VALIDATION AND CALIBRATION OF A MULTIZONE NETWORK AIRFLOW MODEL WITH EXPERIMENTAL DATA

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ABSTRACT

This paper chronicles the development and refinement of a multizone network airflow model to represent a two-story classroom-office building. The model is initially developed during construction based on architectural plans and published leakage information. After construction is complete, envelope leakage is refined based on fan pressurization tests. Measured fan flow rates are then used to refine the air handling system portion of the model. A final revision makes use of automated tracer gas decay tests to fine-tune the flow rates to individual rooms. Predictions of the multizone model with these varying levels of refinement are then compared with additional tracer gas decay tests. The ability of the model to simulate the conditions of the experimental tests is evaluated at each stage of refinement. The experimental effort required for each step in the refinement process is discussed.

INTRODUCTION

Multizone network airflow models allow engineers to predict infiltration, ventilation rates, contaminant transfer, and pressure differences in buildings. Although the mathematics behind these models is well understood, it can be difficult to determine input parameters, particularly for envelope leakage. This may be dealt with by analyzing a range of possible leakages to obtain a bounded solution. Fan flows are easier to estimate, based on the mechanical system design.

In existing buildings, leakage and flow characteristics can be field measured. Fan pressurization, tracer gas tests, and flow measurement are three common techniques that could assist in fine-tuning model inputs. This paper documents the modeling process for one such ongoing project. A two-story classroom building is initially modeled during the design phase using published leakage data and architect's plans. The building leakage is refined based on results of a fan pressurization test, and flows adjusted based on field measurements. The modeled air handling system flows are then further adjusted based on a set of tracer gas decay tests. The refined models are then used to predict future tracer gas concentrations. This work discusses a process that can be used to refine a building model using experimental data. It also provides validation of the model as it might be applied to non-residential buildings.

MULTIZONE MODELING

The public domain multizone network airflow model CONTAMW (Dols et al 2000) was used for this study. In CONTAM, buildings are represented as networks of connected zones (e.g., rooms), within which uniform contaminant concentration is assumed. Zones are connected to one another and the outdoors via paths that represent the building component leakage. A mass balance calculation determines the flow between the zones and concentrations of contaminants distributed by this flow.

Defining the building leakage is perhaps the most difficult aspect of using these models. Buildings have many leakage paths, which may not be obvious from design drawings. The leakage associated with identical components can also vary significantly with construction. Fan driven flows in non-residential buildings can also vary from the design values shown in construction documents. When a building is being modeled in the design phase, it is common to model a range of leakages and fan flows. Modeling of existing buildings allows fine-tuning based on field measurements.

BUILDING DESCRIPTION

A two-story classroom/office building located on a college campus in the United States was used for this case study. Its design was intended to demonstrate innovative technologies and design techniques for reducing the environmental impacts of buildings. Some of its unique features include operable windows, CO_2 demand control, and an onsite biologically engineered wastewater treatment facility called a living machine.

The building has a classroom/office wing that is separated from an auditorium by a large atrium. The living machine is housed in an unconditioned glass enclosure adjacent to the atrium and auditorium and is maintained at a negative pressure relative to these spaces. A

primary air handling system serves the classroom/office wing, while another serves the auditorium and atrium.

The air handling system design seeks to supply 100% outdoor air for ventilation, in quantities modulated based on CO_2 demand control. Many of the occupied spaces are equipped with occupancy and CO_2 sensors. When a room is occupied, its supply damper is opened 50%. When the CO_2 concentration exceeds 800 ppm(v), the supply damper opens to 100%. A pressure sensor in the supply duct is intended to modulate the total outdoor air flow supplied by the air handling unit.

EXPERIMENTAL MEASUREMENTS

Fan pressurizations tests are commonly used to measure exterior envelope leakage in residences and other small buildings (ASTM 1999). The building is pressurized using a calibrated fan and the resulting pressure difference between indoors and outdoors is measured. Results over a range of pressures can be correlated to a powerlaw relationship that can be used to estimate the leakage at a given pressure difference. This method quantifies the gross exterior envelope leakage, without regard for location of specific leakage sites.

The building studied here was small enough that it could be pressurized up to 40 Pa using two calibrated fans of the type that are normally used in residences. One test was conducted with all interior doors open to obtain the overall exterior leakage. Since the auditorium wing was easily isolated from the rest of the building, it was tested separately as well.

