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Validation of Multizone IAQ Modeling of Residential-Scale Buildings: A Review

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ABSTRACT

This paper reviews empirical validation studies of the application of multizone indoor air quality (IAQ) models to residential-scale buildings. This review focuses on empirical verification efforts, although models have also been subjected to analytical verification and inter-model comparisons. In most reports, experimental data were compared to predictions of only one model – typically, either the CONTAM or COMIS models. However, inter-model comparisons have demonstrated consistency between these and other multizone models so most comparisons can be generalized to all multizone models. Few of the empirical verifications reported statistical analyses of the comparison between measurements and predictions. Where sufficient data were available in the literature, additional statistical analyses have been performed and reported. Also, most published reports did not address the issue of measurement uncertainty.

No single reported multizone IAQ model validation effort can be considered to be complete due to limitations in scope, inadequate detail describing experimental and/or modeling procedures, lack of rigorous statistical analysis, inclusion of only small ranges of airflows and concentrations, questions on independence of validation datasets, and other shortcomings. However, if one considers the body of published validation work, it may be concluded that a knowledgeable user can expect to make reasonable predictions of air change rates, interzonal flows, and contaminant concentrations for residential-scale buildings dominated by stack-driven or ventilation flows with inert pollutants. In contrast, more work is clearly needed for applications with high wind speeds, reactive contaminants, or specialized situations such as ambient pollutant entry, small time scales, and non-trace contaminants.

Additionally, future model validation efforts will be more useful if more statistical analyses are performed and if more detail on both the measurements and modeling are reported.

INTRODUCTION

Multizone indoor air quality (IAQ) modeling has been available as a research and analysis tool for over 20 years. However, due to improvements in such modeling programs (particularly the development of user-friendly graphic interfaces), the spread of cheap computing power, and more complex building design requirements, the application of such programs has greatly increased and is moving from the research world to a broader audience. This has, in turn, increased the need for establishing the validity of these models.

There are two general types of computer simulation techniques for studying airflow and contaminant transport in buildings – zonal modeling and multizone modeling. Zonal (or room airflow) modeling takes a microscopic view of IAQ by applying a computational fluid dynamics (CFD) program to examine the detailed flow fields and pollutant concentration distributions within a room or rooms. A thorough treatment may be found in many textbooks on the subject (such as Anderson et al. 1984) or in a NIST report (Kurabuchi et al. 1990). Multizone airflow and pollutant transport modeling takes a macroscopic view of air movement and IAQ by evaluating average pollutant concentrations in the different zones of a building as contaminants are transported through the building and its HVAC system. Each

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approach has strengths and limitations for studying different building ventilation and IAQ problems.

The multizone approach is implemented by constructing a network of elements describing the flow paths (HVAC ducts, doors, windows, cracks, etc.) between the zones of a building. The network nodes represent the zones that are modeled at a uniform pressure, temperature, and pollutant concentration. After calculating the airflow between zones and ambient, zonal pollutant concentrations are calculated by applying mass balance equations to the zones that may contain pollutant sources or sinks. A survey of multizone airflow models was described by Feustel and Dieris (1992).

A critical point was made by Herrlin in a general discussion on multizone model validation (Herrlin 1992). Because the number of cases a complex multizone model can simulate are unlimited, an absolute validation is impossible. However, validation efforts are still important to identify and eliminate large errors and to establish the range of applicability of the model. Therefore, a model's performance should be evaluated under a variety of situations. Herrlin also stressed that it is important for users to recognize that a model's predictions will always have a degree of uncertainty.

Herrlin listed three techniques of model validation:

1. Analytical verification—comparison to simple, analytically solved cases
2. Inter-model comparison—comparison of one model to another
3. Empirical validation—comparison to experimental tests

Herrlin also discussed some of the specific difficulties in validating multizone airflow models. These include input uncertainty (particularly of air leakage distribution) and attempting to simulate processes that cannot be modeled (e.g., using a steady-state airflow model to simulate the dynamic airflow process).

Although a few validation efforts have been targeted at the application of multizone models to large buildings (e.g., Furbringer et al. 1993; Said and MacDonald 1991; Upham 1997), this paper focuses on their application to residential-scale buildings, which constitutes the majority of the published multizone validation work.

ANALYTICAL VERIFICATION

Analytical verifications are routinely performed to check a numerical solution. For example, CONTAM has been checked for a number of analytical cases including airflow elements in series and parallel, power law airflow elements, quadratic flow elements, stack effect, wind pressure, doorway elements, duct elements, fan elements, contaminant dispersal, a contaminant filter, and a simple kinetic reaction. Although some of these analytical tests have not been published, some were described by Walton (1989). Unfortunately, most buildings are too complicated for the equations describing the airflow and pollutant transport to be solved analytically. Therefore, analytical verification is of limited value in determining the adequacy of a multizone IAQ model for practical applications.

INTER-MODEL COMPARISON

Inter-model comparison provides a relative check of the assumptions and numerical solutions of different models. As with analytical verification, inter-model comparisons are of limited value in evaluating a model’s adequacy for practical applications. However, good inter-model comparisons also enable generalization of empirical validation conclusions beyond the specific model studied.

Haghighat and Megri (1996) reported “good” agreement between CONTAM (current version of CONTAM is CONTAMW [Dols et al. 2000]), COMIS (Feustel et al. 1989), AIRNET (Walton 1989), CBSAIR (Haghighat and Rao 1991), and BUS (Tuomaala 1993) for airflow predictions for a four-zone model. The “building” was two stories tall with power law flow elements for leakage. A single set of temperatures and wind-induced pressures were simulated. The model predictions for zone pressures and flow rates were within 5% and 13%, respectively.

