gas method

INTRODUCTION

For many residential houses in the U.S, infiltration is the main source of ventilation. Airtight buildings raise concern in indoor air quality (IAQ) unless mechanical ventilation is used (Skon et al., 2011). It requires measuring or predicting the ACH in better accuracy. The two standard methods to measure ACH are the building pressurization method and tracer gas method (ASTM E779-10, 2010; ASTM E741-11, 2011). Building pressurization method uses to compare infiltration between buildings and to measure building leakage characteristic. However, it is not applicable to near-real time infiltration measurement. Tracer gas method is the most accurate infiltration measurement near-real time. The choices of the tracer gas are limited. The presence of the occupant in test site could affect the measurement for tracer gas like carbon dioxide. Therefore, tracer gas methods are also not applicable at occupant presence.

Infiltration models are an alternative way to determine the infiltration rate in the building. The most common infiltration models are Reduction Pressurization Test, Regression Technique, ASHRAE Model, Building Research Establishment (BRE) model, Lawrence Berkley

Laboratory (LBL) model, and Alberta Infiltration model (AIM-2) (Awbi, 2003). All the infiltration models required blower door test to determine building leakage characteristics. Physics based models, LBL and AIM-2, gives a better prediction than the other models. These models derives base on the infiltration driving forces: wind and stack effect induced pressure differences across the building enclosure. They also include all of the important parameters like neutral pressure level, wind shield effect and building leakage characteristics. The accuracy of these models heavily depends on quantifying these factors. However, these factors are specific to individual buildings.

The objective of this paper is to combine the infiltration model, LBL or AIM-2, with tracer gas decay method to predict the ACH in near-real time for occupied naturally ventilated houses with a better accuracy.

METHODS

A methodology is developed to combine infiltration model (AIM-2 or LBL) with tracer gas method. As it is shown in Figure 1 below, the methodology has two parts: building calibration and monitoring. Steps only needed for building calibration are indicated by dotted line.

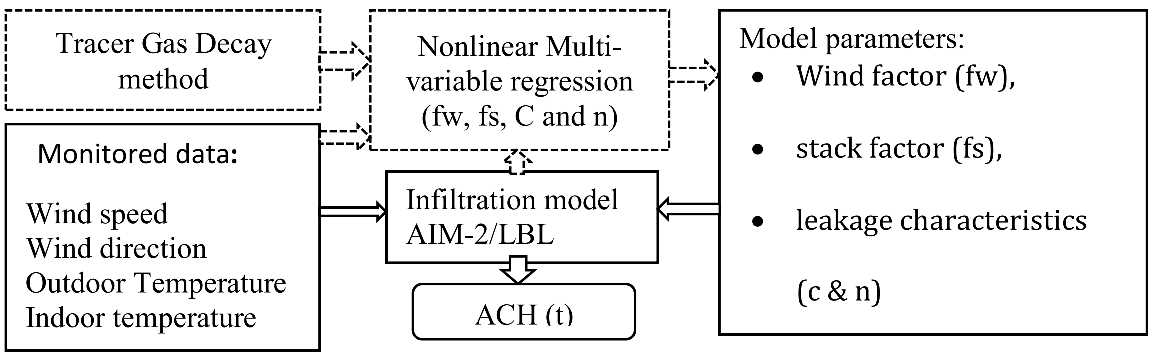


Figure 1. Methodology **to** determine ACH near-real time using tracer gas and weather data in the infiltration model

To determine the infiltration model parameter, preparing the house for a tracer gas decay test is the starting point. The calibration should be done in the absence of occupants. All door and windows should be closed. The indoor air temperature is set to 75°F and measured every minute. The weather data (temperature, wind speed and wind direction) for every minute is obtained from the nearby weather station. For this study, the National Oceanic and Atmospheric Administration (NOAA) weather data collected at Syracuse airport was used. A well mix condition is created inside the house by running the circulation fan continuously. The next step is to apply tracer gas method to determine the infiltration rate. The detail of the tracer gas technique was described in detail in (Sherman, M.H. 1990). CO2 is injected until it reaches 1200 ppm. Occupant generated CO2 can be used as the tracer gas for easier implementation of the method. This tracer gas concentration limit is set based on CO2 sensor capacity. It can be injected in the return duct or after the circulation fan. The CO2 concentration is measured in every minute. For leaky house the infiltration rate is higher. The tracer gas decays faster and reaches the outdoor CO2 concentration before collecting enough data to do the regression. For this kind of situation, the tracer gas is injected again when the room CO2 level reaches 600 ppm. The data collected from the BEST laboratory indicates that the outdoor CO2 concentration is between 360 to 380 ppm. It is important to note that the presence of CO2 in the background would affect the ACH measurement. From the CO2 concentration data, ACH is determined for every minute.

