NATURAL VENTILATION MEASUREMENTS AND SIMULATION AT TWO MILWAUKEE NATURE CENTERS

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ABSTRACT

A series of measurements and simulations carried out on two naturally ventilated spaces at Milwaukee area nature centers suggest that while wind is admittedly an intermittent and unpredictable driving force, satisfactory ventilation and carbon dioxide removal rates of interior spaces can be reliably achieved and can be reasonably simulated.

INTRODUCTION

Wisconsin energy code does not currently allow natural ventilation to be considered as a means for providing building occupants with required amounts of fresh air in part because wind is a variable (unpredictable) driving force and in part because methods for predicting the performance of natural ventilation systems are arguably in their infancy. However, Wisconsin's low humidity and cooler temperatures in spring, early summer, and autumn make it an appropriate location for naturally ventilated buildings. Over the past year, a number of experiments were carried out to monitor carbon dioxide levels at two nature centers near Milwaukee, WI. At the Urban Ecology Center, carbon dioxide levels were continuously monitored while the building was operated under mechanical heating, natural ventilation, and mechanical cooling modes for nearly half a year. In a second set of experiments, the auditorium space at the Schlitz Audubon Nature Center was filled to a higher than ambient CO_2 concentration. The space was then allowed to vent under a number of different window opening configurations without the aid of mechanical ventilation. Space temperature and CO_2 concentration as well as ambient conditions were monitored throughout the experiment. Ambient data was then used to drive a CONTAM (Dols, 2002) simulation model of the same space.

URBAN ECOLOGY CENTER

Natural Ventilation Configuration

The 1760 m^2 (19000 ft^2) Urban Ecology Center (UEC) includes a basement zone, which is not naturally ventilated and two floors of public and office spaces designed to maximize natural ventilation during mild weather. The public zone includes a two-story public space and three classrooms. All spaces have three exterior orientations with operable windows on each face. The opening area is between 5% and 10% of the floor area. The main public space includes high operable clerestory windows allowing stack as well as cross-flow ventilation. The public space is not air-conditioned. The office spaces are located on the first and second floor of the northeast corner of the building. A third floor mezzanine for three staff members is located above the 2nd floor office space. All office spaces have at least two exterior orientations with operable windows on both orientations. The opening area is between 3% and 7% of the floor area. Both stack and cross-flow natural ventilation are possible. The office area can be air-conditioned. The wall separating the office and public areas of the building includes operable windows permitting air flow between zones when the building is naturally ventilated. As the office spaces are continually occupied and the occupants can choose between opening windows and turning on the air-conditioner, the office space was chosen to evaluate the effectiveness of natural ventilation. The UEC office plans are illustrated in Figures 1 and 2.

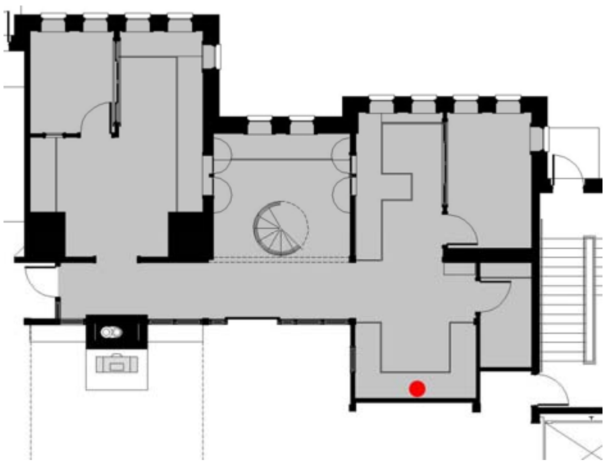

Figure 1: Partial UEC first floor plan (northeast corner). Office area is illustrated in grey. CO_2 meter location is indicated by red dot.