Another study reported “good agreement” between CONTAM, COMIS, MZAP (unpublished), and BREEZE (BRE 1994) airflow predictions for a three-story building model (Fubringer et al. 1996).

Once again, power law flow elements and airflow elements were used to connect the four interior zones with each other and the ambient zone. A single wind speed and ambient temperature condition were applied. It should be noted that both inter-model comparisons discussed test the models for only a very limited range of conditions.

REVIEW OF EMPIRICAL VALIDATION EFFORTS

Empirical validation attempts to compare model assumptions and numerical solutions with a more absolute standard. However, the standard is only as accurate as the measurements used to produce it. Also, good agreement between measurements and predictions could result from offsetting errors in the model.

ASTM guide D5157, *Standard Guide for Statistical Evaluation of Indoor Air Quality Models* (ASTM 1991), provides information on establishing evaluation objectives, choosing datasets for evaluation, statistical tools for assessing model performance, and considerations in applying the statistical tools. The ASTM guide stresses that the data used for the evaluation process should be independent of the data used to develop the model. Also, sufficiently detailed information should be available for both the measured pollutant concentrations and the required input parameters. The ASTM guide also discusses the nature of model validation as consisting of more than one evaluation, with each evaluation assessing performance in specific situations.

ASTM D5157 provides three statistical tools for evaluating the accuracy of IAQ predictions and two additional statistical tools for assessing bias. Values for these statistical criteria are provided to indicate whether the model performance is adequate. The measures for assessing agreement between predictions include the following:

1. The correlation coefficient of predictions vs. measurements should be 0.9 or greater.
2. The line of regression between the predictions and measurements should have a slope between 0.75 and 1.25 and an intercept less than 25% of the average measured concentration.
3. The normalized mean square error (NMSE) should be less than 0.25. NMSE is calculated as

$$NMSE = \sum_{i=1}^{N} (C_{pi} - C_{oi})^2 / (n\bar{C}_o\bar{C}_p) \tag{1}$$

where C_p is the predicted concentration and C_o is the observed concentration.

The measures for assessing bias include:

1. Normalized or fractional bias (FB) of the mean concentrations. Fractional bias should be 0.25 or lower and is calculated as

$$FB = 2(\bar{C}_p - \bar{C}_o)/(\bar{C}_p + \bar{C}_o). \tag{2}$$

2. Fractional bias based on the variance (FS), which should be 0.5 or lower. FS is calculated as

$$FS = 2(\sigma^2\bar{C}_p - \sigma^2\bar{C}_o)/(\sigma^2\bar{C}_p + \sigma^2\bar{C}_o). \tag{3}$$

The research literature was reviewed for reports of empirical model validation efforts. Multizone IAQ models are actually made up of many models for specific components and processes, which enable them to simulate the pollutant concentrations in building zones from inputs concerning building features, weather conditions, and pollutant generation and removal processes. However, multizone IAQ models may be divided into two general submodels, a multizone airflow model and a multizone pollutant transport model, and various validation efforts of these two submodels are reported in the literature. There are many reports of validation efforts of multizone airflow models, most of which focus on predictions of whole building air change rates with a few also considering the prediction of individual zone air change rates or specific airflows. Fewer reports of validation efforts of multizone pollutant transport model predictions of zone pollutant concentrations (some with known or estimated airflows as input) exist.

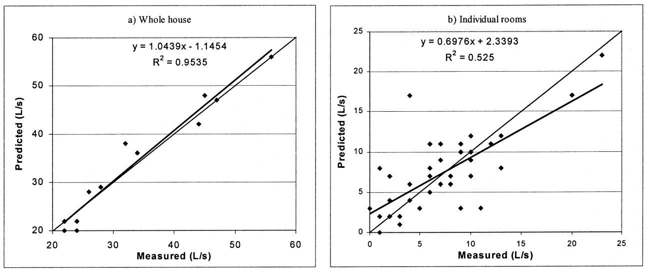

Figure 1 *Linear regression of measured and predicted rates for 12 houses (Blomsterberg et al. 1999).*

None of the published validation reports applied the ASTM Guide D5157 measures to evaluate the results. Only a few reports discussed below included limited statistical evaluations such as correlation coefficients. However, for those cases with sufficient published data, several of the statistical measures from Guide D5157 were calculated for this review. Although the statistical measures from Guide D5157 specifically address concentrations, they have been used to compare predicted and measured airflow rates also.

Airflow Predictions Only

In one of the earliest evaluations of multizone airflow model predictions, Liddament and Allen (1983) described a large validation effort of ten infiltration models, five of which were multizone models, by comparing predicted whole house air change rates to measured values in three houses. They found that most models made predictions within 25% most of the time. No further statistical analysis was reported. Important parameters were identified as the external pressure distribution and the air leakage characteristics of the building. A key difficulty was prediction of the air change rate for a sheltered building because of shielding effects on wind pressure coefficients.

In another early airflow prediction evaluation, Perera and Warren (1985) compared predictions of the multizone airflow program BREEZE to measured airflows in a duplex. They found "good comparison between measured and predicted whole house infiltration rates" but "the comparison was... poor when individual room rates were determined." Some component specific leakages were included with the remaining leakage distributed uniformly on the building envelope. This approach to leakage distribution was cited as a main difficulty with predicting interzonal airflow. No statistical comparison of measurements and predictions were made, and the published data were not sufficient to perform such an analysis.