Fan driven flows throughout the building were also verified. Flow rates for localized exhaust fans were measured using a flow hood. Gross air handling system supply and return flow rates were measured by pitot tube duct traverse, a method commonly used in testing and balancing (ASHRAE 1988). A pitot tube and differential pressure gauge are used to measure the velocity pressure at evenly spaced points over a cross section of the duct, to obtain air speed. These readings are then averaged and multiplied by the duct cross sectional area to obtain the duct flow rate.

Smoke tests are another useful method to qualitatively document airflow behavior in buildings. Tubes, candles and other devices can be used to generate a small amount of smoke for flow visualization. This technique was used to verify the direction of flow between rooms under normal operating conditions.

Building air change rates under actual operating conditions were measured using tracer gas decay (ASTM 2000a). Sulfur hexafluoride (SF_6) tracer gas was periodically released upstream of the air handling unit supply fan to maximize mixing and achieve as uniform as possible distribution throughout the building. This technique allows calculation of the building air change rate based on decay of the tracer gas over time.

Automated tracer gas injections were enabled at each of the two air-handling units at two hour intervals. Pressure switches were used to indicate fan on/off status so that no injection would be made when an air-handling fan was off. Air sampling pumps were used to collect samples from nine building rooms and the outdoors via a network of polyethylene tubing. These samples were analyzed using a gas chromatograph equipped with an electron capture detector, calibrated to determine SF_6 concentration between 5 and 300 ppb.

CONSTRUCTION STAGE MODEL

During construction, the architect's plans were used in conjunction with published leakage data to obtain a model representation of the building. Building envelope leakage was specified for the CONTAM model using a hybrid approach that considered some easily identified leakage sites (such as doors and windows) and a distributed envelope leakage to describe wall construction and other details. This approach allowed the impact of easily identified leakage sites to be applied in the correct location, while reducing the input effort for less obvious leakage paths.

Door and window leakages were taken from ASHRAE residential data (ASHRAE 1997). Distributed envelope leakage of 0.75 cm^2/m^2 was also specified. This leakage was chosen to provide an overall leakage of 1.1 cm^2/m^2 (at 10 Pa, C_D=0.6) in a simulated fan pressurization test. This leakage is slightly lower than the average of 79 office and school buildings in the US, Canada and UK that were surveyed in a recent review (Persily 1999). Interior partitions, ceilings, and floors were modeled with twice the leakage of the exterior walls. An air handling system, with diffuser flows taken from the mechanical design drawings was also specified. Figure 1 shows the layout of zones, leakage paths, and HVAC diffusers for a portion of one floor of the building.

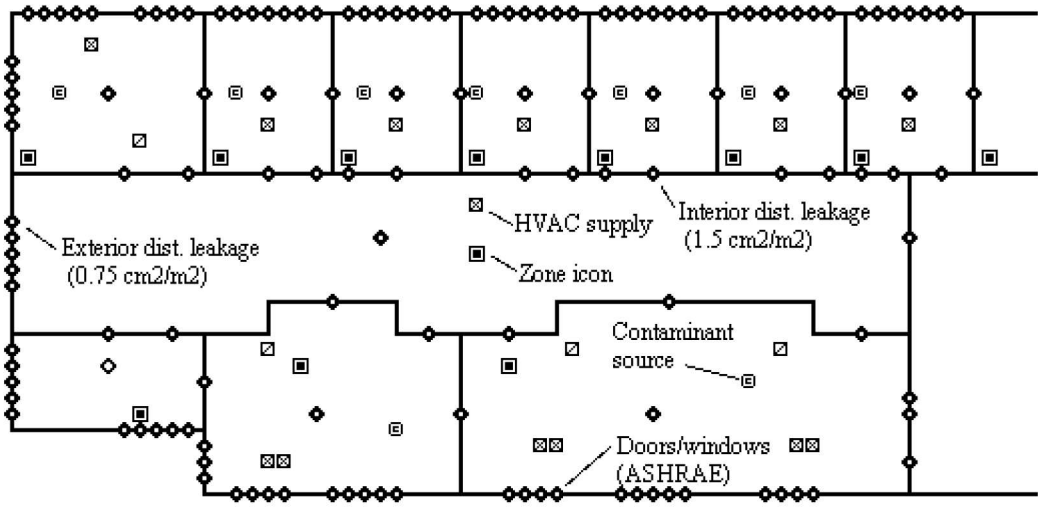


Figure 1. CONTAM model of representative floor and modeling assumptions.

