

Performance Test Results for a Large Coupled Indoor/Outdoor Environmental Simulator (C-I/O-ES)

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ABSTRACT

This paper provides a summary of the methods and results of performance testing for a coupled Indoor/Outdoor Environmental Simulator (C-I/O-ES). The simulator consists of an IEQ chamber, a climate chamber, and a replaceable "separation/test wall" assembly. Both chambers have stainless steel interior surfaces, and are equipped with independent heating, ventilating, and air conditioning (HVAC) systems for simulating indoor and outdoor thermal and air quality conditions, respectively. The "separation/test wall" assembly can be used to physically model building envelope assemblies and allows the studies of combined air, heat, moisture, and contaminant transport through these assemblies. The simulator can be used to study various emission sources of chemical, particulate, and biological pollutants, space air diffusion systems, air cleaning technologies, HVAC control systems, building envelope assemblies, and mechanical, natural or hybrid building ventilation systems and components.

KEYWORDS: Environmental Chamber, Material Emissions, VOCs, Room Air Distribution, Building Envelope, and Climate Simulator

INTRODUCTION

Indoor environmental quality (IEQ) and building energy efficiency (BEE) are critical to human health, safety, comfort, and performance (e.g., Fisk and Rosenfeld 1997). Full-scale laboratory testing has been used as a reliable method for studying the pollutant sources and/or their transport in built environmental systems. Wu et al. (1990) developed a full-scale room ventilation simulator (RVS) to investigate the air and air contaminant distribution in ventilated spaces. The RVS consists of a full-scale conditioned inner test room within an outer room that simulates the outdoor climate conditions. Both the outer and inner test rooms were constructed from regular building materials with plywood as interior surfaces, and were thus not suitable for conducting tests where contaminant emission or sorption on material surfaces is a significant factor. For studying the effects of total IEQ on occupants' satisfaction and performance, Shaw et al. (1995) developed a full-scale facility that can simulate a wide range of indoor lighting, acoustic, air quality and thermal comfort conditions. The facility uses typical furnishing materials for offices, and was not intended for studies in which contaminant sorption by materials can significantly affect the test results. For studying the emissions of volatile organic compounds (VOCs) from building materials and their impact on indoor air quality, ultra-clean full-scale environmental chambers have been developed (Howard et al. 1995 and Zhang et al. 1996). These chambers have stainless steel interior surfaces to minimize VOC emission or sorption effects. The chambers have dedicated HVAC systems that provide ultra-clean and conditioned air. They can simulate realistic indoor air and contaminant flows with negligible system background contamination (ASTM 2001).

The objective of this study is to assess the ability of a new and unique full-scale research facility to simulate various indoor and outdoor air quality and thermal environmental conditions and indoor-outdoor interactions with minimal background contamination from the facility itself. The facility, herefore called Coupled Indoor/Outdoor Environmental Simulator (C-I/O-ES) has an IEQ chamber, a climate chamber,

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and a replaceable “separation/testing wall” that couple the two chambers. In this paper, we discuss the results of performance testing of the chambers individually and in a coupled configuration in which a typical residential wall assembly was placed between the two chambers.

DESCRIPTION OF THE FACILITY

The C-I/O-ES has three major components: a 4.87 m by 3.66 m by 3.05 m high (16 ft by 12 ft by 10 ft) IEQ chamber, a 1.83 m by 3.66 m by 3.05 m high (6 ft by 12 ft by 10 ft) outdoor climate chamber, and a replaceable "separation/test wall" assembly frame that is used to couple the two chambers (Figure 1). Both chambers and their respective HVAC systems use stainless steel interior surfaces and PTFE gaskets to minimize pollutant emissions and adsorptions in the facility.

The HVAC systems for the IEQ and Climate chambers are both controlled with a direct digital control (DDC) system. System schematics showing typical control system values are provided in Figures 2 and 3.

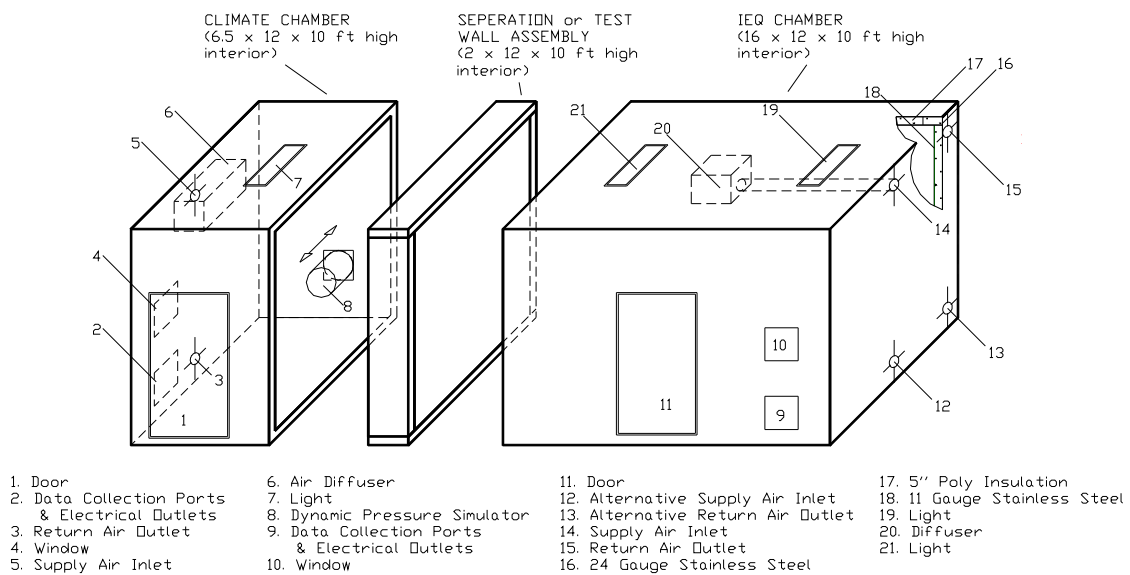


Figure 1. The Coupled Indoor/Outdoor Environmental Simulator (C-I/O-ES)