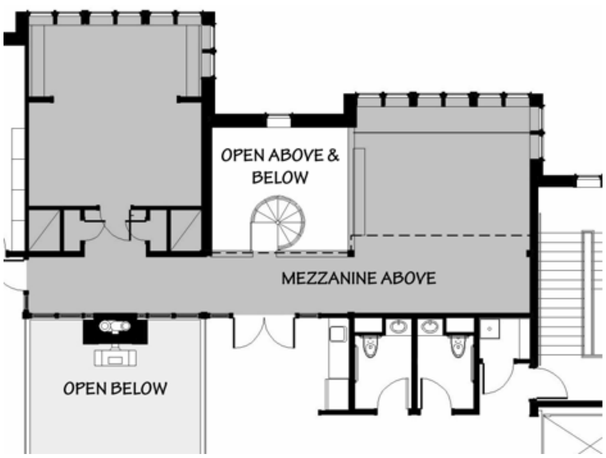

Figure 2: Partial UEC second floor plan (northeast corner). Office area is illustrated in grey.

Experimental Setup

The staff offices at UEC are typically occupied from 8:30 am until 5 pm Monday through Friday. Teaching staff members are typically in and out of the office, but administrative staff are usually in the office throughout the day. To evaluate the effectiveness of the natural ventilation system, the average CO_2 concentration in the administrative offices when windows were open was compared with the average CO_2 concentration on days when the administrative offices were either air-conditioned or heated. CO_2 levels were measured in parts per million (ppm) using a portable Telaire CO_2 sensor connected to an Onset HOBO^{TM} data logger. The sensor was calibrated at the beginning of the experiment in June and again in October (zero point calibration).

The data logger was located on a desk in the administrative area (red dot in Figure 1). As can be seen in the plan, there are no ventilation windows to the south or east. This area was chosen because it is continually occupied (typically one staff member on either side of the sensor location) and not the best location for natural ventilation. CO_2 concentration was longed once every 5 minutes and averaged over 15 minute intervals. 5 minute averaged ambient temperature was also recorded at the site. All weekend, holiday, and staff retreat days were removed from the study as were days in which CO_2 concentration were not measured over the entire occupancy period. What remained was 104 work days between June 20 and November 30, 2005. For 87 of those days the office was naturally ventilated, for 7 days the office was air-conditioned and for 10 days the office was heated.

Results

For each of the 104 days**,** the average CO_2 concentration and average outdoor air temperature between 8:30 am and 5:00 pm were computed. Pairs of CO_2 concentration and outdoor temperature for each day are plotted in Figure 3. The natural ventilation group is further subdivided into monthly bins.

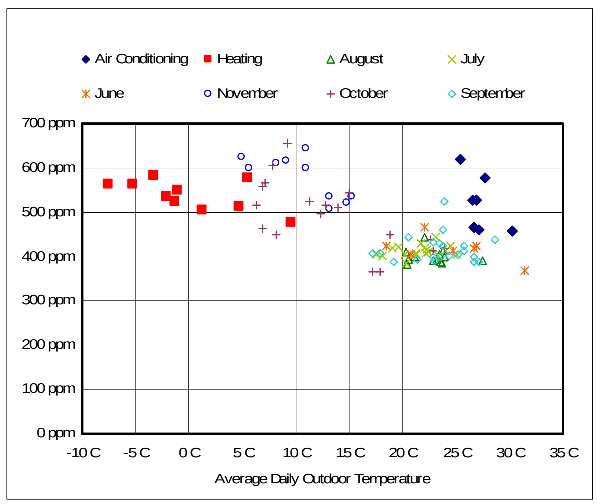

Figure 3: Average CO_2 Concentration versus Ambient Temperature

When the office is heated or air-conditioned, average CO_2 concentrations are typically between 500 and 600 ppm. During mild weather (outdoor air temperatures above 15C (59F)) most windows at the UEC are open and CO_2 concentrations average just above 400 ppm, indicating a ventilation level better than the mechanical system. When temperatures are cool (lower than 15C (59F)), fewer windows are open and CO_2 concentrations during natural ventilation are similar to CO_2 concentrations when heating. For all situations, the highest average concentrations occur during cool weather (outdoor air temperatures between 5C and 10C (41F - 50F)) when the heating system is not on and opening windows causes uncomfortably cool drafts. Average daily CO_2 concentrations exceed 600 ppm on a number of these days. Appendix C of the ANSI/ASHRAE Standard 62.1-2004 Ventilation for Acceptable Indoor Air Quality (ASHRAE, 2004) suggest that occupants will be satisfied with air quality if CO_2 concentration in occupied spaces does not exceed the outdoor ambient concentration plus 700 ppm. For typical outdoor air concentrations of 380 ppm, this limit would be 1080 ppm, a value that was not reached or exceeded in any of the observed data.

