Field Testing of Data Driven Multizone Model Calibration Procedure

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SUMMARY

Field tests of a proposed efficient air flow model calibration method were performed on two classroom/office buildings. Models developed using CONTAM multizone software were tuned via an iterative procedure that sought to maximize the fraction of correctly predicted interzonal flow directions. Site measurements during a concentrated period of testing, including HVAC air flows, envelope leakage, and site weather data were used to update the multizone models. Following an initial group of mandatory measurement, CO_2 tracer gas experiments were conducted to permit independent assessment of model quality using ASTM Standard D5157-97. In one case, the procedure was quite effective, improving the number of correct interzonal flow directions from an initial value of 52% to a final value of 81% and significant improvement was also indicated by the ASTM method. Tuning produced only minor improvement in the second building. Greater difficulties in acquiring site measurements and the greater complexity of the second building are possible reasons that performance was less satisfactory in that case.

INTRODUCTION

In recent years, the public, governmental agencies, and the HVAC industry have shown increased interest in understanding and predicting air and contaminant movement through buildings for purposes of indoor air quality evaluation and the analysis of extraordinary incidents. A number of documents available to the public [1, 2] give generic guidance on making buildings resistant to airborne chemical and biological releases. However, prediction of air and contaminant flow for a particular building of interest is necessary for risk assessment, development of emergency procedures, and system design for building protection against both intentional and accidental events.

Modeling with various types of software can be a quick and cost-effective way to analyze the consequences of an event of interest. Multizone models, although limited by the use of the well-mixed zone assumption, are considered the most practical and useful choice for modeling air and contaminant flows in whole buildings [3]. However, due to the many simplifications and assumptions inherent in multizone methods, an uncalibrated model may be a poor representation of a particular real building. Although highly desirable, calibration can be a time consuming and expensive process.

Field tests were performed as part of a project to develop a method for rapidly developing and tuning multizone air flow models of real buildings constructed with the widely used CONTAM software [4] via relatively simple, inexpensive measurements taken at the site.

This paper summarizes the findings of those tests with respect to the degree of model quality improvement achieved as a result of the tuning process.

METHODS

Equipment and Measurement Techniques

The procedure requires a variety of measurements and the appropriate instruments to perform them, including indoor temperature (hand held thermometer), diffuser air flow rate (flow measuring hood), differential pressure for leakage tests (wireless pressure sensor), interior air flow direction (smoke bottle), AHU flow rates (fan inlet airflow sensor or pitot traverse), and weather conditions (portable weather station). Additionally, transient CO_2 tracer gas tests were performed in an effort to validate the procedure (portable infrared CO_2 gas analyzers).

Test Sites

Calibration exercises were performed for two buildings. The first (RB-1) is a three story (plus basement), 3,810 m^2 building mainly comprised of office spaces, but also including conferences areas and a snack bar. The building is air-conditioned by three air handling units (AHUs). AHU 1 serves three large conference spaces on the first floor with ducted supply and return. AHU 2 serves the remainder of the first floor and the entire second floor. The first floor has ducted supply and return, while the second floor has ducted supply and plenum return. AHU 3 serves the third floor with ducted supply and return. Bathrooms are connected to an exhaust system and receive makeup air through transfer grilles.

The second building (RB-2) is a larger, more complex five story (plus basement), 8,500 m^2 structure comprised of classrooms, office spaces, and conferences areas. The area excluding the basement, which was not modeled, is 6,920 m^2. The first two floors house classrooms and medium-sized lecture halls, while the third through fifth floors house faculty, staff, and graduate student offices. Each floor is served by its own AHU via ducted supply and return. The first floor also has two large lecture halls with dedicated single-zone AHUs, but these are isolated from the rest of the building and were not considered in the modeling.

Model Tuning Procedure

The tuning procedure was initially developed from “virtual building” testing in which a simplified multizone model was tuned to match a reference model through the use of simulated measurements (i.e., the use of data values from the reference model to update the simplified model) [5 - 7]. The approach is similar to the heuristic method described by Musser et al [8], differing mainly through the use of a more structured technique based on iterative improvement of a suitable performance metric.