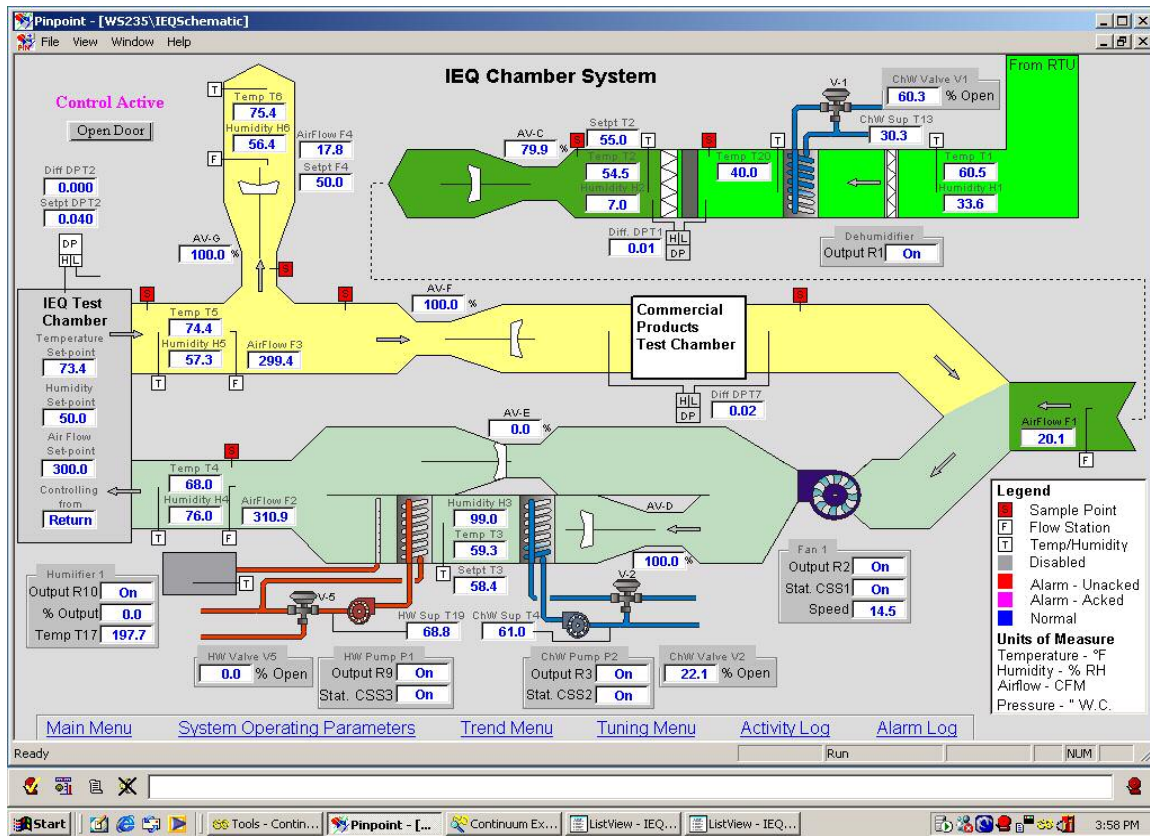


Figure 2. Control System Schematic for IEQ Chamber

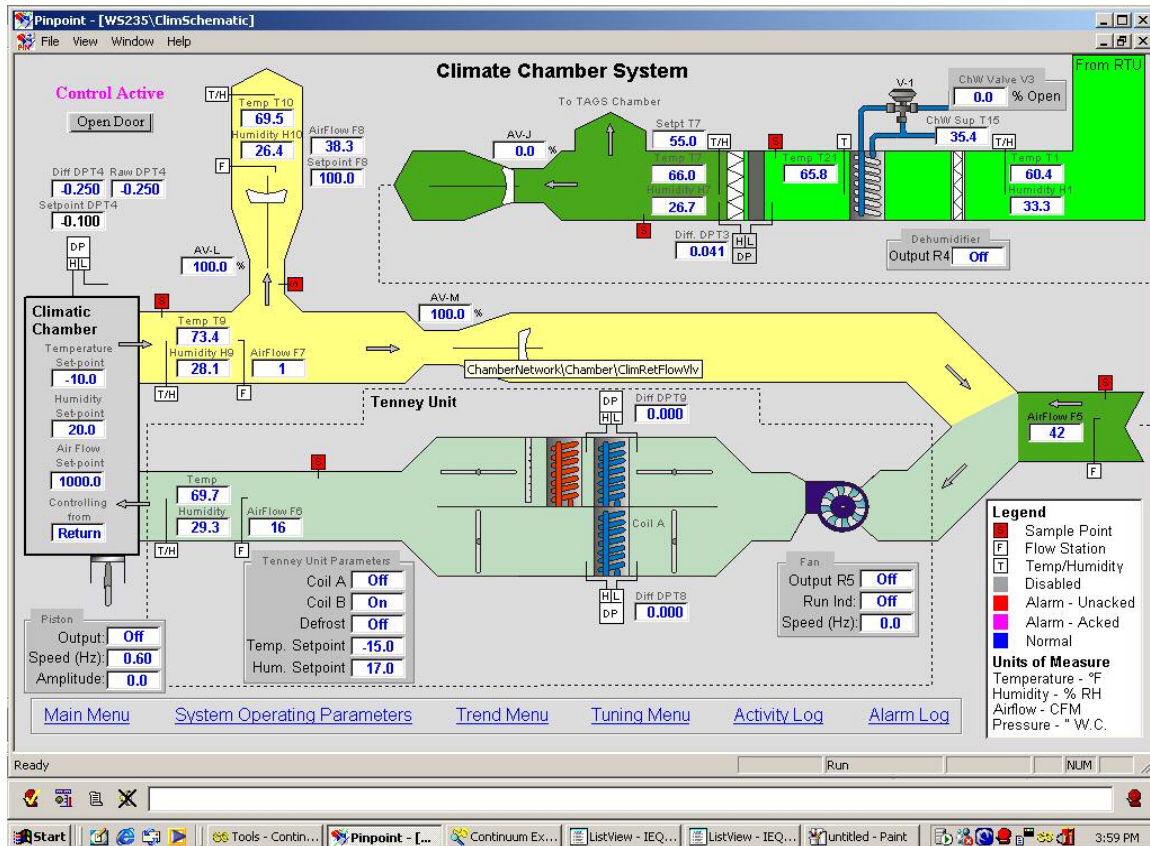


Figure 3. Control System Schematic for Climate Chamber

In addition to the control of airflow rates, temperature and humidity in both chambers, the climate chamber also has a dynamic pressure simulator (DPS) to simulate average and dynamic wind pressures that are typically experienced by building envelopes (Figure 4). The DPS can simulate pressures between 5 and 15 Pa (0.02 to 0.06 inches of water gage) with a single sinusoidal frequency between 0.1 and 1 Hz.

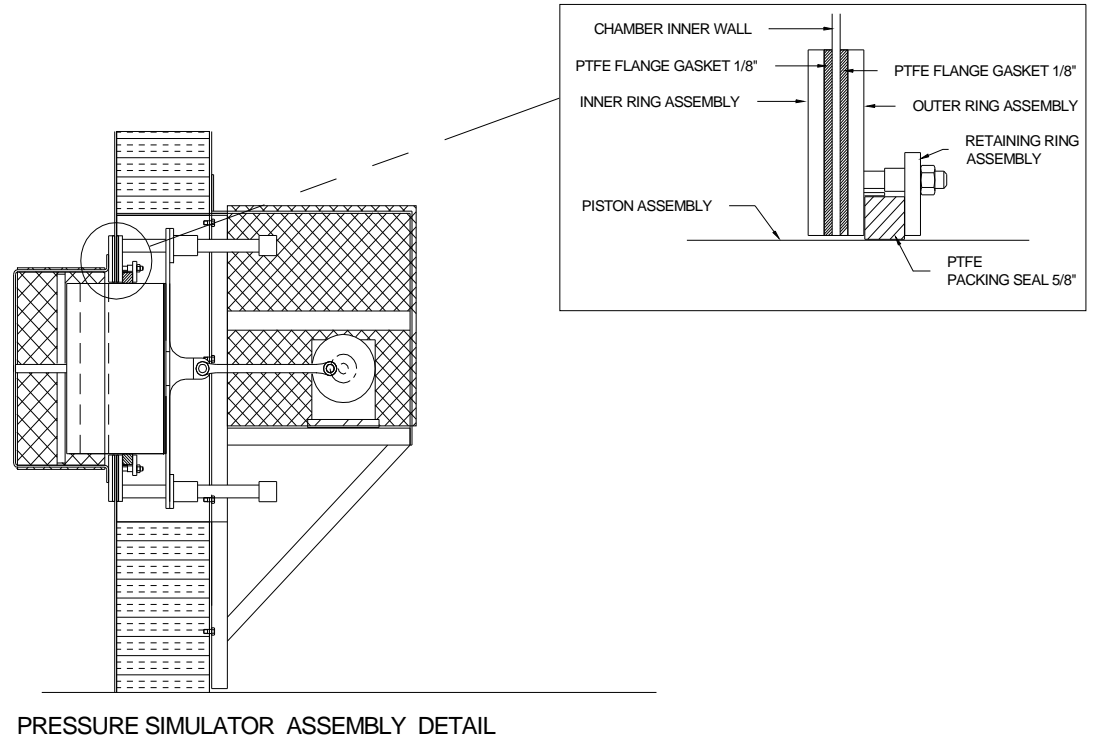


Figure 4. Dynamic Pressure Simulator (DPS)

The “separation/test wall” consists of two wall assemblies. The “separation wall” is heavily insulated stainless steel and allows the two test chambers to operate completely independently of each other. The “test wall” consists of a stainless steel frame with a wooden thermal break. Various types of assemblies, including wall panels, windows and window-type air-conditioning units can be installed in the test wall to study the combined transport of air, heat, moisture and various gaseous, particulate and biological contaminants of interest. Table 1 summarizes the design parameters for the IEQ and climate chambers.

Table 1. Chamber Design Parameters

| <u>Parameters</u> | <u>IEQ Chamber</u> | <u>Climate Chamber</u> |
|-----------------------------|-----------------------------|--|
| Temperature (°C) | 15 to 35 (60 – 95°F) | -25 to 38 (-13 – 100°F) |
| Relative Humidity (% RH) | 30% to 80% | 20% to 90% |
| Air Tightness | 0.03ACH at 10Pa | 0.1ACH at 50Pa |
| Clean Airflow Rate (l/s) | 7.1 to 141.5 (15 – 300 cfm) | 4.7 to 47 (10 – 100 cfm) |
| Clean Air Change Rate (1/h) | 0.47 to 9.38 | 0.77 to 7.7 |
| Total Airflow Rate (l/s) | 28.3 to 236 (60 – 500 cfm) | 4.7 to 472 (10 – 100 cfm) |
| Total Air Change Rate (1/h) | 1.88 to 17.2 | 0.77 to 7.7 |
| Chamber Pressure (Pa) | 5 to 10 | Average: -50 to 50, +/-5 Dynamic: 5 to 15 Pa at 0.1 to 1 Hz |

The simulator is unique in that it is capable of simulating various indoor and outdoor environmental conditions simultaneously with negligible pollutant emission and sorption by the test facility itself. The design of the facility has a replaceable “separation/test wall” feature that allows independent testing of each chamber. Further, it is capable of testing various wall assemblies placed between the IEQ and climate chambers, and how the outdoor climate and pollution affect the indoor environment.

INDIVIDUAL CHAMBER PERFORMANCE TESTS

In order to assess the capabilities of the system, the performance of its individual components needs to be understood. To that end, testing was first performed on the IEQ and Climate chambers individually. Performance aspects included: background contamination levels, air-tightness, HVAC system capacity and control accuracies, sorption strength (sink effect), and accuracy in emission rate measurements. Test methods and procedures described in the ASTM Standard Practice (ASTM 2001) were applied in these tests except for evaluation of the dynamic pressure simulator. The purpose of these tests were to ensure the integrity of the chamber system, and each chamber individually met the design specifications (Table 1).