The data suggests that for this building, over the course of a year, 15 to 25 work days will require air-conditioning (based on ambient temperature), 125 to 150 work days, heating and for 100 to 125 days, ventilation requirements could be met by natural ventilation. Buildings designed to take advantage of natural ventilation have the potential to save considerable electrical energy in avoided ventilation fan usage. The office zone supply and return fans total 3 hp and the public zone supply and return fans total 4 hp. Required electrical power is on the order of 5 kW. Avoided electrical energy consumption over the year will be on the order of 3,000 kWh to 5,000 kWh, roughly 4% of the measured annual electric energy use at the Urban Ecology Center.

SCHLITZ AUDUBON NATURE CENTER

Natural Ventilation Configuration

The Schlitz Audubon Nature Center (SANC) building includes three spaces that were expressly designed to promote natural ventilation. Experiments were carried out on an auditorium zone that forms one of the short arms of the cross-shaped building. The auditorium is one floor high but includes an unoccupied clerestory ridge space that runs south to north along its middle. The clerestory includes operable windows along its length to allow daylight into the space below and to promote exhausting auditorium air through promotion of the stack effect. The auditorium also includes six operable windows placed low on the walls of the occupied space to act as fresh air intakes when the zone is operating in a natural ventilation configuration. Lastly, the auditorium includes an architectural screen that hangs approximately 30 cm (1 ft) below the opening between the occupied and clerestory spaces.

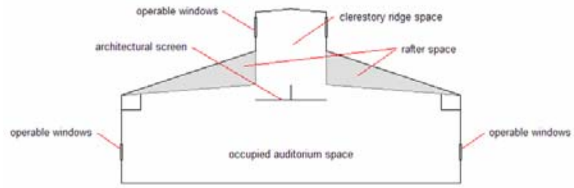

Figure 4: SANC Auditorium Section (facing north)

The intent of the auditorium natural ventilation system is that occupants would open both the windward and leeward low windows to promote cross ventilation. However, since these windows are comparatively small (0.372 m^2 (4 ft^2) each) and are placed quite low to the floor (0.914 m (3 ft)) there was concern that the cross flow would not extend up into the upper levels of the occupied space. Occupants can therefore open the leeward clerestory ridge windows promoting an upwards suction on the cross flow.

Experimental Setup

The auditorium was prepared for the experiments by duct-taping foam-core board over all of the ventilation system supply and return grills. The SANC building is equipped with sensors that disable the mechanical ventilation systems whenever a window is opened. Still, it was deemed appropriate to minimize airflow path connections between the auditorium and the rest of the building to as large an extent as possible. Unfortunately, the doors between the auditorium and the building foyer could not be taped shut as they had to remain accessible (although minimally) to building personnel throughout the experiment.

The carbon dioxide level in the auditorium and the ambient carbon dioxide level were measured using three portable Telaire CO_2 sensors that sent time averaged data to an Onset HOBO™ data logger once every 15 seconds. In addition to measuring CO_2 level in ppm, the Telaire data loggers recorded temperature and relative humidity. One of these devices was placed midway between the south and north wall of the auditorium approximately 3.35 m (11 ft) from the west wall. The other was placed midway between the north and south walls approximately 3.35 m from the east wall. Since the room is 13.41 m (44 ft) wide, placing the sensors 3.35 m (11 ft) from each wall put them at one quarter and three quarters of the way across the room along the cross flow ventilation path. The third logger was placed outdoors and provided measurements of ambient CO_2 level as well as ambient temperature and relative humidity. Lastly, wind speed and direction were measured using a 3 m (9.8 ft) tripod tower and another Onset sensor placed 4 m (13.2 ft) north of the auditorium.

CO_2 was added to the space by means of a gas cylinder that could deliver almost 0.566 m^3/hr (20 ft^3/hr) of gas through a regulator valve. There were a number of reasons behind the use of CO_2 in the experiment. First, it is inexpensive to obtain and relatively easy to measure. Second, CO_2 is the contaminant that drives design decisions when it comes to complying with standards such as ASHRAE 62.1-2004. In order to convince authorities that CO_2 can be effectively removed from a space by natural ventilation, it was convenient to use CO_2 in experimentation.