In a more recent study, Blomsterberg et al. (1999) compared measurements of air change rates for both entire residences and individual rooms in Swedish single-family houses and low-rise apartment flats to predictions with the COMIS model. The tested buildings included ones with passive stack natural ventilation, exhaust fan ventilation, and balanced mechanical ventilation systems. Building envelope airtightness was determined by performing fan pressurization tests. Comparisons were made for periods lasting from one to six days. Agreement between measurements and predictions of average whole dwelling air change rates was good for all three types of ventilation systems in both apartments and houses. The worst case, out of a total of 12, overpredicted by 26%. A linear regression on the measured and COMIS-

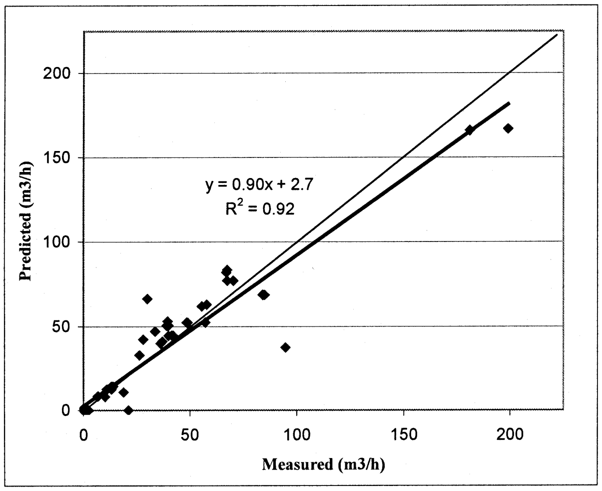

Figure 2 *Predicted and measured interzonal airflows for a multizone test cell (Haghighat and Megri 1996).*

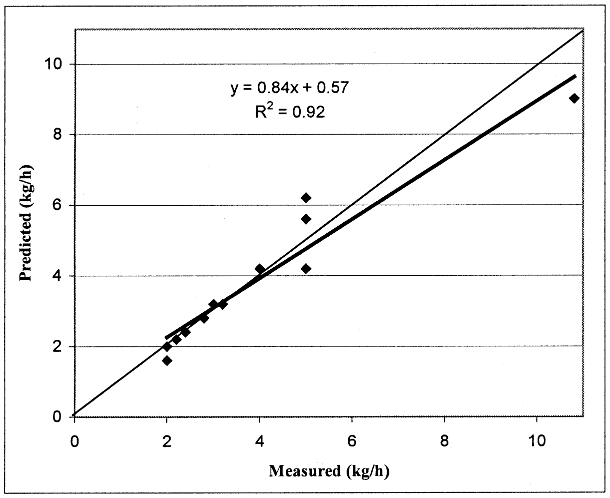

Figure 3 *Predicted and measured room airflows for a single-story house (Haghighat and Megri 1996).*

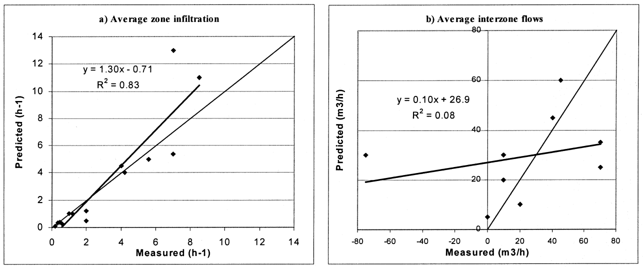

Figure 4 *Linear regression of measured and predicted zone infiltration and interzonal flows (Bassett 1990).*

predicted average whole house air change rates yielded a correlation coefficient of 0.98 (see Figure 1). The normalized mean square error (NMSE) and fractional bias (FB) calculated for the whole house air change rates were 0.01 and 0.01, respectively.

Agreement was poorer for transient whole dwelling air change rates for all types of ventilation systems but particularly for the naturally ventilated buildings. Similarly, agreement was poorer for average individual room air change rates for most cases and particularly for the naturally ventilated buildings. It is important to note that there is also greater uncertainty in the measurement of individual room air change rates. A linear regression on the measured and COMIS-predicted average individual room air change rates yielded a correlation coefficient of 0.72 (see Figure 1). The NMSE and FB calculated for the individual room air change rates were 0.24 and 0.03, respectively. As might be expected, the most consistent comparisons between predictions and measurements over time and space (i.e., individual rooms) were for the cases with balanced mechanical ventilation systems.

In another recent effort, Haghighat and Megri (1996) compared infiltration and interzonal airflow predictions from the multizone models CONTAM and COMIS to measurements for both a multizone laboratory space and a single-family house. The laboratory test space was constructed, in part, for the purpose of validating multizone models, and its airflow parameters are controlled and have been well characterized (Amara et al. 1992). In general, most of the airflow predictions were within 20% of the measured flows with greater differences occurring when the test cell was configured to simulate a higher wind pressure. A linear regression of the measured interzonal airflows and the airflows predicted by CONTAM yielded a correlation coefficient of 0.96 (see Figure 2). The NMSE and FB calculated for the interzonal airflows were 0.18 and 0.002, respectively. Although limited detail was presented, comparisons of predicted and measured room airflows for the one-story house also showed good agreement, with most differences less than 15%. A linear regression of the measured and CONTAM airflows for the house also yielded a correlation coefficient of 0.96 (see Figure 3). NMSE and FB calculated for the room airflows were 0.04 and –0.02, respectively.