Background Concentrations

VOCs. Testing was performed at standard conditions of 23°C (73.4 °F), 50% RH, 5.0 ACH total airflow and 0.5 ACH fresh air makeup. Table 2 provides a summary of the criteria that were obtained from ASTM (2001) and the results of the testing performed on both chambers. The VOC levels were initially very high due to Toluene contamination from adhesive used in sensor mounting and from compounds released from the neoprene gasket core used for the door seals. Once the adhesive was cleaned from the ductwork and the system was flushed at elevated temperature and humidity, the background concentration was significantly reduced. Sampling was performed using a sampling device placed inside each chamber. The VOCs were collected using sorbent tubes and analyzed with a GC-FID. As shown in Table 2, the measured VOC concentrations were well below the criteria levels.

Table 2. Chamber Background Concentrations

| <i>Criteria</i> | <i>IEQ Chamber</i> | <i>Climate Chamber</i> |
|---|--------------------|------------------------|
| TVOC $\leq 10 \mu\text{g}/\text{m}^3$ | 0.077 | 0.137 |
| Individual Compounds $\leq 2.0 \mu\text{g}/\text{m}^3$ | | |
| - Hexane | 0.010 | 0.004 |
| - Toluene | 0.052 | 0.008 |
| - Ethylbenzene | | 0.0031 |
| - m-xylene, p-xylene | | 0.006 |
| - o-xylene | | 0.002 |
| - 2-butoxyethanol | | 0.048 |
| - 1,4-dichlorobenzene | | 0.002 |
| - phenol | | 0.021 |
| - 1-dodecanol | | 0.004 |
| - Dodecamethylcyclhexasiloxane | 0.010 | 0.012 |
| - Dodecane | | 0.008 |
| - Decane | | 0.003 |
| - others | 0.004 | 0.017 |
| Particulates $\leq 100 \text{ particles}/\text{m}^3$ (0.5 μm diameter or larger) | 65 | 10 |

Particles. Particulate sampling was performed using a sample pump operating at 2.5 l/min and measured using a laser particle counter. The particle counter was placed inside the chamber with the door closed, and the HVAC system was operated with 5 ACH total air flow and 0.5 ACH fresh air makeup.

Figure 5 shows the decrease in particulate concentrations over time in the IEQ chamber once the filter system has been placed in operation following the chamber being open to the ambient atmosphere.

The climate chamber had a significantly lower particulate count than the IEQ chamber. A distinction that may explain this is the Climate chamber supply is near the ceiling in the chamber and the exhaust near the floor. The IEQ chamber supply and exhaust are both near the ceiling. Although the IEQ chamber has excellent mixing as discussed later in this paper, the mixing test is performed using extremely light compounds. The particulates in the IEQ chamber are significantly heavier and would have to be sufficiently buoyant to remain entrained in the air leaving the chamber. Since the results met the design specification (Table 2), no additional testing was performed to test this hypothesis.

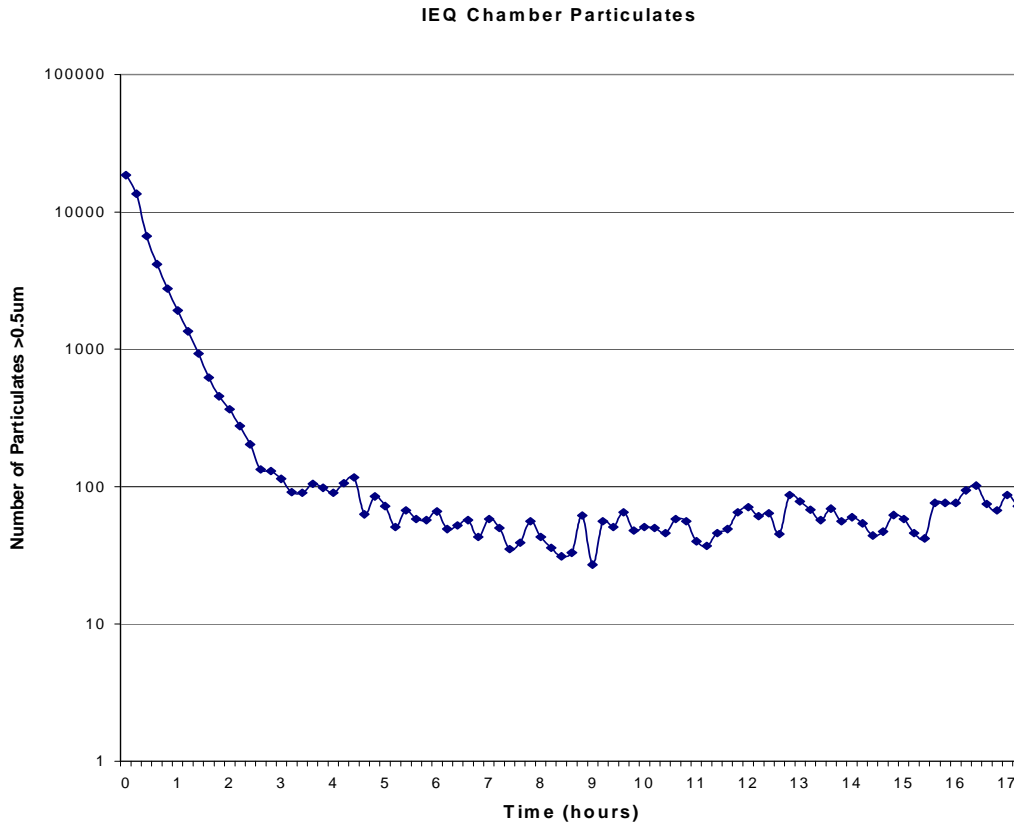


Figure 5. Particle count trend supply showing filter effectiveness – IEQ Chamber

Air Tightness

Air leakage through the chamber and ventilation system components can affect the accuracy of the emission test results. Because of this, ASTM 2001 establishes a recommended limit of 0.05 ACH with a differential pressure of 10 Pa between the chamber system and the ambient environment.

The air-tightness of the chambers was established using two methods: a pressurization method and a tracer gas method. The pressurization method is performed by measuring the supply airflow rate that is required to maintain a differential pressure between the inside and outside of each chamber system. In the tracer gas decay method, CO₂ was injected into the supply air duct until its concentration in the chamber becomes constant. CO₂ concentration decay over time was then measured, and the air change rate calculated using equation (1).

$$Nl = \frac{1}{t} \ln \left\{ \frac{C_o}{C_t} \right\} \quad (1)$$

Where t is the time, C_o and C_t are the initial and final tracer concentrations, respectively and Nl is the air change rate due to air leakage (ASTM 1995).

The results for the IEQ chamber showed that the leakage was 0.028 ACH using the pressurization method and 0.004 ACH using the tracer decay method. The climate chamber leakage was 0.019 ACH using the pressurization method and 0.017 ACH using the tracer decay method. Both chambers show excellent performance. The highest measured leakage rate is approximately 3 to 5 times lower than that specified. The pressurization method was performed at a higher differential pressure of 62.5Pa (0.25 inches of water) due to the limitations of the regulator used. The tracer gas test was conducted at 10 Pa as specified for the system design. This may help to explain the higher indicated leakage rates obtained using this method. Additional studies will need to be performed to assess the use of the pressurization method as an alternative to the tracer decay method for the same pressure differential (i.e., 10 Pa). The potential advantages of this method are the ease with which it can be performed and the reduction in time needed to perform the leakage testing. This is because leakage is measured directly using the pressurization method.

Process Variable Control Capability

The control accuracy and precision of each of these process variables was assessed. Control accuracy is defined as the difference between the mean value of the parameter and its set point. Control precision is defined as the standard deviation of the parameter from its mean value.

Control accuracy and precision for each chamber was determined by collecting process parameter data from the control system instrumentation and exporting the data to a spreadsheet for analysis. Instruments were all calibrated to NIST traceable standards. Results (Table 3) showed that the accuracy and precision for airflow rate, RH, pressure and temperature were less than half that specified.