The basic sequence of an experiment was to fill the room to a chosen CO_2 concentration level, to then shut off the regulator and open up some combination of windows as quickly as possible and to leave the room for a given time period. As the room was filling with CO_2, it was quite common to see significant differentials (10 to 20%) between the two indoor CO_2 sensor readings. The difference was seen as undesirable so an effort was made to mix the zone as well as possible.

Experiment 1: Brought room to 1000 ppm (11:00 to 11:35). At 11:35 opened a single windward (east façade) and a single leeward (west façade) window. Vented from 11:35 to 12:00

Experiment 2: Brought room to 1200 ppm (12:00 to 13:00). At 13:00 opened all six auditorium windows (three on the east façade, three on the west). Vented from 13:00 to 13:30.

Experiment 3: Brought room to 1300 ppm (13:30 to 14:00). At 14:00 opened six auditorium windows and two leeward (clerestory west façade) windows. Vented from 14:00 and 14:30.

Experiment 4: Brought room to 1200 ppm (14:30 to 15:00). All windows remained closed. Vented room at natural (closed) decay rate from 15:00 to 15:30.

The measured CO_2 level in the space throughout the course of all experiments is shown in the following figure. Note the dramatic drop in ambient CO_2 level at the end of the day was caused by moving the recorder.

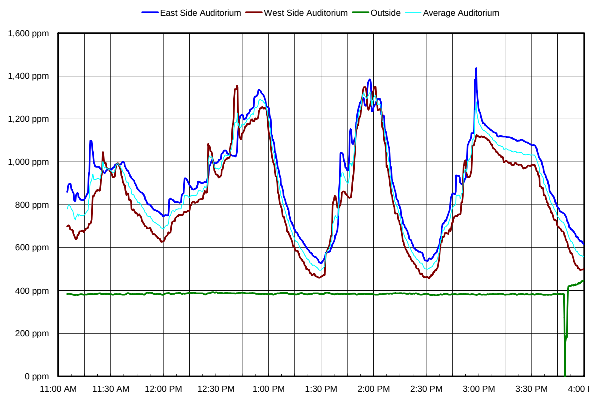

Figure 5: CO_2 Level during Experimentation

Weather conditions throughout the experiment were conducive both to natural ventilation and to simulation. The wind blew quite steadily from the east-north-east at an average speed of just under 1 m/s (2.24 mi/hr), never gusting to more than 1.6 m/s (2.27 mi/hr) and never dropping below 0.4 m/s (0.82 mi/hr). The wind direction was ideal for promoting cross-flow in the auditorium, whose long axis runs south to north. The low wind speed was ideal to look at air change rates and contaminant expulsion in the space under a near worst case scenario and the lack of gusting meant that there was a steady driving force for simulations instead of one that varied widely from one experiment to another.

CONTAM Model

CONTAM (Dols, 2002) is a bulk airflow modeling tool developed by the National Institute of Standards and Technology. A building is divided into isobaric pressure nodes called zones. Each zone has an associated floor area and volume and is connected to other zones or to the ambient by airflow paths. The volumetric flow through a given path is usually given by a power law equation of the form:

$$\dot{Q} = C(\Delta p)^n$$

in which Q is the volumetric flow rate, Δp is the pressure difference across the path, C is a discharge coefficient and n varies between 0.5 and 1.0 in theory. Larger openings have a smaller exponent value while crack-like openings have an exponent near 0.65. Rarely does one encounter higher exponents. The pressure difference is driven by buoyancy effects and by external wind pressure. The effect of wind pressure is set by a wind pressure profile; a dimensionless coefficient between -1 and 1 is defined for each wind direction that impacts a given opening. The wind pressure coefficient is both an effect of the building's surroundings and an effect of the building's own geometry. Wind pressure coefficients are ideally determined using strain gauges and a wind tunnel test but more practically, are determined using software such as CpGenerator (Heijmans, 2003) or CPCALC+ (Grosso, 1995). Wind pressure profiles for the SANC building were generated using CpGenerator.