FAN PRESSURIZATION MODEL

After construction of the building was complete, fan pressurization tests indicated that the exterior envelope of the building was roughly four times leakier than was originally assumed. Based on this result, the distributed exterior envelope leakage of the model was changed from 1.1 cm^2/m^2 to 4.3 cm^2/m^2 to match the experimental test. This was a significant increase, so the interior leakage was also adjusted to maintain a ratio of 2:1 between interior and exterior leakage.

The isolated pressurization test of the auditorium was used to specify large leakage paths that were visually apparent between that space and the attached living machine. This was done by assuming that the distributed exterior leakage was the same as for the building as a whole, and the excess measured leakage was used to define a path connecting to the living machine.

Figure 2 shows simulated fan pressurization tests for the construction stage model (leakages estimated from published data) and the fan pressurization model (leakages adjusted to match the actual fan pressurization tests). The large differences in the two curves underscores the importance of modeling a range of leakages in cases where the actual leakage cannot be measured.

MEASURED FLOW RATE MODEL

The next step in collection of experimental data was to field verify as many fan-driven flow rates as possible. Several "service" areas located on the first floor are ventilated by local exhaust fans. These are controlled using a variety of means including thermostat, occupancy sensors, and switch. Flow rates for all of the accessible fans were verified using a flow hood. A few of these fans were not accessible, so the design flow rate listed on the mechanical schedule was used.

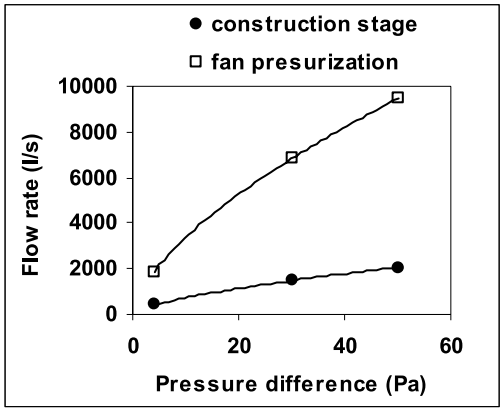


Figure 2. Fan pressurization test of construction stage and fan pressurization models.

The exhaust fan used to depressurize the living machine was too large for use of a flow hood. It was originally specified to operate at constant flow rate, but was oversized and the doors had to be kept locked to keep them from blowing open when the fan was operating. To solve the problem, a variable speed drive was installed and controlled to maintain a 20 Pa pressure difference between the living machine and the adjacent atrium. In CONTAM, this fan was therefore specified to maintain a pressure difference of 20 Pa.

Duct traverse velocity measurements were used to determine the overall supply and return volumes of the two air handling systems. Duct velocity measurements taken with the dampers in the spaces with CO_2 demand control dampers commanded to various positions

showed that the duct pressure feedback mechanism did not reduce the total volume of outside air supplied to the building. Therefore, the design flow rate was supplied by the system at all times, regardless of damper position in the individual spaces. The operation of dampers at each of the rooms served to change the distribution of the ventilation air among the spaces, rather than reduce the overall volume of supply air to the building. This was not easily remedied, and this operating scenario continued throughout the tests.

It was also discovered at this stage that the auditorium had not been scheduled for classes during the first semester of building operation. As a result, the air handling system serving that part of the building was usually off and was deactivated in the CONTAM model.

The primary air handling system design supply and return flow rates at each diffuser were scaled down proportionally to match the measured overall system flow. Little change was made to the supply flow, which was within about 10% of the design volume. The measured return volume was only about 60% of that which was expected based on the design drawings, so it was scaled back more significantly in the model.