Table 3. Control Accuracy and Precision Results Under Standard Conditions*

| IEQ Chamber | | | | |
|------------------------|--------------------------|--------------------------|---------------------------|---------------------------|
| <i>Parameter</i> | <i>Accuracy Criteria</i> | <i>Measured Accuracy</i> | <i>Precision Criteria</i> | <i>Measured Precision</i> |
| Airflow Rate (Total) | +/- 3% of setpoint | -1.1% | +/-5% of mean | +/-3.0% |
| Airflow Rate (MUA) | +/- 3% of setpoint | 0.0% | +/-5% of mean | +/-2.0% |
| RH | +/-2% | +0.1% | +/- 5% | +/-0.3% |
| Pressure | +/- 1Pa | 0.0Pa | +/- 2 Pa | +/-1.2Pa |
| Temperature | +/-0.5°C (0.9 °F) | 0.0°C | +/-0.5°C | +/-0.1°C |
| Climate Chamber | | | | |
| <i>Parameter</i> | <i>Accuracy Criteria</i> | <i>Measured Accuracy</i> | <i>Precision Criteria</i> | <i>Measured Precision</i> |
| Airflow Rate (Total) | +/- 3% of setpoint | 0.0% | +/-5% of mean | +/-0.3% |
| Airflow Rate (MUA) | +/- 3% of setpoint | +0.8% | +/-5% of mean | +/-2.0% |
| RH | +/-2% | 0.0% | +/- 5% | +/-0.1% |
| Pressure | +/- 1Pa | 0.0Pa | +/- 2 Pa | +/-0.4Pa |
| Temperature | +/-0.5°C | 0.0°C | +/-0.5°C | +/-0.0°C |

* Results were from 24 hour tests under conditions: 5ACH, 50% RH, 10Pa (0.04 inch water gage) and 23°C (73.4 °F) for the IEQ Chamber and 29ACH, 50% RH 50Pa and 23°C for the Climate Chamber

In addition to tests performed under standard conditions, tests were performed to assess the control system capability at high and low temperatures. Table 4 shows the parameters and the results of this testing at high and low temperature extremes for the IEQ Chamber. Table 5 shows the parameters and the results of this testing at high and low temperature extremes for the Climate Chamber.

Table 4. IEQ Control Accuracy and Precision Results - Extreme Design Temperature

| IEQ Chamber (low temperature; 12.8C) | | | |
|--|--------------------|--------------------------|---------------------------|
| <i>Parameter</i> | <i>Setpoint</i> | <i>Measured Accuracy</i> | <i>Measured Precision</i> |
| Airflow Rate (Total) | 5ACH | -0.4% | +/-0.8% |
| Airflow Rate (MUA) | 0.5ACH | +0.4% | +/-2.8% |
| RH% | 50% | -5.5% | +/-6.3% |
| Pressure | 10Pa (0.04 in H2O) | -0.0Pa | +/-0.0Pa |
| Temperature | 12.8°C (55 °F) | +0.40°C | +/-0.0°C |
| IEQ Chamber (high temperature; 37.8C) | | | |
| <i>Parameter</i> | <i>Setpoint</i> | <i>Measured Accuracy</i> | <i>Measured Precision</i> |
| Airflow Rate (Total) | 5ACH | +3.5% | +/-0.5% |
| Airflow Rate (MUA) | 0.5ACH | -0.1% | +/-3.1% |
| RH | 50% | -17% | +/-0.4% |
| Pressure | 10Pa | +2.5Pa | +/-1.6Pa |
| Temperature | 37.8°C (100 °F) | -0.1°C | +/-0.0°C |

Table 5. Climate Accuracy and Precision Results - Extreme Design Temperature

| Climate Chamber (low temperature; -29C) | | | |
|--|-----------------|--------------------------|---------------------------|
| <i>Parameter</i> | <i>Setpoint</i> | <i>Measured Accuracy</i> | <i>Measured Precision</i> |
| Airflow Rate (Total) | 29ACH | 0.0% | +/-0.4% |
| Airflow Rate (MUA) | 0.8ACH | +0.4% | +/-7.4% |
| RH▲ | NA | NA | NA |
| Pressure | 10Pa | 0.0Pa | +/-1.4Pa |
| Temperature | -29°C (-21°F) | +/-0.1°C | +/-0.0°C |
| Climate Chamber (high temperature; 37.8C) | | | |
| <i>Parameter</i> | <i>Setpoint</i> | <i>Measured Accuracy</i> | <i>Measured Precision</i> |
| Airflow Rate (Total) | 29ACH | 0.0% | +/-0.3% |
| Airflow Rate (MUA) | 1.7ACH | 0.0% | +/-1.4% |
| RH | 50% | +8.0% | +/-0.7% |
| Pressure | 10Pa | 0.0Pa | +/-0.7Pa |
| Temperature | 37.8°C (100°F) | 0.0°C | +/-0.0°C |

▲ Relative Humidity cannot be controlled at temperatures below freezing.

The IEQ chamber exhibited fairly good control system performance over its design temperature range with excellent performance at standard conditions. Process control parameters were within specification at low temperature conditions for total airflow, pressure and temperatures as well as makeup airflow and temperature accuracy. Relative humidity was out of specification for accuracy and precision. The humidifier required re-tuning for proper performance at lower temperatures and removal of a moisture output restriction in the control system. Process control for the IEQ chamber was also fair at the high temperature setpoint of 37.8°C with total airflow and pressure accuracy being slightly out of specification and the relative humidity accuracy significantly low out of specification. The moisture output restriction in the control system limited the amount of moisture that could be added, significantly impacting the ability of the system to achieve the desired humidity at higher temperatures. Makeup and total airflow, relative humidity, pressure and temperature precision were all within specification. Since the range of typical indoor air temperatures in conditioned spaces are much less than those used for testing, this should have no impact on the intended performance of the chamber for its intended uses in the near term. Additional modifications to the control system are being implemented to allow use of the chamber over a wider temperature range.

The climate chamber exhibited very good control system performance over its temperature range. All process control parameters were well within specification at low temperatures with the exception of makeup airflow precision. A required restrictor plate was found to be missing that helps to control pressure. This was the first test control system performance test that was conducted. The restrictor plate was reinstalled and later control tests confirmed good pressure control performance. Process control for the climate chamber at high temperature was extremely good with only relative humidity out of specification high at +8.8 %RH. This was due to a system controller parameter limitation. The controller program had a maximum deviation between the return and the supply humidity of 10%. This is why the return humidity was high. This problem was subsequently corrected by increasing the maximum deviation to 30% and the maximum output to 90%. All other process parameters were significantly below the criteria used for standard conditions. This shows that the climate chamber can be used to simulate outdoor conditions for a wide range of possible geographic locations.

Mixing Conditions

Good air-mixing in a chamber ensures that contamination gradients within the chamber are minimized. This is essential if concentrations measured at the return or exhaust duct are used to represent the average concentrations in the chamber (ASTM 2001). Air mixing depends on the design of the ventilation system,

including the supply air diffuser and flow rate (ACH) used for a particular test (Zhang et al. 1996). For the IEQ chamber, the supply air was discharged through a square diffuser located in the center of the ceiling and the return air was exhausted through a circular opening with a perforated plate located near the top of the enclosure on a side wall. For the Climate chamber, the supply air is discharged through a plenum diffuser on a side wall near the top of the chamber and exhausted from a circular opening with a perforated plate located near the bottom of the chamber on the same wall.

The tracer gas stepup technique was used to assess the mixing conditions within the chambers using CO₂ as the tracer gas. The total airflow rate (outside air plus recirculated air) in the IEQ chamber was 5ACH, with 0.65 ACH outside makeup air. The total airflow rate in the Climate chamber was 29 ACH with 1.33ACH outside makeup air. The CO₂ was injected through the fresh makeup air supply duct through a mass flow control valve at 0.906 l/min to maintain a constant concentration at the inlet. Due to the different makeup rates, a higher equilibrium concentration of CO₂ was reached in the Climate chamber as compared to the IEQ chamber. Immediately after the injection, the gas concentrations are measured continuously at the return or exhaust air duct. It is important to note that there was initial difficulty in collecting accurate data. The CO₂ probe uses a non-dispersive infrared (NDIR) detection based sensor. The probe had to be placed completely inside the return duct to obtain accurate readings.

The standard method for assessing the mixing condition in a conditioned space uses multiple concentration measurements at local points within the space. Because only a single sensor was available, the overall mixing condition of the chamber was assessed by comparing the measured gas concentration at the return or exhaust with the theoretical curve expected for the uniform concentration condition using equation (2);

$$\eta = \left\{ 1 - \frac{\int_0^{t_n} |C_m(t) - C(t)| dt}{\int_0^{t_n} C(t) dt} \right\} \times 100\% \quad (2)$$

where,

η = mixing level;

t_n = nominal residence time of the clean air supply (equal to 60/N), min;

$C_m(t)$ = measured CO₂ concentration, ppm;

$C(t)$ = theoretical concentration at the return air under the uniform concentration condition, ppm [note that $C(t)$ was modified to account for the tracer gas concentration in the chamber air supply as shown in equation (3) below];

N = makeup air change rate, air change per hour, 1/h; and

t = time, hours.