Similarly, Bassett (1990) compared calculated and measured individual zone infiltration rates and interzonal airflows for five single-family houses. The multizone airflow model used was an early version of CONTAM (Walton 1981). The houses were divided into one zone per floor. Weather conditions were measured locally. Bassett found that zone infiltration rates were “mostly well reproduced” with most calculated rates within 75% of the measured values and 30% to 40% of calculated rates within 25% of measured values. A linear regression of the average measured and CONTAM-predicted zone infiltration rates yielded a correlation coefficient of 0.91 (see Figure 4). The NMSE and FB calculated for the zone infiltration rates were 0.18 and 0.002, respectively. Interzonal airflows were “often well reproduced from simple assumptions” (no attempt was made to model all leakage paths nor were any interzonal leakage areas measured on site). A linear regression on the average measured and CONTAM-predicted interzonal flows yielded a correlation coefficient of only 0.27 (see Figure 4). The NMSE and FB calculated for the interzonal airflows were 2.98 and 0.37, respectively. However, elimination of one rogue data point increases the correlation coefficient greatly to 0.48 and reduces the NMSE and FB to 0.64 and –0.06, respectively. Whether this point is in error or not, its impact indicates a limitation of validation studies using a minimal number of comparison conditions. Once again, key difficulties cited were distribution of leakage paths (the model assumed that leakage was distributed uniformly based on area) and wind pressure coefficients (values were taken from the literature rather than measured). Bassett also found that calculated airflows were more sensitive to wind direction than measured airflows.

More encouraging results for interzonal flow predictions were reported by Borchiellini et al. (1995) for a comparison of airflows measured in two detached test houses in Italy with predicted airflows from COMIS. The permeabilities of the test houses were measured by the guarded zone method and weather conditions were measured locally. Wind speeds were low during the tests. Results were reported for two types of tests. In the first, a natural ventilation system was tested at various settings in a single room of the building that was sealed off from the rest of the house. In the second, the house was treated as two zones with one room separated by a closed internal door from the rest of the house, which was treated as one zone. While the authors did estimate experimental uncertainties, they did not calculate correlations between measurements and predictions. A linear regression was performed on the average interzonal flows from the two zone tests (including flows between the zones and ambient), which yielded a correlation coefficient of 0.84 (see Figure 5). The NMSE and FB calculated for the interzonal airflows were 0.41 and –0.24, respectively. Some of the two-zone tests were performed after resealing small leaks not accounted for in the model. The correlation coefficient for the measured and predicted interzonal flows improves significantly to 0.97 for the tests performed after the resealing. The NMSE and FB dropped to 0.04 and –0.02, respectively, after resealing.

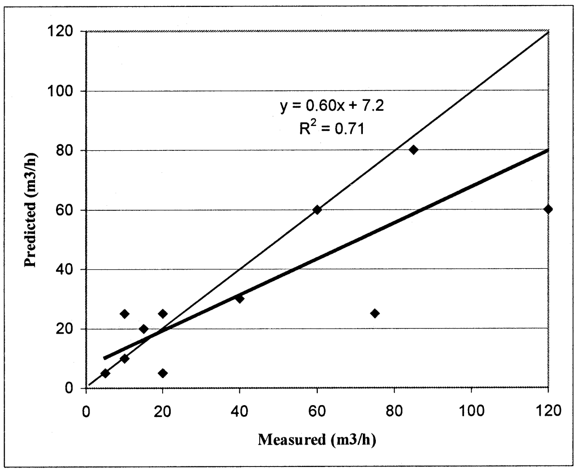

Figure 5 *Linear regression of measured and predicted interzonal flows (Borchiellini et al. 1995).*

Pollutant Transport Predictions

In a detailed report on pollutant transport predictions, Koontz et al. (1992) evaluated the performance of four pollutant transport models (CCEM, CONTAM, INDOOR, and MCCEM) at predicting concentrations for five independent experimental cases. These cases included both test chamber and research house measurements. The experimental cases included the following:

1. Release of Methylene Chloride in Aerosol Spray Paint in a Room-sized Chamber – 2 hours (MRI 1987)
2. Release of Diethylene Glycol Monobutyl Ether Acetate from Latex Wall Paint in a Room-sized Chamber – 100 hours (Guest et al. 1985)
3. Release of CO Tracer Gas in a Research House – 4 hours (Koontz et al. 1988)
4. Release of Para-dichlorobenzene from Moth Crystals in a Research House - 18 days (Tichenor et al. 1988a)
5. Release of Perchloroethylene from Dry-Cleaned Clothes in a Research House – 8 days (Tichenor et al. 1988b)

In all five cases, airflows were not predicted but were an input to the simulations and were assumed constant even for the long-term tests. Statistical indices (including correlation coefficient, slope and intercept for regression line, standard error of the estimate, normalized mean square error, and fractional bias) were calculated for cases 1, 2, and 3 to make quantitative statements regarding the level of agreement between measurements and predictions of transient pollutant concentrations. Table 1 summarizes the reported correlation coefficients. For cases 4 and 5, the authors made qualitative comparisons and compared average concentrations but no statistical indices were calculated. The report warns that disagreement may exist for several reasons including inappropriate model assumptions, incomplete or inappropriate model inputs, and unrepresentative, inaccurate, or imprecise measurements. The authors found that, “In most cases, all of the models that were tested provided reasonably accurate predictions of measured indoor concentrations. However, in some cases the nominal inputs that were initially used required some adjustment to obtain predictive accuracy.”

TABLE 1
Correlation Coefficients for Three Experimental Cases
(Koontz et al. 1988)

Case \ Model	CCEM	CONTAM	INDOOR	MCCEM
1	0.983	0.983	0.987	0.984
2	0.340	NA	0.800	0.874
3	0.80	0.96	0.96	0.97

Notes: Case 2 is the average correlation of three tests at different ventilation rates.
Case 2 was not simulated with CONTAM.
Case 3 is the average correlation of concentrations in two different rooms.