The plan view of the CONTAM model is shown in Figure 6. The four zones at the left of the diagram represent the remainder of the building, two vestibules, and a projection room. The light gray zone with the stepped right hand end is the auditorium zone while the black zone superimposed over it is the clerestory ridge zone above the auditorium.

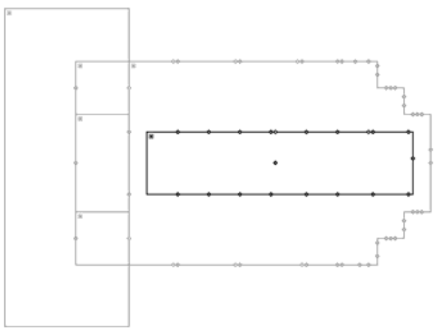

Figure 6: CONTAM Model in Plan View

A number of noteworthy simplifications were made in assembling the CONTAM auditorium model. Prime among these is that the remainder of the building was treated as a constant temperature zone with no links to ambient conditions. This is likely a poor assumption since the remainder of the building clearly has penetrations to the outside and may cause significant airflow either from or to the auditorium even though the doors separating the two remain closed. The remainder of the building was not modeled simply because it was occupied during the experiment and because insufficient data was available to be able to construct a meaningful model of the space.

Another simplification in the auditorium model concerns the architectural screen that hangs below the opening of the clerestory ridge zone. This device certainly affects air exchange between the two zones. The screen was characterized using a multiplier on the airflow through the path that linked the clerestory and auditorium pressure nodes (zones). It was not possible to directly measure how much the presence of the screen impeded air exchange between the auditorium and clerestory space so a parametric study was carried out to see the simulated effect, comparing each simulated result to the measured results. The following figure shows the idealized auditorium as it was modeled in CONTAM (note: bulk airflow modeling tools do not model the surfaces of a zone directly, only its area and volume. Thus the inclined ceiling is modeled as a flat roof.) The screen is modeled as an artificial flow restriction between the two zones when in fact it hangs approximately 1.5 feet below the bottom of the clerestory ridge zone.

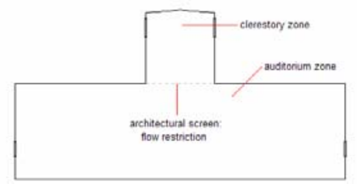

Figure 7: Idealized CONTAM Model Cross Section

The final simplification made in modeling the auditorium space was to neglect the effect of the rafter space above the auditorium ceiling and beneath the auditorium roof.

A primary set of airflow paths within the auditorium space was identified. They fell into the following categories.

• Frames around windows, and exterior doors.

• Operable windows in the auditorium and clerestory.

• Large openings between the auditorium and the vestibules.

• Closed interior doors between the vestibules and remainder of the building, between the auditorium and the projection room, and between the projection room and the remainder of the building.

• Floor / Wall and Ceiling / Wall joints for all walls in the auditorium and clerestory ridge zones.

• Large horizontal opening between the auditorium and the clerestory space.

In addition to the primary flow paths, a number of secondary flow paths were defined. The secondary airflow paths are distinguished from primary flow paths only in that they were expected to transfer significantly less air. They were considered after it became apparent that simulated air exchange rates were lower than measured rates.

• Electrical outlets.

• Leak factors for the walls and ceilings themselves.

• Floor / Wall joint to model the joint between a masonry knee wall and the frame wall above.

• Ceiling light penetrations.

• HVAC penetrations for the supply duct running along the top of the east and west facades in the auditorium.

• Wall / Wall corner joints at each wall junction in the auditorium and clerestory space.

Lastly, since the goal of the project was to come as close as possible to simulating the carbon dioxide expulsion from the auditorium under measured exterior wind conditions and known window opening sizes, the makeup of air in the zone was defined as a set of five contaminants: Argon, Oxygen, Nitrogen, Water Vapor, and Carbon Dioxide. Molecular weight, initial concentration, diffusion coefficient, mean particle diameter, effective density, and specific heat were entered for each defined contaminant so that its concentration over time could be traced by the simulation.