The term $C(t)$ in equation (2) had to be modified to account for the background concentration of the CO₂ tracer gas as follows:

$$C(t) = C_{in}(1 - e^{-Nt}) + C_b e^{-Nt} \quad (3)$$

where,

C_{in} = inlet concentration of CO₂ gas being injected (approximately 1860 ppm for the climate chamber and 1460 ppm for the IEQ chamber);

C_b = background concentration of CO₂ gas concentration in the air supply, (approximately 330 ppm);

Equation (3) provides the concentration decay of tracer gas with nonzero initial concentration of the CO₂ tracer gas, where C_b is tracer gas background concentration in the chamber air. Physically, the term

“ $C_{in}(1-e^{-Nt})$ ” represents the concentration increase due to a constant concentration at the make-up air (injected plus outdoor CO₂ concentrations), the term “ $C_b e^{-Nt}$ ” represents the decay of the initial background concentration in the chamber, which was different than that in the fresh air makeup from outside. The background CO₂ concentration from outside was steady and averaged approximately 336 ppm during the test.

Note that only the measured concentrations from time zero to t_n are used in the above procedure, which makes the mixing level, η , more sensitive to the non-uniform concentration condition in the chamber. A mixing level of higher than 80% may be considered satisfactory since the corresponding spatial non-uniformity (maximum concentration difference between the sampling locations inside the chamber and at the exhaust, divided by the average concentration between the measured locations) of the tracer gas concentration inside the chamber is estimated to be less than 5% based on the experimental results of Zhang et al. 1996. For sources with a constant emission rate, 5% non-uniformity in the chamber concentration is estimated to cause a maximum of 5% error in the determination of the emission rate (ASTM 2001).

The results of the mixing level test showed excellent mixing, with a mixing level of 94% in the IEQ chamber and 96% in the Climate Chamber (Figure 6).

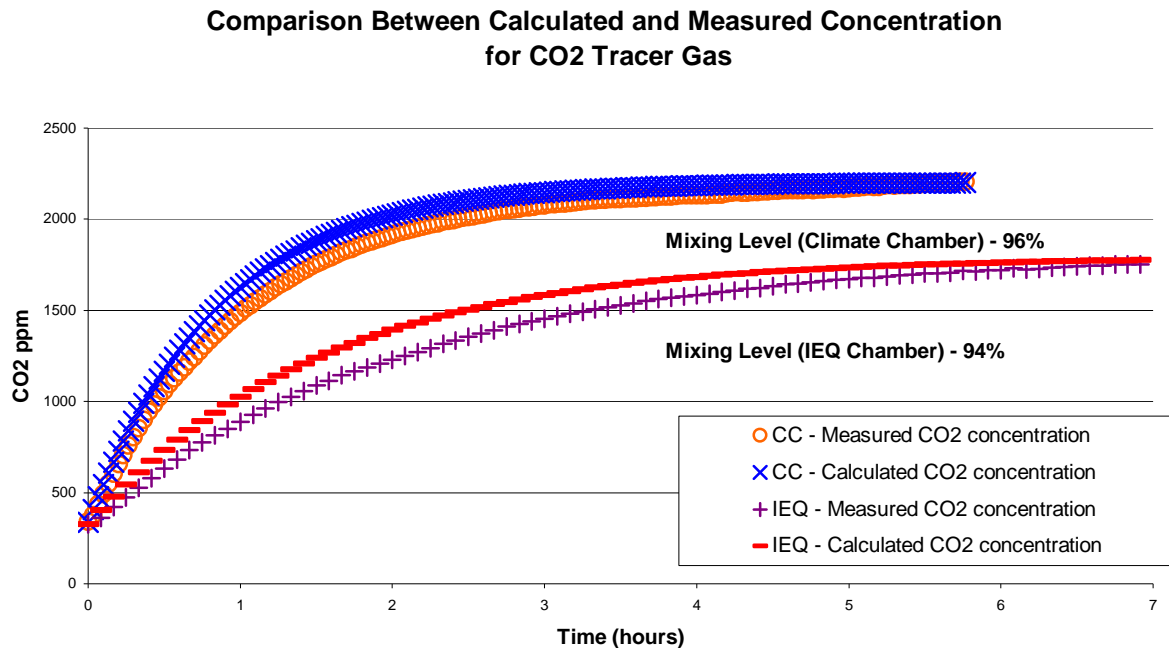


Figure 6. IEQ Chamber Mixing Effectiveness

Air Distribution, Velocity and Turbulence

It is important to understand air distribution patterns and turbulence levels in the chamber because air velocity and turbulence affect the evaporative mass transfer from both solid and liquid sources. For “wet” materials such as paints, stains, and varnishes, whose initial emission period is primarily controlled by evaporative mass transfer, increasing the air velocity and turbulence will lead to an increase in emission rates of VOCs. Since the validity of the mass balance equation used to assess the emission rate of various materials depends on how well the chamber’s actual operation meets the assumed conditions under which the material will be used, the air velocity and turbulence at representative locations within the chambers must be characterized (Zhang et al. 1996). In order to characterize the air velocity and turbulence levels, measurements were taken at various locations in each chamber.

For the IEQ chamber, approximately one measurement was taken for each cubic meter of space, resulting a total of 48 measurement locations (a grid of 4 x 12 bounded by 0.1m to 1.7m above the floor).

An omnidirectional anemometer was used to perform air velocity and turbulence measurements. Measurements were taken by attaching the anemometer probe to a test stand. The sensor measures velocity between 0.01 and 5.0 m/s with a response time of 0.5s for measuring turbulence intensity and an accuracy of 0.01 m/s. Data for air velocity and turbulence was collected for a minimum of three minutes at each test point. An average and standard deviation was calculated from the data collected. For a mixing type ventilation system with a ceiling square diffuser tested, the average mean air velocity for all test locations was 0.07 m/s (13.8 ft/min) with a standard deviation of 0.04, and the average turbulence intensity was 41% with a standard deviation of 17%. The results show that the tested system can provide realistic velocity and turbulence levels representative of those found in typical office settings (Zhang et al. 1996). The chamber can also be configured to simulate displacement ventilation system or task/ambient ventilation with under floor air distribution.

A similar test was not performed for the Climate chamber, which will not be used for testing indoor emission sources. It is expected that the significantly higher air change rates and use of the dynamic pressure simulator will create higher velocities and turbulence levels than those typically encountered indoors.

Sink Effect

One of the factors affecting the performance of the chambers is the sink effect. The sink effect is the measure of the adsorption/desorption characteristics of the chamber for various VOCs of interest. Previous studies (Colombo et al. 1993) have shown that chamber surfaces adsorb and reemit VOCs such that the apparent emissions profile of the source may be affected. The procedure in ASTM 2001 provides a method for characterizing the chamber sink effect in dynamic test chambers.

A test was performed with the chamber system in the partial recirculation mode with 5ACH total airflow and 0.5ACH makeup airflow for the IEQ chamber. The Climate chamber test was run similar to the test for the IEQ chamber.

The chamber was first pre-conditioned at 23°C and 50% RH and the background concentration of VOCs checked to ensure that the levels of any test VOCs is insignificant. Two small mixing fans are located at opposite corners of the chamber and operated throughout the test to ensure good air mixing in the chamber. Next, a mixture of test VOCs consisting of Ethylbenzene, Decane, 1,4-Dichlorobenzene and Dodecane was introduced into a container and heated on a hot plate at 250°C to ensure rapid release into the chamber airflow. The chamber was then operated for an 18-hour adsorption period and a 48-hour desorption period. The tracer gas decay method, described previously, was used to monitor the air change rate at various periods of the test. VOC concentrations were measured at pre-determined time intervals to quantify the sink characteristics of each chamber. Duplicate VOC samples were taken periodically at the chamber exhaust and the chamber space to assess the uniformity of VOC concentrations.

The first-order reversible sink model is used here to describe the sink effect of the chamber:

$$s(t) = \frac{dm(t)}{dt} = k_a C(t) - k_d m(t) \quad (4)$$

where,

C = concentration over the sink surface, mg/m³ (at $t=0$, $C=C_{eq}$);

k_a = adsorption rate constant, m/h;

k_d = desorption rate constant, 1/h;

m = mass in the sink per unit surface area, mg/m²;

s = sink rate, mg/(m²h);

The ratio between the adsorption and desorption rate constants is called the equilibrium constant, k_e , and it can be derived from Equation (4) as:

$$k_e = \frac{k_a}{k_d} = \frac{m_e}{C_{eq}} = \frac{VM_{sr}}{A_s M_{air}} \quad (5)$$

where,

A_s = the total area of the sink surfaces in the chamber system, m^2 ;

m_e = reemitted VOC mass adsorbed in the sink per unit surface area at equilibrium ($m_e = M_{s,r}/A_s$), mg/m^2 .

Assuming perfect mixing, the concentration of an individual VOC in the chamber during the desorption period can be described by the following mass balance equation:

$$V \frac{dC(t)}{dt} = -A_s s(t) - QC(t) = -A_s [k_a C(t) - k_d m(t)] - QC(t) \quad (6)$$

at $t=0$: $C(t) = C_{eq}$, $m(t) = m_e$

Solving Equations (4) and (6), we obtain:

$$C(t) = \frac{C_{eq} [(N - r_2)e^{-r_1 t} - (N - r_1)e^{-r_2 t}]}{r_1 - r_2} \quad (7)$$

where,

$$r_{1,2} = \frac{(N + k_a L_s + k_d) \pm [(N + k_a L_s + k_d)^2 - 4Nk_d]^{1/2}}{2}$$

The adsorption rate constant k_a and equilibrium constant k_e for each VOC can be calculated by fitting the experimental concentration curve during the desorption period.