One possible quality measure is ASTM Standard D5157-97 [9]. However, this standard requires the use of tracer gas testing and was deemed too difficult and costly for widespread application by building modelers or owners. After considering various options, the fraction of correctly predicted interzonal flow directions (or equivalently, the relative pressurization of zones) was selected as the principle quality metric. A flow direction map of a building can be developed rapidly and inexpensively using simple hand-held flow visualization devices such as smoke bottles.

The first step in the procedure is initial model development. This model is based on construction documents and data values from literature (e.g., component leakage, terrain coefficients, etc) and requires no site data, although sources such as commissioning reports may be of use, if available.

At the beginning of the site measurement phase, a weather station should be set up to log ambient conditions throughout the test. The first iteration of building measurements includes mapping of interzonal flow directions and measurement of main air flows such as supply, return, and outside air at air handlers and, if possible, envelope and shaft leakage. The model is updated with these data.

Prior to the first model update and after each update, predicted flow directions are compared with measure directions to determine the value of the performance metric and to identify areas of discrepancy within the building. Air flows to zones connected by flow path with incorrectly modeled flow direction are measured (Figure 1), the model is updated, and new predictions of interzonal flows are generated. This process is repeated until a stopping criteria is reached, which may be the point of diminishing returns in improvement of the predicted flow direction distribution, the completion of all possible measurements, or some other condition determined by the analyst.

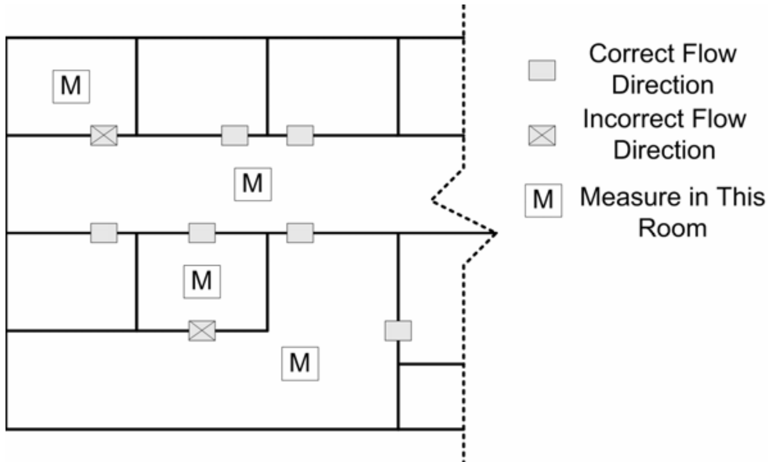


Figure 1. Example of measurement guidance based on location of incorrect airflow directions

The final step in tuning is an analytical process in which optimal (in the sense of reducing error) values of difficult or impossible to measure model parameters are determined. To date, this processs has been applied to four parameters: average exterior leakage, average interior leakage, average shaft leakage, and terrain coefficient (used to calculate wind pressure on the envelope in CONTAM). Any of these parameters that have been measured previously are excluded from this step.

Validation Methodology

Two key questions arise in the validation of the tuning procedure. The first is whether the measurement and model correction process leads to improvement in the correct flow direction performance measure. The second is whether improvement in this metric parallels improvement as measured by an independent standard such as ASTM D5157.

ASTM D5157 employs six statistical measures (correlation coefficient, regression slope, regression intercept, normalized mean square error, fractional bias, and fractional variance) to compare modeled and observed tracer concentrations at a given sampling location. Satisfactory ranges are defined for each parameter. How to apply the standard to multiple sampling points is not discussed in the standard. In the present case, the approaches used were 1) to tabulate the percentage of all metrics (six per sampling location) that fell within the satisfactory range at each stage of correction and 2) to examine the distribution of values of a particular metric at different points in the tuning process.

In RB-1, releases were performed in all three AHUs in turn and measured at all AHU returns (three locations) with a repeat of each release. In RB-2, releases were performed at the AHUs serving floors one, three, and five and measured at all five AHU returns. The quantity of CO_2 injected was intended to raise concentration in the area served by the release AHU by1600 ppmv in order to obtain an easily measured signal.