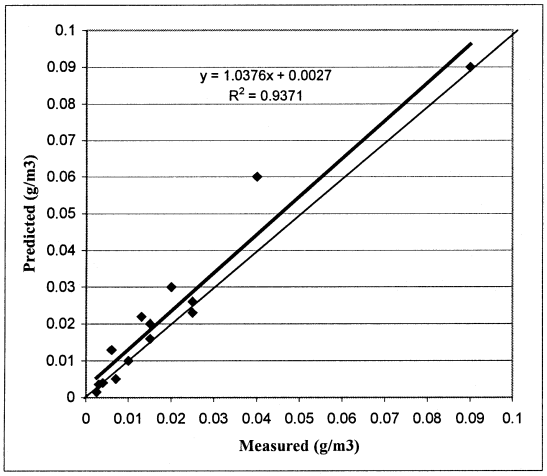

Figure 6 *Linear regression of measured and predicted transient tracer gas concentrations (Sextro et al. 1999).*

Predictions of the EPA multizone model INDOOR were also compared to experimental datasets 4 and 5 mentioned above and to measurements of combustion products from a kerosene heater in a research house (Sparks et al. 1988, 1989). Pollutant source strengths were measured in separate chamber studies. Pollutant sink values were estimated from literature reports except for the case of the perchloroethylene tests, which were estimated from tests in the house. Model agreement was reported as ranging from good to excellent for these cases despite the use of constant airflow rates in long-term tests. Sparks states that "when IAQ is dominated by a large point source, knowledge of the source strength and rough estimates of the various airflows are sufficient to predict concentrations within reasonable (a factor of 2) accuracy for much of the building." Experimental uncertainty for the measurements was not addressed, and insufficient data were included to perform a statistical analysis.

In another early work, Axley (1988) compared predictions of the model CONTAM87 to reported measurements of CO, NO, and NO_2 concentrations in a townhouse (Borazzo et al. 1987). Airflows were used as inputs with some measured and others assumed. Agreement was found within the reported uncertainty of emissions for CO and NO. "Some agreement" was also reported for NO_2, but Axley warns that the agreement may be artificial as the measured data were used to determine the reactivity constants for the simulations.

Combined Airflow and Pollutant Transport Predictions

Several recent efforts have attempted to validate combined airflow and pollutant transport predictions. Zhao et al. (1998) compared simulated and measured air change rates and pollutant concentrations in a tight, two-story test house. Leakage areas of internal doors, exterior walls, and windows were measured for input to a ten-zone model of the house in COMIS. Weather conditions including wind pressures were measured locally. Small mixing fans were used to ensure uniform tracer gas concentrations within rooms. Two separate tests were compared. In the first test, tracer gas was injected throughout the house to determine air change rates and interzonal flows. The authors performed a linear regression between measured and predicted air change rates for individual rooms that yielded a regression coefficient of 0.92 and a correlation coefficient of 0.72. In the second test, tracer gas was injected in a single zone to measure the pollutant transport to the other house zones. A linear regression between the measured and predicted zone pollutant concentrations yielded a regression coefficient of 0.93 and a correlation coefficient of 0.94. The significantly higher correlation for the pollutant concentrations compared to the room air change rates suggests the possibility of accuracy limitations on the measurement of room air change rates. Another possible explanation is a coincidental cancellation of errors in the prediction of concentrations.

Recently, Sextro et al. (1999) compared measured and predicted tracer gas concentrations in a three-story test building. Extensive tests were performed to determine interzonal flow parameters, leakage rates, ventilation flow rates, and operating conditions for the building. Tests were performed by a burst release of propylene either at the system return plenum or in the center of a room. Concentrations were measured at 30-second intervals at the center of each of the seven rooms and on each of the three stairwell landings. No mixing fans were used in the experiments. Although 13 tests were performed with varied conditions of ventilation system operation, weather, and interior door position, limited results are presented for only two cases – one with the ventilation on and interior doors open and one with the ventilation system off and interior doors closed. Although no statistical analysis is presented, the authors report "reasonable – and in some cases, quite good – agreement." A particular difficulty cited was the possibility of poorly mixed conditions in the attic due to large air leakage and an unusual shape. A linear regression was performed on the transient tracer gas concentrations in the source zone and one non-source zone (at one-hour intervals beginning at least one-half hour after the burst release), which yielded a correlation coefficient of 0.97 (see Figure 6). The NMSE and FB calculated for tracer gas concentrations were 0.10 and 0.16, respectively.

In an earlier study, Yoshino et al. (1995) reported comparisons of both airflow and pollutant concentration predictions of the COMIS model to measurements in a three-room test house for a case of natural ventilation. Weather conditions including wind pressures were measured locally. A multiple tracer gas system was used for the measurements. Three cases with varied room temperatures and weather conditions were evaluated. For airflow, they found "encouraging" agreement with most predicted air change rates within 25% of measurements (linear regression coefficient of 0.87 and correlation

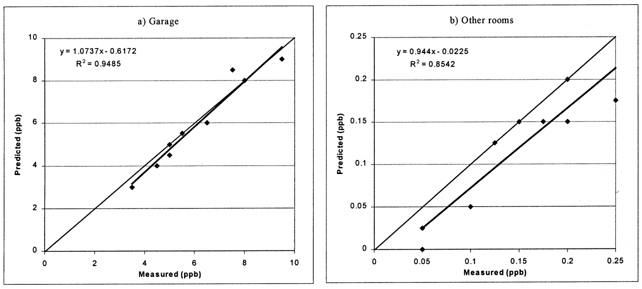

Figure 7 *Linear regression on predictions and measurements of transient tracer gas measurements in a house (Lansari et al. 1996).*

coefficient of 0.79). For pollutant concentrations, the comparison was better with an average linear regression coefficient of 1.06 and correlation coefficient of 0.98.