To evaluate the performance of this and the previous two models, their predictions were compared with the results of ten tracer gas decay tests. In CONTAM, each decay test was modeled separately; with initial concentrations of SF_6 tracer gas specified as the measured concentration in each room at the start of the decay period. For spaces in which the SF_6 concentration was not measured directly, the concentration for a similar space was used. This did not cause much of a problem, because most of these spaces were depressurized with respect to those in which SF_6 concentration was measured. However, the corridors were an exception. The corridors received a large volume of supply air from the air handling system, and communicated significantly with the atrium and auditorium through flow driven by the large exhaust fan in the living machine. At this step, the initial concentrations of tracer gas in the two corridors (C_{est}) were estimated using a simple mass balance for a tracer gas that is uniformly mixed in the supply air and the design supply flow rate. The quantity VC_{est}/Q_s in the corridor was approximated by the average of VC_{meas}/Q_s in the rooms in which SF_6 was measured. Here, V denotes the room volume, C_{meas} is the measured initial SF_6 concentration, and Q_s is the volume of air supplied to each room by the air handling system.

CONTAM simulations for the three levels of model refinement were compared with measurements of SF_6 concentration in each room taken at ten minute intervals. These comparisons were quantified using correlation coefficient and normalized mean square error as defined by the ASTM Guide for Statistical Evaluation of Indoor Air Quality Models (ASTM 2000a).

The correlation coefficient (r) is defined as:

$$r = \frac{\sum_{i=1}^{n}\left[\left(C_{m,i}-\overline{C_m}\right)\left(C_{p,i}-\overline{C_p}\right)\right]}{\sqrt{\left[\sum_{i=1}^{n}\left(C_{m,i}-\overline{C_m}\right)^2\right]\left[\sum_{i=1}^{n}\left(C_{p,i}-\overline{C_p}\right)^2\right]}}$$

where, C_m is the measured concentration and C_p is the concentration predicted by the model. Correlation coefficient measures the degree of linear relationship between the two data sets. Its maximum value of 1 indicates a perfectly linear positive relationship, while the minimum value of –1 signifies a perfect negative relationship. It is important to note that either data set could be multiplied by a constant without changing r (Devore 1987). This means that two parallel decay curves would have r=1, even though the concentrations might be very different. However, since in this case all modeled concentration curves begin with the same concentration as was initially measured, different concentrations at later times must be accompanied by a difference in the slope of the decay curve.

The normalized mean square error (NMSE) measures the magnitude of the difference between the predicted (C_p) and measured (C_m) concentrations, and is defined as,

$$NMSE = \frac{\overline{\left(C_p-C_m\right)^2}}{\overline{C_p}\,\overline{C_m}}$$

NMSE will equal zero when the predicted and measured concentrations are equal. For cases in which the two data sets differ consistently by 50%, NMSE will be about 0.2, and when they differ by 100%, NMSE will be about 0.5. When considered in conjunction with the correlation coefficient, NMSE helps to identify cases in which the concentration profiles are parallel but not equal.

The correlation coefficients and NMSE values shown in Table 1 are averages for ten decay periods. In most of the spaces, the model predictions did not improve significantly as the model was refined. Because the flow in these rooms is primarily fan-driven, the predictions of the first two models are not very different, even though the building envelope is much leakier in

the second model. This would not be expected to be the case in the absence of fan-driven flow, since the infiltration performance of the two models would depend on building leakage. In the third model, the fan flows were adjusted to reflect the overall measured flow to the building. However, since the overall supply flow was close to design, this did not result in a significant change for these spaces either.

Tracer gas decay rates in the administration, classrooms, conference room, and library all tended to be over-predicted by the three computational models. A typical decay period for one of these spaces is shown in Figure 3a. These spaces tended to be pressurized by the air handling system with respect to the outdoors and corridors. Therefore, the experimental profile is similar to an ideal exponential decay curve.

The spaces discussed above all utilize CO_2 demand control. The building was lightly occupied during the test period and CO_2 levels (also documented by our instrumentation system) rarely exceeded 800 ppm, so the dampers serving these spaces would have been in the 50% open position during most hours of operation. Since the system is still supplying the same volume of supply air to the entire building, some of the supply air intended for these spaces would be diverted to duct leakage and the spaces without demand control. These include the six offices (represented by typical office 1) and the corridors on the first and second floors. Visual inspection of the concentration profiles for the office verified a higher measured tracer gas decay rate than was planned during design. Based on this observation, it is likely that a larger than intended volume of supply air was supplied to the corridors as well.