Discussion of Results

Initial Comparisons

Figures 8 through 11 show the simulated and measured CO_2 concentration in the auditorium zone during Experiments 1 through 4:

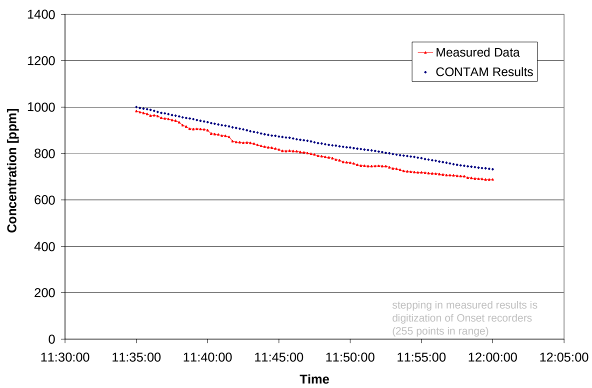

Figure 8: Single Leeward and Single Windward Windows Open. (Exp 1)

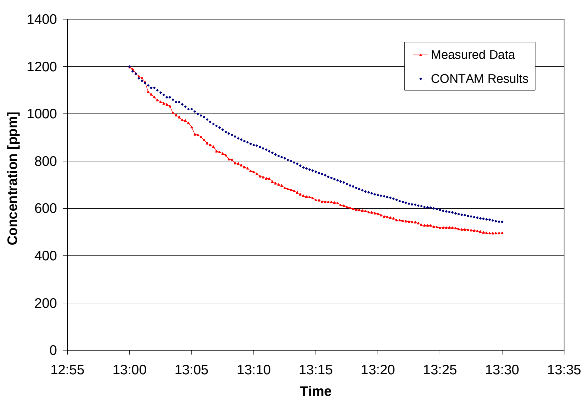

Figure 9: Three Leeward and Three Windward Open Windows (Exp 2)

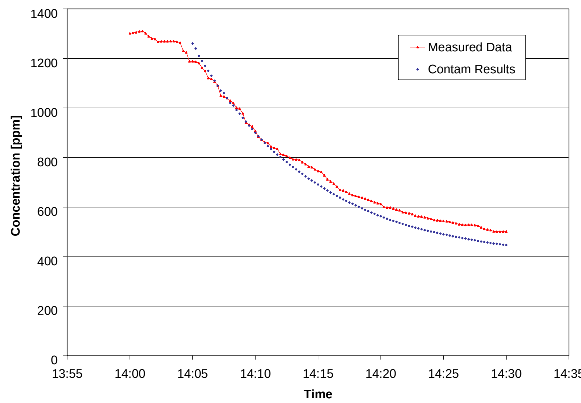

Figure 10: Three Leeward, Three Windward Auditorium Windows, Two Leeward Clerestory Windows Open. (Exp 3)

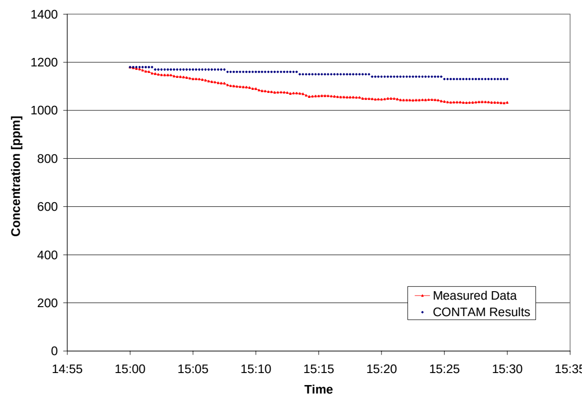

Figure 11: No Open Windows (Natural Decay). (Exp 4)

It is readily evident that experiments 1, 2, and 4 show markedly similar differences between simulation and measured result; in all cases, the simulated CO_2 decay rate was slower than measured. Experiment 3 differs from the others in that it is the only experiment in which the clerestory windows were open and thus was the only experiment in which the architectural screen played a role.

Interzonal Airflow Sensitivity

In the simulation that generated Figure 10, it was assumed that the architectural screen did not impede airflow between the auditorium space and the clerestory ridge. A series of simulations were next carried out assuming different levels of flow restriction between the two zones. Results of those simulations are shown in Figure 12.