Since the number of experimental points were not enough to get a good fit to equation (7) directly with two parameters (k_a , k_e), the experimental results were first fitted to a double exponential expression [$C(t) = ae^{-bt} + c * e^{-dt}$, where a, b, c & d are regression coefficients]. k_a & k_e were then obtained by fitting to equation (7) using values from double exponential expression.

The measured and modeled concentration of each VOC during the desorption period are shown in Figure 7. Since the regression analysis is not successful for ethylbenzene due to experimental uncertainty and small sink effect, only a double exponential fitting is shown here.

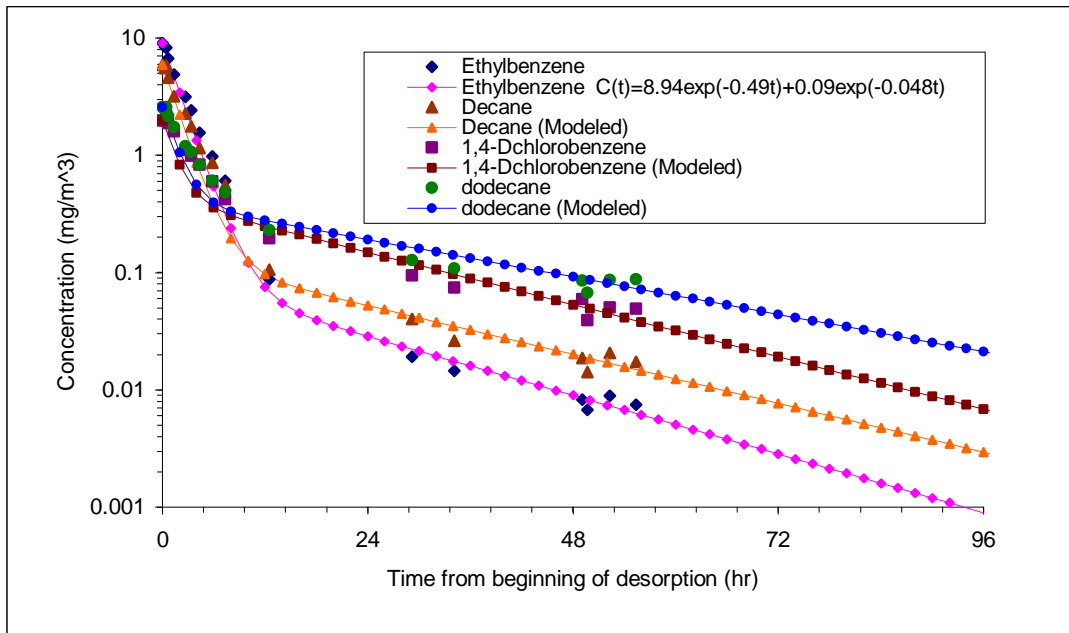


Figure 7. IEQ Sink Test Result under Partial Ventilation Mode

Total Sink Ratio, Irreversible Sink Ratio and Reversible Sink Ratio are also calculated. The equations for calculating each parameter are given below.

The total sink ratio is calculated using equation (8):

$$r_{st} = \frac{M_{st}}{M_t} = \frac{M_o - M_{leak} - M_{air}}{M_o - M_{leak}} = 1 - \frac{C_{eq} V}{M_o - M_{leak}} \quad (8)$$

where,

r_{st} = total sink ratio;

M_{st} = total VOC mass adsorbed by the chamber surfaces (sink) at the end of the adsorption period, mg;

M_t = total VOC mass in the chamber ($M_{st} + M_{air}$) at the end of adsorption period, mg;

M_o = VOC mass injected, mg;

M_{leak} = VOC mass loss due to air leakage during the 18 hour adsorption period, mg;

M_{air} = VOC mass in the chamber air at equilibrium ($M_{air} = C_{eq} V$), mg;

C_{eq} = the concentration at the end of the adsorption period (i.e., the start of the desorption period), which is assumed to be the equilibrium concentration, mg/m³; and

V = volume of the chamber system (including the air volume of the recirculation loop if the loop is included in the test), m³.

The irreversible sink ratio is calculated using equation (9):

$$r_{si} = \frac{M_{si}}{M_t} = \frac{M_t - M_{exit}}{M_o - M_{leak}} = 1 - \frac{Q \int_0^{\infty} C(t) dt}{M_o - M_{leak}} \quad (9)$$

where,

r_{si} = irreversible sink ratio ($1 - r_{si}$ is sometimes called mass recovery ratio, quantifying the mass recovered from the air exhausted from the chamber);

M_{si} = VOC mass that is not re-emitted from the sink (i.e., irreversible), mg;

M_{exit} = VOC mass exhausted from the chamber during the desorption period, mg;

Q = clean airflow rate (which is equal to the exhaust airflow rate), m³/h;

$C(t)$ = concentration of exhausted air, mg/m³ (at $t=0$, $C=C_{eq}$); and

t = elapsed time since the start of the desorption period (i.e., $t=0$), h.

The reversible sink ratio is calculated using the equation (10):

$$r_{sr} = \frac{M_{sr}}{M_t} = \frac{M_{exit} - M_{air}}{M_o - M_{leak}} = \frac{Q \int_0^{\infty} C(t) dt - VC_{eq}}{M_o - M_{leak}} \quad (10)$$

where,

r_{sr} = reversible sink ratio; and

M_{sr} = VOC mass re-emitted from the sink, mg.

The calculated results are summarized in Table 6.

Table 6. Calculated Sink Parameters for IEQ Chamber in Partial Ventilation Mode ^{a,b,c}

| Compound | r_{st} (%) | r_{si} (%) | | | r_{sr} (%) | | | k_a \pm std ^d (m/h) | k_{d1} (1/h) | k_e \pm std ^d (m) | C_{eq} (mg /m ³) | M_{0-} M_{leak} (mg) |
|---------------------------------|-----------------|-----------------|-----------------|----------------------|-----------------|-----------------|----------------------|--|-------------------|--|--------------------------------------|--------------------------------|
| | | $t_N =$ 48 h | $t_N =$ 96 h | $t_N =$ $+\infty$ | $t_N =$ 48 h | $t_N =$ 96 h | $t_N =$ $+\infty$ | | | | | |
| Ethylbenzene | 1 | -4 | -4 | -4 | 5. | 5. | 5. | N/A ^e | N/A ^e | 0.03 | 9.02 | 523 |
| Decane | 37.5 | 12.8 | 10.0 | 8.9 | 24.7 | 27.5 | 28.6 | 0.0052 \pm 0.0009 | 0.041 | 0.1267 \pm 0.0121 | 5.89 | 538 |
| Dodecane | 74.4 | 23 | 10.4 | 3.2 | 51.4 | 64.0 | 71.2 | 0.0417 \pm 0.0046 | 0.036 | 1.1607 \pm 0.0652 | 2.57 | 573 |
| 1,4-Dchlorobenzene ^f | 79.1 | 34.6 | 27 | 24 | 44.5 | 52.1 | 55.1 | 0.0578 \pm 0.0076 | 0.053 | 1.0843 \pm 0.0670 | 1.97 | 538 |

a. k_a and k_e were calculated using 48 h measured data by regression.

b. r_{si} , r_{sr} were calculated according to double exponential expression fitting.

c. $V=57.12$ m³, $A_s=110.7$ m² (estimated value according to chamber and duct size)

d. Standard deviation of the estimate, k_a and k_e

e. The regression analysis was not successful due to experimental uncertainty and small sink effect.

f. 1,4-Dchlorobenzene was directly heated from solid phase to vapour phase.

Test results showed that the chamber had a negligible sink effect for Ethylbenzene, while much stronger sink effects for Decane, Dodecane and 1,4-Dichlorobenzene compared with the results of J.S.Zhang et al, (1999). Additional tests on Ethylbenzene, Decane, and Dodecane as single compound under full-exhaust ventilation mode also showed similar trends. Some possible reasons for the strong sink effect for Decane, Dodecane and 1,4-Dichlorobenzene that were considered are analyzed below.