RESULTS

RB-1 Model Tuning

Tuning of the model of RB-1 was completed in seven iterations, as outlined in Table 1. It should be evident from the decreasing number of measurements at later iterations that the measurement time per iteration decreased significantly as the process progresses.

Table 1. Summary of RB-1 Tuning Process

Iteration	Description
0	Model developed using design document data
1	Interzonal air flow directions and supply, return, and outdoor air flows of all AHUs are measured. Recording of weather conditions (temperature, wind speed) begins.
2	122 diffuser measurements based on location of incorrect airflow directions
3	24 diffuser measurements based on location of incorrect airflow directions
4	10 diffuser measurements based on location of incorrect airflow directions
5	6 diffuser measurements based on location of incorrect airflow directions
6	2 diffuser measurements based on location of incorrect airflow directions
7	Interior leakage, exterior leakage, shaft leakage, and terrain coefficient & exponent are adjusted based on minimization of regression equation.

Figure 2 shows the progression of the percentage of correct interior airflow directions and the percentage of satisfactory ASTM metrics for the seven iterations described in Table 1. A single point in the ASTM data set represents, in this case, one hundred and eight data points: 2 sets of releases x 3 releases per set (at AHU 1, 2, and 3) x 3 measurement points per release x 6 statistical metrics per measurement points. The percentage of correct interior airflow directions is initially 52% and increases to a final value of 81% over the course of the tuning exercise. The greatest improvement occurs during iterations one (to 63%) and two (to 72%). The automated tuning process (iteration 7) produced no change in this metric, probably because the only parameter changed was shaft leakage value.

In the base model, 31% of ASTM D5157 metrics were within satisfactory ranges. The first iteration of tuning increased the total to 41%, but subsequent iterations, evaluated in this way, produced little change. The lack of improvement in later iterations is very likely the result of there having been a small number of measurement locations in the field test, and the placement of those sampling points in the AHU returns. The concentration of tracer returning to these locations represents the average of all connected zones, therefore, changes in flows between zones are likely to have little effect on what is observed there. Sampling points within spaces would be needed to provide a more refined indication of the effect of local flow adjustments. Previous application of ASTM D5157 during “virtual building” tests permitted evaluation of the ASTM statistical metrics in every zone. In these tests, improvement in quality as measured by the ASTM standard paralleled quality as indicated by improvement in correct flow directions and continued throughout the tuning process [5-7]

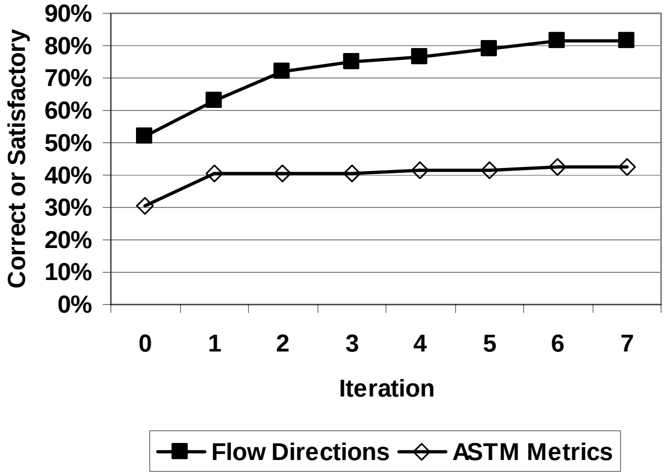


Figure 2. Correct interzonal flow direction and satisfactory ASTM metrics for RB-1 model tuning.

The use of a binary satisfactory/not satisfactory criterion for evaluating model quality using ASTM D5157 does not account for the possibility that unsatisfactory metrics move closer to the satisfactory range as a result of tuning. They may remain unsatisfactory as defined by the standard, but nevertheless are improved. One way to investigate this issue is to compare the distribution of values of a metric with the ASTM D5157 criterion over the course of several tuning iterations. For example, Figure 3 shows a cumulative distribution plot of correlation coefficient values from iterations 0 and 1 (during which essentially all of the change in ASTM metrics occurred). Lines indicating perfect and minimally acceptable values are shown for reference. . This result was the same for all statistical measures (except normalized mean square error, which showed no change), so this way of analyzing the data lends credence to the previous analysis.