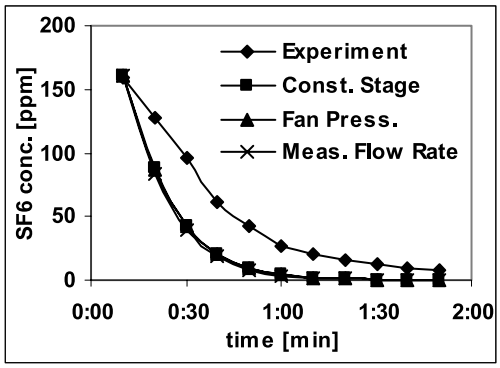
The much lower correlation coefficients obtained for the auditorium indicate a difference in shape between the predicted and measured concentration profiles. This effect was also present in the atrium, but to a somewhat lesser degree. During the decay period, the tracer gas concentrations in these spaces did not follow an exponential decay profile. This is because the air handling system that supplies ventilation air directly to these spaces was not operating during the tests. The large exhaust fan in the living machine created an airflow pattern that moved air from corridors into the atrium, through the auditorium and out via the living machine. Figure 3b shows typical measured and modeled concentration profiles for the atrium. These show a tendency of the three models to predict some transfer of tracer gas into the atrium after the injection, but it is not as high as was measured. This is consistent with the three models under-predicting the volume of supply air (and thus tracer gas) delivered to the corridors.

Likewise, there was not a notable reduction in the NMSE with these three model refinements. One exception is that the fan pressurization model improves the auditorium prediction. This happens because the leakier building components allow more tracer gas to enter the auditorium. However, the predicted tracer gas concentrations are still lower than were measured.

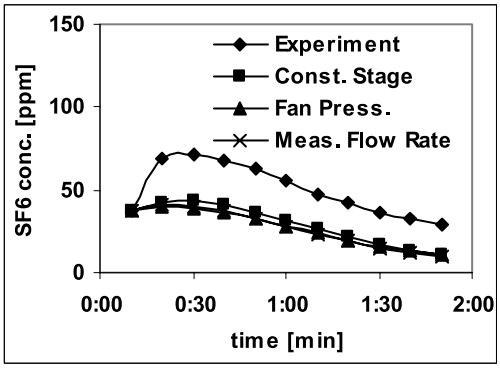
All three models also consistently under-predicted the tracer gas decay rate in the mechanical room. The flow rate of the exhaust fan in that room could not be measured using a flow hood because access to the fan was blocked by equipment. Therefore, the under-prediction in airflow rates by all three models suggests that the fan is actually removing more air than is specified on the design drawings.

Space	Construction stage model		Fan pressurization model		Measured flow rate model	
	r	NMSE	r	NMSE	r	NMSE
Administration	0.94	0.31	0.94	0.25	0.94	0.29
Atrium	0.91	0.25	0.89	0.27	0.90	0.26
Auditorium	0.47	0.73	0.71	0.38	0.77	0.33
Classroom 1	0.96	0.26	0.96	0.24	0.96	0.30
Classroom 2	0.97	0.26	0.97	0.26	0.97	0.29
Conference	0.96	0.48	0.96	0.42	0.95	0.53
Library	0.96	0.32	0.97	0.24	0.97	0.30
Mechanical	0.96	0.23	0.97	0.21	0.95	0.30
Office 1	0.97	0.10	0.96	0.15	0.96	0.16

Table 1. Average Correlation Coefficient and Normalized Mean Square Error.



(a) Classroom 1



(b) atrium

Figure 3. Measured and Predicted tracer gas decay.

TRACER GAS DECAY MODEL

The final model refinement considered average air change rates in each of the rooms based on one month of tracer gas data. The tracer gas decay technique estimates air change rates in any enclosure that acts as a single zone. Testing of an entire building requires that the tracer gas be at a uniform concentration throughout the building at the start of the test. The method could also be applied to a single room provided that no tracer gas enters it from adjacent spaces during the test. In this case, modeling and smoke testing had shown that the rooms receiving supply air from the air handling unit were pressurized with respect to most of the neighboring spaces, with little tracer gas leaking back into them. This was supported by the observation that the tracer gas decay profiles for these rooms resembled exponential decay curves. For these spaces, average air change rates for the month were estimated based on tracer gas decay for each room, and are shown in Table 2.

Tracer gas was only released when the air handling system was operating, so Table 2 represents this condition. Air change rates were then compared with the prediction of the measured flow rate model for the rooms in which tracer gas concentration was measured directly. Again, air change rates in spaces with CO_2 demand control tended to be overestimated by the model while the air change rate in the office, which is not demand controlled, was under predicted.