Once the weather data, the infiltration rate and the room temperature are known for every minute, nonlinear multi-variable regression technique is used to determine the infiltration model parameters. The regression variables, which are also the infiltration model parameters, are building leakage characteristics, building leakage exponent, wind factor and stack factor. To get valid results from the regression test, it is important to use the following the reasonable constraints:

1. Building exponent is between 0.5 and 1.
2. The building leakage coefficient is always greater than 0.
3. The combined shield and wind factor is between 0 and 1.
4. The stack factor is between 0 and 1.

Once the infiltration model parameters are determined from the regression, the infiltration of the house is calculated more accurately from the monitored wind speed, wind direction, the indoor temperature and the outdoor temperature.

Modified Infiltration Models

AIM-2 and LBL models are discussed in detail in (Walker and Wilson 1990) and (Sherman and Grimsrud, 1980) respectively.

In this paper, a discrete function is used to determine the wind factor and to capture the effect of the terrain and building microclimate as a function of wind direction. The wind factor function is given as:

$$fw = \begin{cases} f1 & where \;\; 0 \leq \phi < 30 \\ f2 & where \;\; 30 \leq \phi < 60 \\ f3 & where \;\; 60 \leq \phi < 90 \\ & \;\;\;\;\vdots \\ f12 & where \;\; 330 \leq \phi < 360 \end{cases} \tag{1}$$

where fw is the wind factor and ϕ is the wind direction. Wind angels 0, 90, 180 and 270 indicate wind blows from north, east, south and west respectively.

Error calculation

The absolute percentage error was used to compare the AIM2-Regression and LBL-Regression results. The error is calculated using the following equation:

$$|Error\%| = \frac{|(ACH_{measusred} - ACH_{Predicted})|}{ACH_{measured}} * 100 \tag{2}$$

where $|Error\%|$ is the percentage error, $ACH_{measusred}$ is the air change rate measured using tracer gas method, and $ACH_{Predicted}$ is the air change rate calculated using AIM-2 or LBL model.

Test House and location

The experiment was performed in Building Enclosure System Technology (BEST) laboratory located at Sky top Rd, Syracuse NY. The BEST laboratory is a two story building constructed in 2009 with the collaboration of Oakridge National Lab, Air Barrier Association of America, NYSERDA, and Syracuse University. The building has 41ft length, 33ft width and 21ft height. It has no internal partitions. The first story and the second story of the building are connected with a stairway opening. The building has central air system to cool and heat the house. The circulation system fan can set to run continuously. The building is also equipped with blower door test equipment. INNOVA gas monitoring system is used for tracer gas methods.

The building east side is shielded by trees. An office building is located in the west side the test house. The south side has no shield. There is a hill on the south west side of the BEST laboratory building. The elevation difference is around 120 feet.