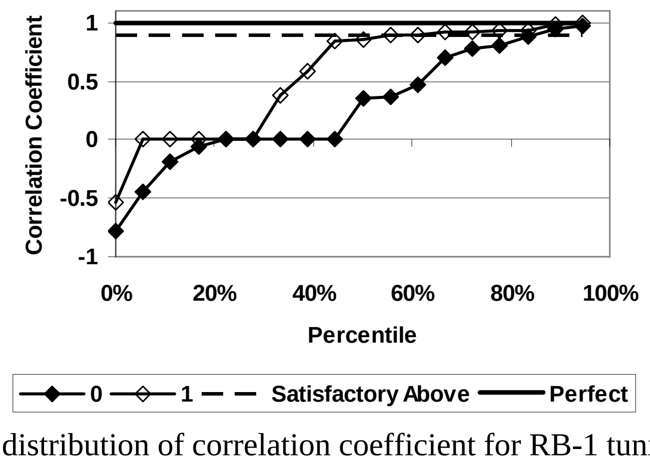


Figure 3. Percentile distribution of correlation coefficient for RB-1 tuning for iteration 0 and iteration 1.

RB-2 Model Tuning

The model of RB-2 was tuned in four iterations, described in Table 2. Iterations 4a and 4b are Alternative applications of regression to determine unmeasured parameters. Iteration 4a included estimation of exterior leakage while 4b did not.

Table 2. RB-2 tuning steps

Iteration	Description
0	Model developed using design document data
1	Interzonal air flow directions and supply, return, and outdoor air flows of all AHUs are measured. Recording of weather conditions (temperature, wind speed) begins.
2	229 diffuser measurements based on location of incorrect airflow directions
3	52 diffuser measurements based on location of incorrect airflow directions
4a	Interior leakage, exterior leakage, shaft leakage, and terrain coefficient & exponent are adjusted based on minimization of regression equation.
4b	Interior leakage, exterior leakage, shaft leakage, and terrain coefficient & exponent are adjusted based on minimization of regression equation. Measured exterior leakage is used

Figure 4 shows the progression of the percentage of correct interior airflow directions and the percentage of satisfactory ASTM metrics.

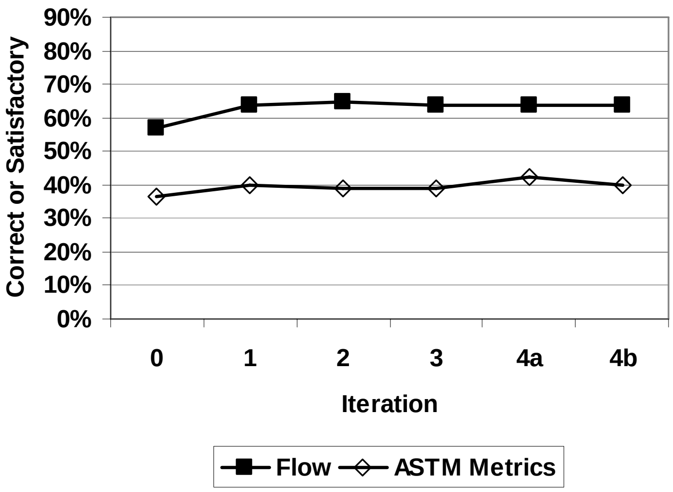
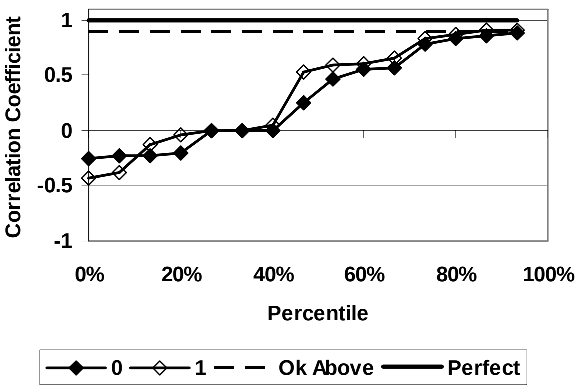


Figure 4. Correct flow direction and satisfactory ASTM metrics for RB-2 model tuning.