As part of a study of the transport of pollutants from attached garages to residences, Lansari et al. (1996) compared measurements of transient tracer gas concentrations in a garage and in other rooms of a two-story house to CONTAM predictions. For this test, the tracer gas SF_6 was released in the garage and concentrations were measured at two locations in the garage, and at one location in three other rooms over a 70-minute period. The wind speed during the test was less than 0.5 m/s. Leak parameters used in the model were based on literature values, but flows from the HVAC system – which was on during all tests – were measured. The authors conclude that “the garage concentrations of SF_6 were reasonably well predicted under well-mixed conditions, but these concentrations were underpredicted within rooms of the house in which mixing was probably incomplete.” Figure 7 presents linear regressions performed on (a) the garage zone concentrations and (b) concentrations in three other rooms of the house that yielded correlation coefficients of 0.97 and 0.92, respectively. The NMSE and FB calculated for tracer gas concentrations in the garage were 0.01 and –0.03, respectively. The NMSE and FB calculated for tracer gas concentrations in other rooms were 0.12 and –0.27, respectively. The measured garage concentrations are based on an average of the two locations.

Few reports have attempted to validate predictions of active contaminants (i.e., pollutants that undergo processes such as deposition, sorption, chemical reactions, etc.) and none has specifically addressed the prediction of the potential impact of IAQ control technologies other than ventilation. A recent effort has made an initial attempt within a single-zone space to evaluate the ability of the CONTAM model to predict the impact of particle air cleaners (Emmerich and Nabinger 2000) on airborne particle concentrations. Measurements of the performance of several particulate air-cleaning devices and related particle transport parameters were performed in a one-room test house. A fan pressurization test was performed to determine the tightness of the test house. Airborne particle concentrations were measured with an optical particle counter that yielded counts of particles in four size ranges: 0.3 µm to 0.5 µm, 0.5 µm to 0.7 µm, 0.7 µm to 1.0 µm, and 1.0 µm to 5.0 µm. The particles were modeled for these same size ranges and included consideration of deposition rates, penetration factors, filtration efficiencies, and source terms determined for each size range. Two separate 24-hour tests were performed with two different air cleaners, and the measured particle concentrations were compared to predicted values obtained with the CONTAM model. For both tests, simulated 24-hour average particle concentrations were within 30% of measurements for all particle sizes.

Emmerich and Nabinger calculated the statistical measures from ASTM D5157 (ASTM 1991) discussed above for the predicted particle concentrations for the two 24-hour test cases. All of the model predictions met the criteria for adequate model performance for all the statistical measures with very few exceptions. Specifically, the correlation coefficient was greater than 0.94 for all particle sizes for both cases and was 0.98 to 0.99 for all cases except the two smallest size particles with the electronic air cleaner operating. This work is being continued in a multizone townhouse.

DISCUSSION

Table 2 summarizes the reviewed validation cases for which statistical parameters on model performance were either available or calculated for this report. Included in the table are the reference, the type and number of building(s) studied, the multizone modeling program used, the parameter for which the statistical parameters were calculated, the correlation coefficient, the slope of the regression line, the ratio of the intercept of the regression line to the average measured value, the normalized mean square error, and the fractional bias. As seen in the table, the statistical parameters are within or close to the guidelines of ASTM D5157 for many cases. In general, predicted pollutant concentrations and whole house air change rates agreed with measurements better than predicted individual zone airflows. In fact, the only case with very poor agreement was reported by Bassett (1990) for interzonal airflows.

Before drawing conclusions from this review, some words of caution are appropriate. No single published multizone IAQ model validation effort can be considered to be authoritative. Individual reports typically suffer from limitations in scope, inadequate detail describing experimental and/or modeling procedures, lack of measurement uncertainty analysis, insufficient statistical analysis, questions on independence of validation data sets, and other shortcomings.

The time and expense involved in performing a model validation study necessarily limits the scope of such efforts. Most of the reports performed measurements in only one or two buildings and include only a few driving force conditions (e.g., weather, contaminant source strength and location). This inevitably results in the models being tested for only a small portion of the vast range of potential building features, airflows, and contaminant concen-

TABLE 2
Summary of Reviewed Validation Cases

Reference	Test building	Model	Parameter evaluated	R	m	B	NMSE	FB
Bassett 1990	5 houses	CONTAM	Zone air change rates	0.91	1.31	-0.23	0.35	0.08
			Interzone airflows	0.27	0.10	1.34	2.98	0.37
Blomsterberg et al. 1999	Houses and apartment flats	COMIS	Average whole house air change rates	0.98	1.04	-0.03	0.01	0.01
			Average room air change rates	0.72	0.70	0.32	0.24	0.03
Borchiellini et al. 1995	2 test houses	COMIS	Average interzone airflows	0.84	0.60	0.18	0.41	-0.24
Emmerich and Nabinger 2000	Single-zone test house	CONTAM	0.3 to 5.0 µm particle concentrations	0.94 to 0.99	0.84 to 1.02	-0.25 to 0.29	0.04 to 0.19	-0.26 to 0.16
Koontz et al. 1992	Test chamber	CONTAM	Methylene chloride concentration	0.98	1.08	0.07	0.20	0.16
	2-zone research house	CONTAM	Transient CO concentration (zone 1)	0.94	0.70	0.14	0.15	0.06
			Transient CO concentration (zone 2)	0.98	0.85	0.26	0.02	-0.11
Haghighat and Megri 1996	Multizone laboratory	CONTAM	Interzone airflows	0.96	0.90	0.10	0.18	0.002
	House	CONTAM	Room airflows	0.96	0.84	0.14	0.04	-0.02
Lansari et al. 1996	2-story house with garage	CONTAM	Tracer gas concentrations in garage	0.97	1.07	0.10	0.01	-0.03
			Tracer gas concentrations in other rooms	0.92	0.94	0.18	0.12	-0.27
Sextro et al. 1999	3-story test building	CONTAM	Tracer gas concentrations	0.97	1.04	0.14	0.10	0.16
Yoshino et al. 1995	3-room test house	COMIS	Air change rates	0.79	0.87	NA	NA	NA
			Tracer gas concentrations	0.98	1.06	NA	NA	NA
Zhao et al. 1998	Test house	COMIS	Room air change rates	0.72	0.92	NA	NA	NA
			Tracer gas concentrations	0.93	0.93	NA	NA	NA