Space	Experiment*		Measured flow model
	Air chg. rate (hr^{-1})	Std. Dev.	Air chg. rate (hr^{-1})
Administration	1.00	0.43	1.73
Classroom 1	1.00	0.19	2.63
Classroom2	1.60	0.27	4.19
Conference	1.22	0.24	3.87
Library	1.10	0.23	2.07
Office 1	1.30	0.24	0.93

Table 2. Air Change Rates For Spaces Served by Primary AHU.
**averaged for one month*

In the final model refinement, supply air volumes to each room were fine-tuned to match the air change rates shown in Table 2. Because the air handling system was not capable of reducing its overall supply volume, the amount of air supplied to the two corridors was determined by adding together the supply volumes for all of the other spaces, and subtracting that sum from the total system supply.

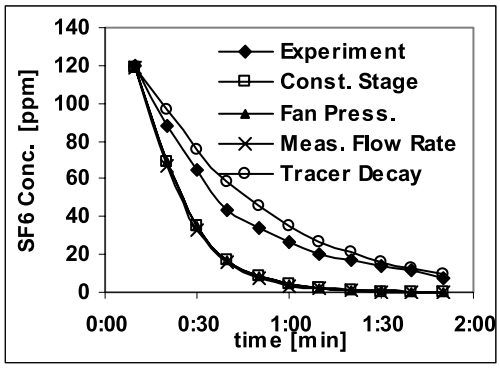
This adjustment resulted in a larger amount of ventilation air supplied to the corridors by the air handling system. In the CONTAM model, the initial concentration of tracer gas in the corridors was estimated using the same technique as for the measured flow rate model. This resulted in higher initial SF_6 concentrations in the corridors.

The tracer gas decay model was then used to simulate five future tracer gas decay tests. Figure 4 shows the predictions of all four models compared with one of these future decay periods. This final model refinement produces a tracer gas decay profile in classroom 1 that is much closer to the measured profile.

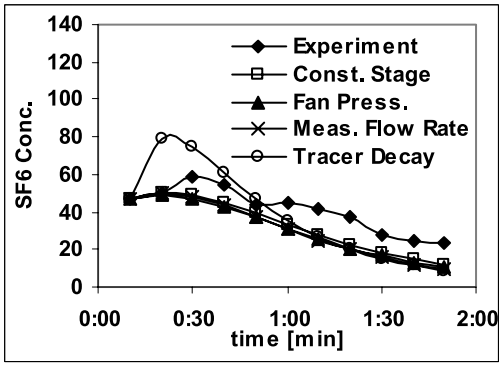
In the atrium (Fig. 4b) and auditorium, the higher initial concentration modeled in the corridors resulted in model predictions that were closer to the experimental measurement, but the agreement was still not as good as for the other rooms. This would be expected, since these large spaces would not be as well represented by a single concentration measurement.

Figures 5 and 6 show the correlation coefficient and NMSE for the tracer gas decay model compared with

those obtained for the other models as shown in Table 1. The increased correlation coefficient in nearly every room indicates that the tracer gas decay model improves the predicted air change rate. Likewise, the NMSE drops significantly for these rooms as well.



(a) Classroom 1



(b) atrium

Figure 4. Measured and predicted tracer gas decay.

Classroom 2 is the single exception to this trend. Upon investigation, it was noted that during three of the five decay intervals used to analyze the tracer gas decay model, the CO_2 readings in this room were above 800 ppm. Since this had rarely occurred during the prior month, it would be expected that the damper to this space would now be 100% open and the model would underpredict the supply flow rate to this room. Thus, to make its predictions more accurate, one would have to devise a mechanism for linking the model to the actual changing room flow condition.

DISCUSSION

Building leakage characteristics have often been stressed as an important contributor to realistic model predictions. However, in this study properly defining the fan driven flows more directly influenced the model results. This occurs because the air change rate under the model conditions is primarily fan driven. Infiltration data collected for this building showed air change rates of approximately 0.25 h^{-1}, compared with approximately 1 h^{-1} when the fan was on. Therefore, the fan flow rate is most important to properly represent the building when the fan is on. If the model were being used to predict infiltration (fan off) conditions, or if the fan flow rate were determined based on pressure control, however, the leakage of the exterior envelope would undoubtedly play a more significant role.