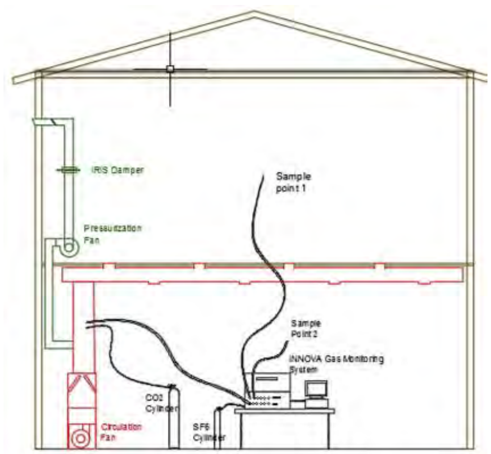
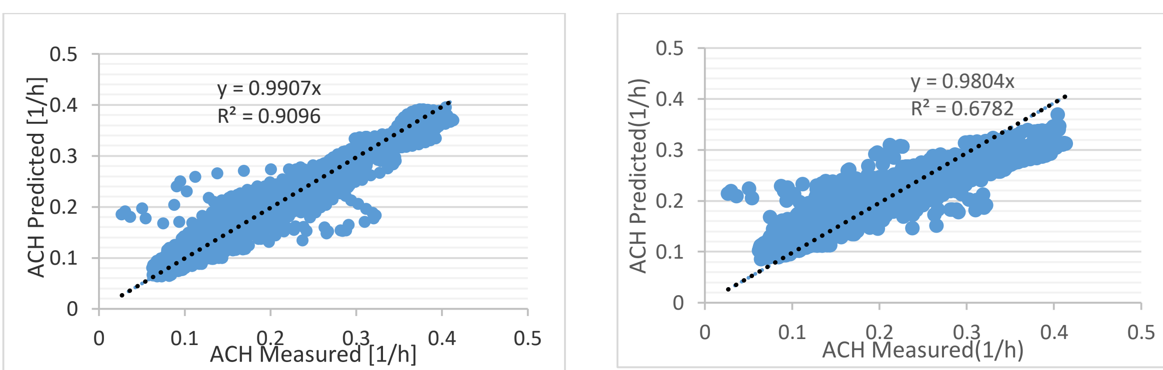


Figure 2. BEST lab equipment and arrangement

RESULTS

A non- linear multi-variable regression was used to determine the model parameters for both AIM2 and LBL models with a ten day data. Figure 3 presents the comparison between the measured and predicted ACH for AIM-2-Regression and LBL-Regression models respectively.



a) b)

Figure 3. Comparison between measured and predicted ACH results. a) AIM-2 model, b) LBL model

Table 1 indicates the AIM2 regression result has average error of 9.7 % with the standard deviation of 9.2%. On other hand LBL regression result indicates an average error of 15.6% with a standard deviation of 14.1%.

Table 1: Average error in percent for LBL and AIM2 model

	AIM2-Regression	LBL-Regression
$|Error\%|$	9.7%	15.6%
Standard deviation	9.2%	14.1%

AIM-2 regression model captures the entire measured infiltration spectrum better than LBL-Regression model. LBL-Regression tends to underestimate the infiltration rate due to the wind effect and overestimate infiltration rate cause by stack effect. The main difference between the AIM-2 regression and LBL regression equation that AIM-2 model considers the interaction between the wind effect and the stack effect. It is also important to notice that the wind effect of the AIM-2 model is as a function of wind velocity square.

Table 2: Comparison of AIM-2 regression with AIM 2 model done in other studies

	AIM2-Regression (BEST Lab)	Standard AIM2 model prediction (BEST Lab)			Francisco and Palmiter, 1996		Wang et al., 2009
Leakage Distribution	Not Applicable	X=R =0.6	X=R= 0.5	X=R=0 .37	X=R	X=0 & R=0.5	X=0 & R=0.5
|Error %|	9.7	17.3	24	35	16.2	46	19
Standard Deviation (%)	9.2	12.7	18.6	22.6			16

Table 2 shows the percentage error of AIM2 model for BEST laboratory and work done in previous studies. We can see that the AIM-2-Regression is the only method able to predict the ACH with an average absolute value error less than 10 %.

DISCUSSIONS

The AIM-2 Regression and LBL Regression model wind factor was expressed in a discrete function. This capture the impact of the building shape and the building surrounding to improve the accuracy of the model. The model parameters are unique for each building and its surrounding. The nonlinear multivariable regression for each building give a better result.

The author likes to mention the following two assumptions were validated. First a wel-mix condition was maintained when the circulation fan was running continuously. Second, Decay tracer gas method can be used to estimate near-real time ACH, if the decay process is capture in a minute interval and the CO2 level is high enough from the background level. The minimum CO2 level for decay test was set to 600 while the background level was around 360ppm.

CONCLUSIONS

The findings are summarized as followed:

- Weather data, IAQ monitoring and decay method can be used to predict the building leakage characterizes wind factor and stack factor.
- AIM2-Regression method predicts ACH better than LBL-Regression
- The accuracy of the new methodology is depending on the number of records obtained for regression.
- AIM-2-Regression predicts the ACH with an average absolute value error less than 10 %.

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