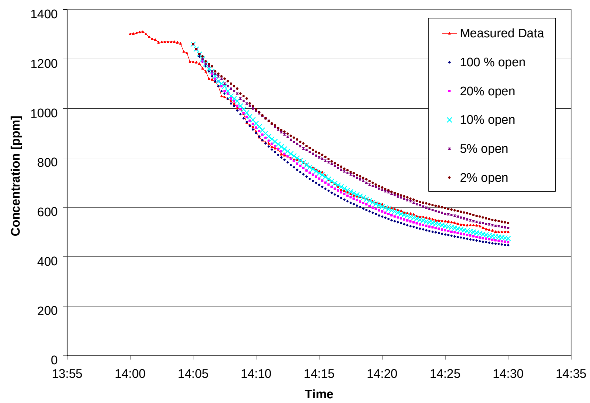

Figure 12: Variation of Auditorium / Clerestory Flow Restriction

It would be incorrect to claim that a particular value of flow restriction is most appropriate to model the architectural screen. Certainly significant restriction makes the simulated CO_2 decay rate look most like it does for other experiments. Significantly more rigorous experimentation would have been necessary in order to model the airflow between auditorium and clerestory with any confidence and it is recommended that such experimentation be carried out. Within the scope of the current experiments, it sufficed to verify that reducing the unimpeded airflow between the auditorium and clerestory by 98% in order to tune Experiment 3's simulation results would not adversely affect the results of other simulated experiments. Indeed resimulating Experiment 2 (pure cross flow with all six auditorium windows open) with and without flow restriction showed absolutely no difference in result as can be seen in Figure 13.

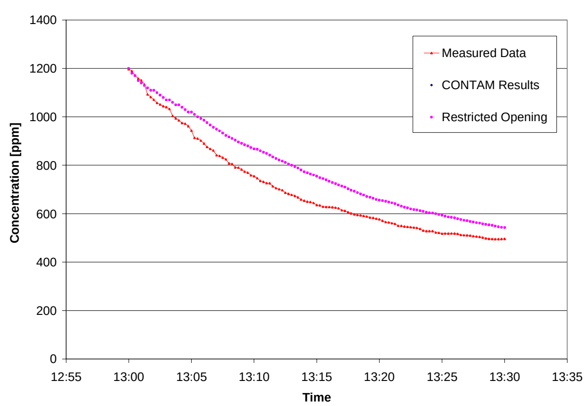

Figure 13: Verification of Flow Restriction Assumption in Experiment 2

It may also be worth noting that seeing no difference between simulation of a cross flow ventilation experiment with and without flow restriction between the auditorium and clerestory is an excellent indication that indeed there is very little air renewal within the upper region of the occupied auditorium space (above the cross flow path and below the ceiling). In other words, there may well be a stagnant air zone above the imaginary plane that connects the windows in the auditorium. Furthermore, the simulation suggests that opening the leeward clerestory windows is the only natural ventilation means by which to achieve draw fresh air up into the area above the plane of the lower windows.

Air Link Sensitivity

One of the greatest unknowns in assembling the CONTAM model came in knowing what constitutes an air link between zones or between a zone and ambient. Some are quite obvious: windows, doors, etc. while others, such as the leak factor of a wall itself, are not so readily apparent. Libraries of airflow path links from ASHRAE and other sources are included with CONTAM but there is something of an art to choosing which paths should be implemented in a given model. Lacking experience in choosing appropriate links, the first round of simulations included those links identified as the primary air link set identified in the previous section. Having then seen that the simulation predicted a slower CO_2 removal rate than was measured, a secondary list of airflow paths was identified and implemented. All simulations were then rerun; Figure 14 shows the results for resimulating Experiment 2.

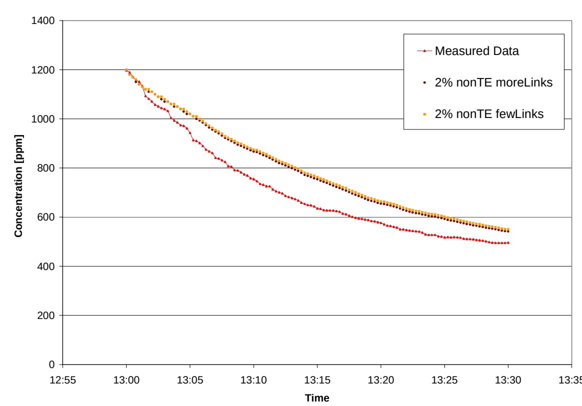

Figure 14: Sensitivity to Adding Secondary Flow Paths

Evidently adding secondary links had little effect on the simulated CO_2 removal rate from the auditorium. The result is not terribly surprising; airflow through any of secondary links would be negligible in comparison to airflow through the open windows. However, the same very slight improvement in simulated result was seen in the natural decay test (Experiment 4) in which there were no open windows. Certainly the secondary set of links was not sufficient to bring simulation and measurement together.