Notes: R is the correlation coefficient.
M is the slope of the regression line.
B is the ratio of the intercept of the regression line to the average measured value.
NMSE is the normalized mean square error.
FB is the fractional bias.
Values for Koontz, Emmerich and Nabinger, Yoshino, and Zhao were reported by the authors.

trations to which they could be applied. Examining the cumulative validation results from many studies significantly alleviates this concern for many typical applications such as problems with stack-dominated flows, ventilation flows, and inert pollutants at trace concentrations. In contrast, more work is clearly needed for applications with high wind speeds, active contaminants, or specialized situations such as ambient pollutant entry, small time scales, and non-trace contaminants.

Unfortunately, the commonly available platforms for widely publicizing research results inhibit inclusion of all important measurement and modeling details. The availability of more detail would enable other modelers to have more confidence in the reported results and to use the data for their own validation efforts. In some cases, additional detail may be available from the investigators. A possible solution to this limitation is a database where such information could be available in a standard format, such as the one being created by the Air Infiltration and Ventilation Centre (Orme 2000).

Nearly all reports lack information on measurement uncertainty, which limits the interpretation of differences between measurements and predictions. Lacking such information, one might attribute all of the differences to model inaccuracy. However, all measurements have some level of inaccuracy and some values, such as airflows between rooms, are particularly difficult to measure accurately. This may explain why most of the instances of particularly poor correlation in Table 2 are for individual room air change rates or interzonal flows and why many studies have reported better model performance for contaminant concentrations than for airflows for the same cases.

Future model validation efforts would also be more useful if more statistical analysis were applied to the comparison of predictions and measurements. Some reports include only averages of or ranges of percent differences between measured and predicted values. This type of comparison provides little information on the effectiveness of a model at predicting spatial or temporal variation in airflows and concentrations and can overemphasize large relative differences found for small absolute values. Also, different model applications require different levels of accuracy. In many cases, it is more important to accurately predict trends or changes to a baseline with an estimate of the uncertainty than to achieve high accuracy at individual data points. ASTM Standard Guide 5157 provides one starting point for statistical evaluation of multizone models.

Despite these caveats and concerns, if one considers the body of validation work reviewed above and summarized in Table 2, it may be concluded that a knowledgeable user can make reasonable predictions of air change rates and contaminant concentrations for residential-scale buildings. Predictions of interzonal airflows and cases with high wind driving forces have proven more troublesome in several of the validation efforts. Also, given the tremendous flexibility of the main models, it would be easy for a user to apply the model in ways far different from the cases that have been evaluated in past validations.

REFERENCES

Amara, F., P. Depecker, and F. Allard. 1992. “Optibat: A Real Scale Cell in Simulated Climatic Environment for Multizone Air Flow Pattern in Building.” *Proceedings of the 13th AIVC Conference*, Air Infiltration and Ventilation Centre.

Anderson, D.A., J. C. Tannehill, and R. H. Pletcher. 1984. *Computational Fluid Mechanics and Heat Transfer*. New York: Hemisphere Publishing Company.

ASHRAE. 1997. *1997 ASHRAE Handbook—Fundamentals*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASTM. 1991. *Standard Guide for Statistical Evaluation of Indoor Air Quality Models*. D5157-91. American Society for Testing and Materials.

Axley, J. 1988. *Progress Toward a General Analytical Method for Predicting Indoor Air Pollution in Buildings - Indoor Air Quality Modeling Phase III Report* (1988) NBSIR 88-3814. National Bureau of Standards.

Bassett, M. 1990. *Infiltration and leakage paths in single family houses - a multizone infiltration case study*. AIVC Technical Note 27, Air Infiltration and Ventilation Centre.

Blomsterberg, A., T. Carlsson, C. Svensson, and J. Kronvall. 1999. “Air flows in dwellings – simulations and measurements.” *Energy and Buildings* 30:87-95.

Borazzo, J.E., J. F. Osborn, R. C. Fortmann, R. L. Keefer, and C. I. Davidson. 1987. “Modeling and Monitoring of CO, NO and NO_2 in a Modern Townhouse.” *Atmospheric Environment* 21:299-311.

Borchiellini, R., M. Cali, and M. Torchio. 1995. “Experimental Evaluation of COMIS Results for Ventilation of a Detached House.” *ASHRAE Transactions* 101(1).

BRE. 1994. *BREEZE 6.0 User Manual*. Building Research Establishment, UK.

Dols, W. S., G. N. Walton, and K. R. Denton. 2000. *CONTAMW 1.0 User Manual* (2000) NISTIR 6476. Gaithersburg, Md.: National Institute of Standards and Technology.

Emmerich, S. J. and S. J. Nabinger. 2000. *Measurement and Simulation of the IAQ Impact of Particle Air Cleaner in a Single-Zone Building*. NISTIR 6461. Gaithersburg, Md.: National Institute of Standards and Technology.

Feustel, H. E., F. Allard, V. B. Dorer, M. Grosso, M. Herrlin, L. Mingsheng, J. C. Phaff, Y. Utsumi, and H. Yoshino. 1989. “The COMIS Infiltration Model.” *Proceedings of the 10th AIVC Conference*, Air Infiltration and Ventilation Centre.