- (1) The chamber here uses more gaskets for sealing than the chamber of Zhang et al (1999), which has stronger adsorption capacity of VOCs than stainless steel surface. This would tend to explain why the sink effect is strong for both chambers in each test. This could be confirmed through small chamber testing of the gasket material.
- (2) The weld surface where the stainless steel panels are joined together could be trapping more of the heavier VOCs. The welded joints in this study were mechanically polished while those in Zhang et al (1999) were not. Testing of specimens of welded surfaces in a small-scale chamber could help to see the extent to which this can influence the sink effect.
- (3) For heavy compounds, samples from return duct always had slightly higher concentration levels than samples from chamberside sampling port, which indicated that heavy compounds might not be well-mixed inside the chamber, giving less representative results. This is less likely. Comparing the results for the sink effect and the overall performance test (described in the next section) showed that there was good performance with decane. Furthermore, the mixing tests showed excellent mixing in both chambers, indicating that poor mixing is an unlikely cause.
- (4) Each time from static adsorption period to dynamic desorption period, flanges needed to be removed from make-up air duct and exhaust air duct manually (typically 20 – 40 minutes), during which some make-up air flow continued. Opening the system would affect both lighter and heavier compounds and would likely have a greater effect on a loss of the lighter compounds and was therefore ruled out.
- (5) The tested VOCs were mixed and heated to about 250°C. The evaporation process was fairly quick due to the high temperature. A white smoke was observed during the heating process, which might indicate that some VOCs were not fully evaporated. This was also ruled out because the test method used was the same as that used for the chamber in a previous study (Zhang et al, 1999) which did not show a significant sink effect. In addition, testing was performed where the compounds were evaporated over a longer period of time (several hours) using a heat lamp and the sink effect was similar; which further ruled this out.

Further small chamber tests need to be performed to confirm the cause of the higher sink effect of the heavier compounds compared to the previous study (Zhang et al, 1999). In the meantime, the sink effect should be compensated in emission testing due to the significant contribution that could occur from the sink effect for heavier compounds.

Overall Performance Using a Standard Source

In order to assess the overall performance of the test chambers, the ASTM 2001 method subjects chambers to a test with a reference source whose emission rate is measured by an independent method. A liquid VOC contained in an uncovered Petri dish is used as a reference emission source.

A pool of pure liquid decane was placed in an uncovered Petri dish (100mm diameter) and its weight loss due to evaporation/emission was measured by an electronic balance to determine the reference emission rate $R_r(t)$ and the concentration of decane was measured at the chamber exhaust to obtain the calculated emission rate $R(t)$ until the concentration in the chamber was less than twice the background concentration. The chamber was operated under a well-mixed air condition with constant air temperature (23°C), RH (50%) and air change rates (0.5 ACH clean make up air, and 5 ACH total supply air). Results show that the measured decane concentrations at the return air follow closely with those calculated from the weight loss data assuming perfect mixing in the chamber. Figure 8 shows the results for the IEQ chamber and Figure 9 shows the results for the Climate chamber. The calculated emission rate was within 17% of the reference emission rate for the IEQ chamber and within 14% for the Climate chamber.

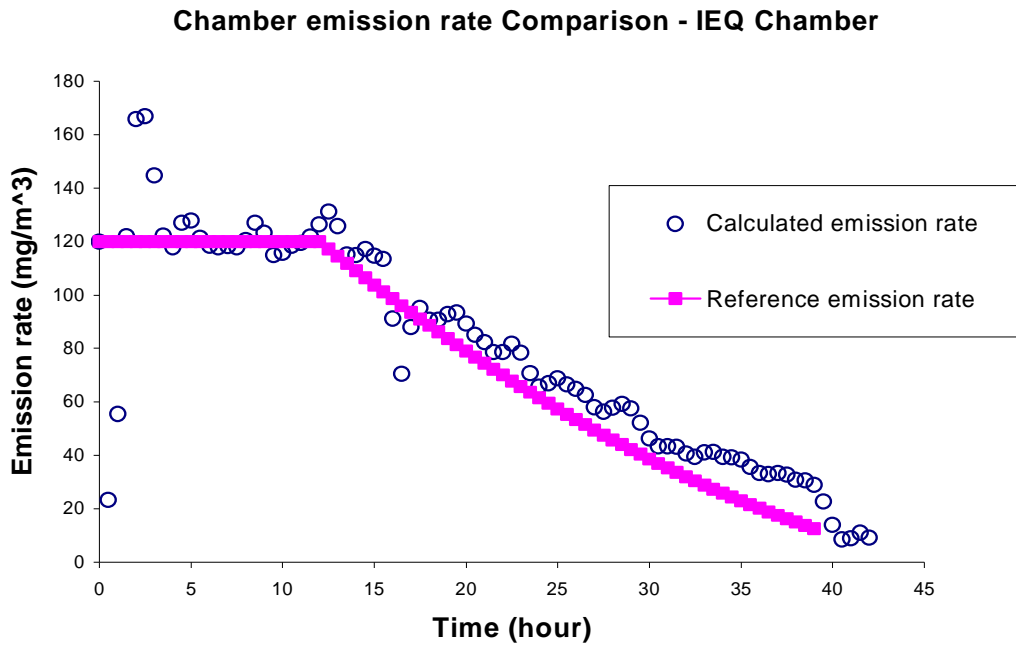


Figure 8 IEQ Chamber Emission Rate Comparison

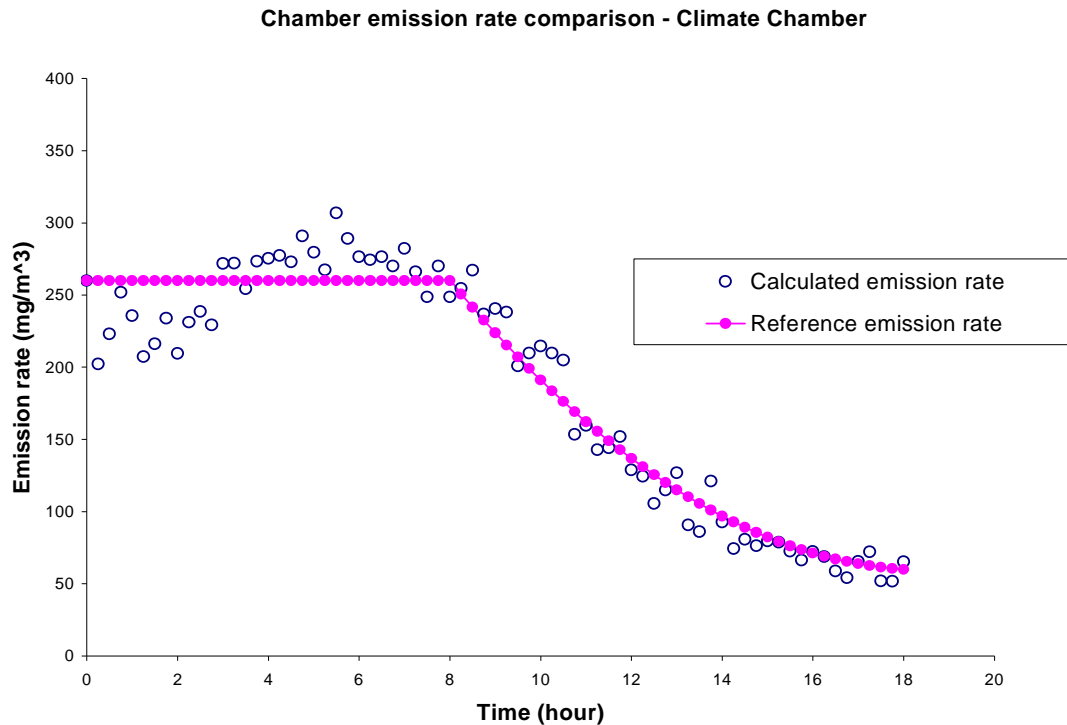


Figure 9 Climate Chamber Emission Rate Comparison

COMBINED CHAMBER PERFORMANCE TESTS

Beyond assessing the capabilities of the individual chambers, the interaction between the two chambers needs to be understood. The combined chamber configuration was commissioned by collecting information with both chambers in operation and by verifying that the individual ventilation systems were able to maintain control with up to 47.2 l/s (100 cfm) leakage from the climate chamber to the IEQ chamber.

The testing was performed with the test wall (refer to Figure 1) installed between the two chambers.

The IEQ chamber and Climate chamber setpoints were both established at standard conditions of 23°C and 50% RH. The actual IEQ chamber temperature averaged 18°C. The IEQ chamber was using 47.2 l/s of makeup air at 12.8°C. Because the maximum setpoint deviation was set at 32.2°C and the system flow rate was 75.5 l/s, there was insufficient heat input to overcome the cold makeup air. As discussed previously, the maximum deviation settings for temperature and RH have been revised to allow for testing under more challenging conditions. The humidity averaged 5.5 % RH. This was due to a failure of the makeup water supply to the IEQ chamber that has since been corrected.

The IEQ chamber was operated with a total chamber airflow rate of 5 ACH and a makeup airflow rate of 0.5 ACH with a static pressure of 35 Pa (0.14 In. H₂O). The Climate chamber was operated with a total chamber airflow rate of 29.2 ACH and a makeup airflow rate of 1.7 ACH with a static pressure of 10 Pa pressure relative to ambient. A window in the test wall was used to establish the airflow rate from the IEQ chamber to the Climate chamber. Table 7 shows the parameters and the results of this testing.