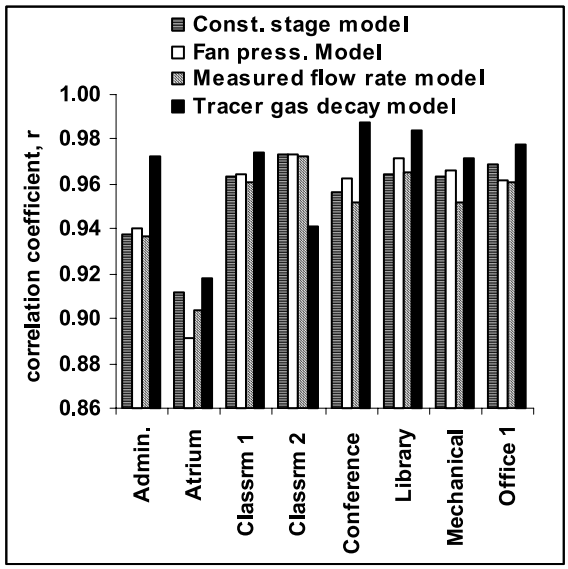


Figure 5. Correlation coefficient

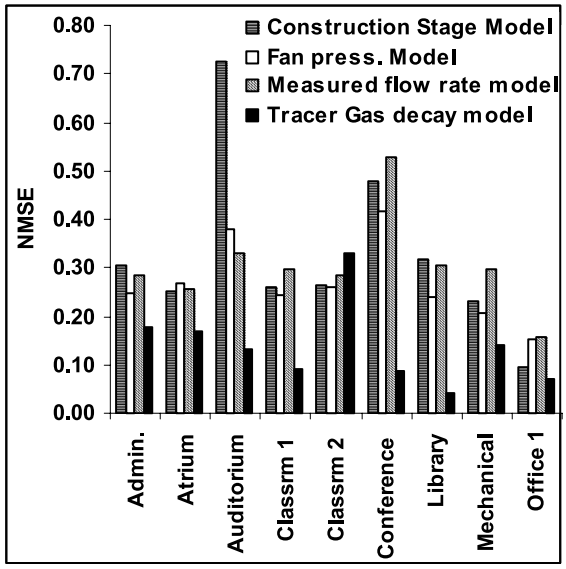


Figure 6. Normalized mean squared error.

Of the experimental techniques used for refinement of the model, the tracer gas decay tests required the most effort. The fan pressurization tests were completed in

a half-day and the data analyzed in an hour. Likewise, the flow hood measurements, smoke test, and duct traverses were conducted in about one day. The tracer gas decay tests required a long-term installation of tubing, measurement equipment and an automation protocol. A temporary setup could have been implemented more quickly, but a significant computing effort was also required to sort and analyze the collected data.

The level of effort needed to adequately characterize fan-driven flows depends on the type of ventilation system and its configuration. A duct traverse at the air handling system is a good first step to verify that the overall volume of supply air is close to what is expected. This measurement is often done as a part of the testing and balancing process. If the system has a mechanism to reduce the overall volume of supply air, a repeated duct traverse in the same location at this partial flow condition can uncover irregularities in part load operation.

Additional duct traverses in downstream branches of the system or flow hood measurements might also be used to field verify the distribution of supply air. In the case of a variable volume system, measurement of another control quantity, such as CO_2 or temperature could help to estimate flow under specific operating conditions. Unique aspects of this building simplified the process somewhat. Despite the fact that damper control did change the distribution of supply air among the spaces, low occupancy resulted in less variability in air change rates in these spaces.

CONCLUSIONS

In comparison to the measured data, the CONTAM predictions were quite good for the pressurized spaces once the flow rates to individual rooms were defined based on experimental measurements. Because this air handling system was not operating as designed at part load, significant measurement effort was required to understand and quantify the actual operating condition.

Proper definition of the fan driven flows was the most important experimental measurement contributing to agreement of the model and the experiment. This is because the building air change rate during the experiment was primarily driven by fan flow and because flow rates were defined directly in the model. If the building fans had been controlled to provide defined pressure differences or if the model had been used to predict infiltration for a period in which the air handling system was off, proper definition of the exterior envelope leakage would have been more critical.

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