Feustel, H. E. and J. Dieris. 1992. “A Survey of Air Flow Models for Multizone Structures.” *Energy and Buildings* 18:79-100.

Furbringer, J. M., V. Dorer, F. Huck, and A. Weber. 1993. “Air Flow Simulation of the LESO Building Including a Comparison with Measurements and a Sensitivity Analysis.” *Proceedings of Indoor Air* Vol. 5.

Furbringer, J. M., C. A. Roulet, and R. Borchiellini (eds.). 1996. Evaluation of COMIS. Swiss Federal Institute of Technology, Institute of Building Technology.

Guest, D., P. J. Deisinger, and J. E. Winter. 1985. *Estimation of the Atmospheric Concentration of Diethylene Glycol Monobutyl Ether Acetate Resulting form the Application of Latex Paint*. Health and Environment Laboratories, Analytical Support Group, Industrial Laboratory, Eastman, Kodak Company.

Haghighat, F. and A. C. Megri. 1996. “A Comprehensive Validation of Two Airflow Models - COMIS and CONTAM.” *Indoor Air* 6:278-288.

Haghighat, F. and J. Rao. 1991. “Computer-aided building ventilation system design – a system theoretic approach.” *Energy and Buildings* Vol. 1:147-155.

Herrlin, M. K. 1992. *Air-Flow Studies in Multizone Buildings - Models and Applications*. Royal Institute of Technology.

Koontz, M. D., H. E. Rector, and N. L. Nagda. 1988. *Preliminary experiments in a research house to investigate contaminant migration in indoor air.* Report No. EPA 560/5-88-004, U.S. Environmental Protection Agency.

Koontz, M.D., H. E. Rector, and N. L. Nagda. 1992. *Consumer Products Exposure Guidelines: Evaluation of Indoor Air Quality Models*. GEOMET Report IE-1980, GEOMET Technologies, Inc.

Kurabuchi, T., J. B. Fang, and R. A. Grot. 1990. *A Numerical Method for Calculating Indoor Airflows Using a Turbulence Model*. NISTIR 89-4211, NIST.

Lansari, A., J. J. Streicher, A. H. Huber, G. H. Crescenti, R. B. Zweidinger, J. W. Duncan, C. P. Weisel, and R. M. Burton. 1996. “Dispersion of Automotive Alternative Fuel Vapors within a Residence and its Attached Garage.” *Indoor Air* 6:118-126.

Liddament, M. and C. Allen. 1983. *The validation and comparison of mathematical models of air infiltration*. AIC Technical Note 11, Air Infiltration Centre.

MRI. 1987. *Evaluation of Exposure to Chemical Products: Final Report for Test with Products Containing Methylene Chloride*. Midwest Research Institute.

Orme, M. 2000. “Applicable Input Data for a Proposed Ventilation Modeling Data Guide.” *ASHRAE Transactions* 106 (2).

Perera, MDAES, and P. R. Warren. 1985. “Influence of Open Windows on the Interzone Air Movement within a Semi-detached Dwelling.” *Proceedings of the 6th AIC Conference*.

Said, M. N. and R. A. MacDonald. 1991. “An Evaluation of a Network Smoke Control Model.” *ASHRAE Transactions* Vol. X Pt X.

Sextro, R.G., J.M. Daisey, H.E. Feustel, Dickerhoff, and C. Jump. 1999. “Comparison of Modeled and Measured Tracer Gas Concentrations in a Multizone Building.” *Proceedings of Indoor Air* 99, Vol.1.

Sparks, L. E., M.D. Jackson, and B. A. Tichenor. 1988. “Comparison of EPA Test House Data with Predictions of an Indoor Air Quality Model.” *Proceedings of ASHRAE IAQ*.

Sparks, L. E., B. A. Tichenor, M. D. Jackson, and J. B. White. 1989. “Verification and Uses of the Environmental Protection Agency (EPA) Indoor Air Quality Model.” *Proceedings of ASHRAE IAQ*.

Tichenor, B. A., L. E. Sparks, J.B. White, and M.D. Jackson. 1988a. “Evaluating Sources of Indoor Air Pollution” 81st Annual Meeting of the Air Pollution Control Association.

Tichenor, B. A., L. E. Sparks, and M. D. Jackson. 1988b. *Evaluation of perchloroethylene emissions from dry-cleaned fabrics*. Report No. EPA/600/2-88/061, U.S. Environmental Protection Agency.

Tuomaala, P. 1993. “New building air flow simulation model: Theoretical bases.” *Building Services Engineering Research and Technology* 14:151-157.

Upham, R. D. 1997. *A Validation Study of Multizone Air Flow and Contaminant Migration Simulation Program CONTAM as Applied to Tall Buildings.* M.S. Thesis, Penn State University.

Walton, G. N. 1981. *Calculation of inter-room movement for multi-room building analysis*. NBSIR 81-2404, National Bureau of Standards.

Walton, G.N. 1989. *AIRNET – A Computer Program for Building Network Modeling*. NISTIR 89-4072, NIST.

Walton, G.N. 1997. *CONTAM96 User Manual.* NISTIR 6056, NIST.

Yoshino, H., Z. Yun, H. Kobayashi, and Y. Utsumi. 1995. “Simulation and measurement of air infiltration and pollutant transport using a passive solar test house.” ASHRAE Transactions 101(1).

Zhao, Y., H. Yoshino, and H. Okuyama. 1998. “Evaluation of the COMIS Model by Comparing Simulation and Measurement of Airflow and Pollutant Concentration.” *Indoor Air* 8:123-130.