Table 7. Control Accuracy and Precision Results – 47.2 l/s (100 ft³/min)

| IEQ Chamber | | | |
|------------------------|---------------------------------|--------------------------|---------------------------|
| <i>Parameter</i> | <i>Setpoint</i> | <i>Measured Accuracy</i> | <i>Measured Precision</i> |
| Airflow Rate (Total) | 5ACH | +0.1% | +/-8.1% |
| Airflow Rate (MUA) | 0.5ACH | 0.0% | +/-1.9% |
| RH | 50% | -44.3% | +/-2.1% |
| Pressure | 35Pa (0.14 in H ₂ O) | 0.0Pa | +/-2.5Pa |
| Temperature | 23°C (73.4 °F) | -5.0°C | +/-1.0°C |
| Climate Chamber | | | |
| <i>Parameter</i> | <i>Setpoint</i> | <i>Measured Accuracy</i> | <i>Measured Precision</i> |
| Airflow Rate (Total) | 29.2ACH | 0.0% | +/-0.3% |
| Airflow Rate (MUA) | 1.7ACH | -0.1% | +/-5.2% |
| RH | 50% | 0.0% | +/-0.2% |
| Pressure | 10Pa (0.04 in H ₂ O) | 0.0Pa | +/- 2.5Pa |
| Temperature | 23°C (73.4 °F) | +1.5°C | +/-0.5°C |

The control systems worked well in controlling pressure in both chambers. The accuracy was good with control accuracy in the climate chamber a + 0.3% and -1.4% for the IEQ chamber. The precision was acceptable with precision in both chambers at 2.5 Pa (0.01 inches of water). More importantly, the chambers were able to maintain stable pressure control with a fairly large air flow rate across the chamber test wall.

Relative Humidity control was extremely good in the climate chamber with accuracy at 0.0 %RH and precision at +/- 0.2 %RH. While precision in the IEQ chamber was good at +/-2.1 %RH, as mentioned above, accuracy was poor with the system operating at 5.5 %RH on average vs a 50 %RH setpoint. The climate chamber humidity control was especially challenged during this test with the IEQ chamber humidity being well out of specification. This caused the climate chamber humidity to have to compensate for the significantly lower humidity air being added from the IEQ chamber.

Temperature control was acceptable in the climate chamber with accuracy at +3.6%. Precision was also acceptable in the climate chamber at +/- 1.1%, but was slightly higher than desired at +/- 2.0% in the IEQ chamber. Accuracy was more problematic in the IEQ chamber at -12.2%. Since the climate chamber had to compensate for the lower temperature and humidity from the 47.2 l/s (100 cfm) air coming in from the IEQ chamber, the climate chamber temperature was higher than the established setpoint.

Flow accuracy was very good in both chambers. For the climate chamber, clean air flow had an accuracy of 0.1%, exhaust flow accuracy was +0.4% and the total flow accuracy value was +0.0%. For the IEQ chamber, clean air flow had an accuracy value of 0.0% and total flow was within +0.1%. Flow precision was generally good, with some exceptions in climate chamber clean air flow and IEQ chamber total flow. For the climate chamber, clean air flow precision was +/- 5.2%, exhaust air precision was +/- 0.9% and total flow precision was +/-0.3%. For the IEQ chamber, clean air flow precision was +/-1.9% and total flow precision was +/-8.1%.

The balance in establishing a 47.2 l/s leakage flow between the climate and the IEQ chamber worked fairly well. Even though the deviation in flows between the two chambers were 12.5%, the precision was good at +/-0.7%. Pressure control was also very good for the coupled chamber, given a target differential pressure of 25 Pa (0.1 inches of water) at 47.2 l/s leakage. The accuracy was -2.1% and the precision was +/-4.4%.

Overall, the coupled chamber system showed reasonably good control and can be used for experiments where leakage from one chamber to the other is desired to monitor contaminant transport once the IEQ humidity control problem is resolved.

SUMMARY AND CONCLUSIONS

Performance testing was performed for an innovative large Coupled Indoor/Outdoor Environmental Simulator (C-I/O-ES). The C-I/O-ES consists of two separate chambers that can be connected using a test wall or separated using a separation wall. One chamber is referred to as the IEQ chamber and the other chamber is referred to as the climate chamber. The IEQ chamber is designed to study the emissions of VOCs from building materials under a variety of environmental conditions and ventilation system configurations. The climate chamber is designed to be capable of establishing varying environmental conditions of temperature, pressure (both static and dynamic) and relative humidity to simulate the outdoor environment. Performance testing was conducted of each chamber individually and then as a coupled system.

The IEQ chamber was tested using the procedures and criteria established in ASTM 2001. The testing identified the background concentration of VOCs, measured air tightness, assessed process variable control capability and mixing conditions, measured air distribution patterns and turbulence levels in the chamber, established the sink effect and assessed overall performance using a standard source. Results of this testing showed that the chamber met all the standard criteria. The sink effect was found to be higher than that described in a previous study (Zhang et al. 1999) and needs to be accounted for until further testing can be performed to identify the cause of the higher than expected sink effect. In addition, testing of process control capability at temperature extremes showed that the IEQ controls are fairly good at lower temperatures but that at temperatures approaching 37 °C, control is not within the desired tolerances. Further testing will be required to confirm process control capability at temperatures significantly above 23 °C.

The climate chamber was also tested using the procedures in ASTM 2001, but only for background concentration of VOCs, air tightness, process variable control capability, mixing conditions and overall performance using a standard source. Air distribution patterns, turbulence levels and sink effect were not measured since the climate chamber is not intended for testing indoor emission sources. Results of climate chamber testing showed that the chamber performed well and met all the standard criteria. Testing of process control capability at temperature extremes showed that the climate chamber has very good process control capability for all parameters except relative humidity accuracy which tends to be low at lower temperatures and high at higher temperatures. Low temperature control accuracy also tends to be difficult at lower temperatures and tends to track higher than the setpoint. This can be accounted for in setting up the controls since in all instances the process precision was very good.

Testing of the chambers in a combined system configuration with a test wall separating the two chambers was also performed to assess the interaction between the chambers in this configuration. The test wall was constructed to simulate a typical residential building envelope. Testing for the purposes of this paper consisted of assessing the process control capability with an airflow from the IEQ chamber to the climate chamber. Although some problems were experienced with relative humidity and temperature control in the IEQ chamber during the test, this verified that the individual ventilation systems are able to maintain control with up to 47.2 l/s leakage between the chambers.

Overall, the system performed very well in configurations where the chambers are operated independently and where they are coupled together. The C-I/O-ES facility enables studies to be performed under conditions not previously available to researchers. The flexibility of the facility also allows multiple studies to be performed simultaneously, providing a significant research tool for studying various emission sources, space air diffusion systems, air cleaning technologies, HVAC system controls and combined air, heat, moisture and pollutant transport in building envelope assemblies.

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REFERENCES

- ASTM. 1995. *ASTM Standard E 741-95*. Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution
- ASTM. 2001. *ASTM Standard D 6670-01*. Standard Practice for Full-Scale Chamber Determination of Volatile Organic Emissions from Indoor Materials/Products
- Colombo, A., DeBortoli, M., Knoppel, H., Pecchio, E., and Vissers, H., "Vapor Deposition of Selected VOCs on Indoor Surface Materials in Test Chambers", in *Proceedings of the 6th International Conference on Indoor Air Quality and Climate, Indoor Air '93*: Helsinki, 1993; Vol. 2, pp 407-412
- Fisk, W. and Rosenfield, A.H. 1997. Estimates of improved productivity and health from better indoor environments. *Indoors Air*. 7:158-172.
- Howard, E. M., M. A. Mason, J. S. Zhang., and S. Brown. 1995. A comparison of design specifications for three large environmental chambers. In *Engineering Solutions to Indoor Air Quality Problems*, VIP-51, Air & Waste Management Association, P.O. Box 1020, Sewickley, PA 15143-1020, U.S.A.
- Shaw, C.Y.; Barakat, S.A.; Newsham, G.R.; Veitch, J.A.; Bradley, J.S. 1995. "NRC indoor environment research facility," 1, 16th AIVC, Annual Conference on Implementing the Results of Ventilation Research (Palm Springs, CA., U.S.A. 9/19/95), pp. 209-220, September 19
- Wu, G.J., L.L. Christianson, J.S. Zhang and G.L. Riskowski. 1990. Room air ventilation simulator for indoor air and air contaminant distribution studies. *Indoor Air '90*. v4, pp237-242.
- Zhang, J.S.; Kanabus-Kaminska, J.M.; Shaw, C.Y.; Weichert, J.H.; Luszyk, E.; Magee, R.J.; Brouzes, M.A. 1996. Performance evaluation of a full-scale chamber for material emission tests and studies. *Indoor Air '96. The 7th International Conference on Indoor Air Quality and Climate* (Nagoya, Japan, 1996) pp. 373-378, vol. 3. (NRCC-38437)
- Zhang, Jianshun S.; Nong, Gang and Shaw, Chia Yu. Sink Characteristics of a Full-Scale Environmental Chamber and their Impact on Material Emission Testing. *HVAC&R Research Journal* Jan 1999 (4311)