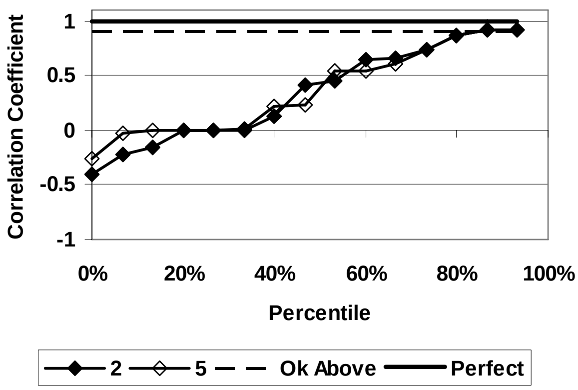
The intial percentage of correct interior airflow directions was 57%. The first iteration increased correctly modeled directions to 64%. Subsequent efforts to tune the model achieved only an additional 1% improvement. Automated tuning did not change the interior, exterior, or shaft leakage, only the terrain coefficient and wind pressure exponent. Since there was not much wind at the time of the test, it is not surprising that this change had little effect.

The overall change in the percentage of satisfactory ASTM metrics also was small, starting at 37%, and increasing to 40% after iteration 1. Regression based tuning of leakage and terrain data increased the satisfactory metrics to 42%. Use of measured envelope leakage characteristics resulted in slightly worse performance (40% satisfactory) than use of a predicted value.

Distributions of correlation coefficient calculated as part of the ASTM D5157 analysis (Figure 4) also show modest improvement from iteration 0 to iteration 1 and little change thereafter, for the same reasons noted with respect to building RB-1. It should be noted in Figure 5 that in this application of the proposed method correlation coefficient at some locations improved as a result of tuning while at others it degraded.



(a)



(b)

Figure 5. Percentile distribution of correlation coefficient for RB-2 model tuning. (a) Iterations 0 and 1. (b) Iterations 2 and 5.

DISCUSSION AND CONCLUSIONS

The tuning of smaller, simpler building RB-1 was successful in terms of improvement in both predicted interzonal flow directions and as indicated by ASTM D5157. The application of the tuning process to the larger more complex building RB-2 produced little evidence of improvement. One possible explanations for the lack of success in tuning the RB-2 model are that the model failed to capture certain important features of the building that were not affected by any of the model modifications made on the basis of measured data. A second possibility is that factors like distribution system leakage that were not measured played a role. A third possibility is that control errors occurred during testing that put the system in some other status than was assumed.

Main air flow measurements assigned to the first iteration produced the largest improvements in both cases. Diffuser measurements based on the location of incorrect interior airflow directions produced smaller, local improvements in air flow direction for RB-1, but had little impact on RB-2. As noted, improvement in ASTM D5157 metrics after iteration 1 was predictably small because of the limited number of tracer measurement points and their location in AHU return air streams. Using regression equation optimization to tune difficult to measure leakage and wind parameters was the least effective tuning measure.

It was observed that the characterization of model quality can vary significantly with the measure used. In the tuning of the model of RB-1, the airflow direction metric improved significantly throughout the tuning process, while the interpretations of ASTM D5157 improved mainly during the first iteration. Results of RB-2 tuning demonstrated that an aggregate measure of quality such as the total number of satisfactory ASTM D5157 metrics can disguise finer scale changes.

Although ASTM D5157 is quite detailed, it leaves unresolved several significant issues regarding what it measures and how it should be applied. First, it defines quality at a particular sampling point relative to a particular tracer release. If the release or sampling location changes, the assessment of model quality will also change. Second, it defines quality in terms of six different metrics and does not indicate whether a model can be satisfactory if one or more of these measures falls outside the satisfactory range. Finally, it does not address the issue of how to judge model quality in a complex building in which multiple sampling locations are used. All of these issues should be addressed in future development of this standard.

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