Additional Testing

While graphical results are not presented in the present paper, sensitivity tests were carried out to examine the applicability of a number of other assumptions made in creating the CONTAM model. Among those assumptions tested were whether simulation results improved if the temperature in the auditorium zone was assumed to be constant or to change with time, whether obstacles surrounding the building were of critical importance in generating wind pressure profiles for the auditorium façades, and whether the carbon dioxide could be considered a trace gas or whether its concentration was significant enough to affect air density. Of the assumptions tested, only accounting strictly for obstacles in generating wind pressure profiles had a significant effect.

Tuning the Model

Having failed to find a set of assumptions that corrected the simulation results, attention turned to adding fictitious devices to the natural decay test in order to force it to look like the experimental data. In so doing, it was assumed that there was some additional amount of leakage through the actual auditorium that was not being modeled correctly. The idea was that the natural decay simulation would be forced to look like the measured result and then that same change would be applied to the other simulations to see if their results improved. Figure 15 shows the natural decay test with a pair of fans, one flowing 0.05 kg/s into the east façade of the auditorium, the other extracting the same amount from the west façade. The value of 0.05 kg/s was chosen so as to obtain the same CO_2 concentration at the end of the simulation as was measured at the end of the experiment.

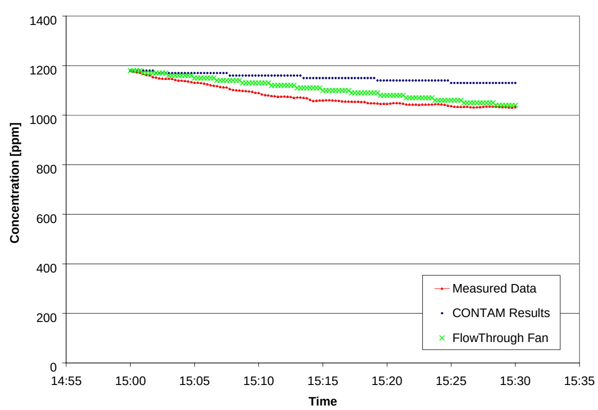

Figure 15: Natural Decay Test with Flow through Fan Tuning Factor

The same fans were then added to the simulation of Experiment 2; results are shown in Figure 16.

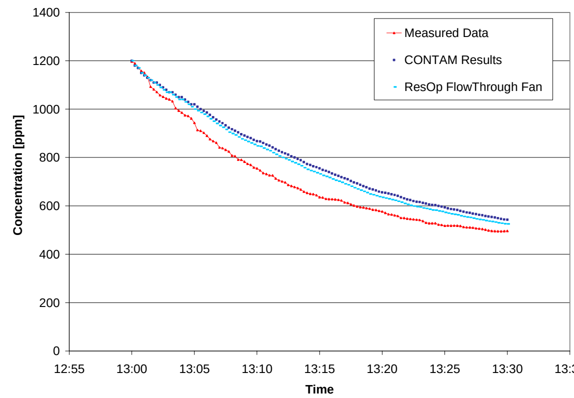

Figure 16: Experiment 2 with Flow-Through Fans

It is evident that increasing cross flow ventilation through the auditorium, although it helps, is insufficient to explain the differences between measured and simulated results. It is also interesting to note that while the end concentration in the natural decay test could be matched, the curvature of the experimental result could not. In the simulation of the natural decay test both with and without additional fans, the decay rate of CO_2 is extremely linear. It is assumed that if the simulation had been extended, the CO_2 decay rate would have leveled off at the ambient CO_2 concentration. It reality, the building would probably have leveled off at some CO_2 concentration above ambient due to CO_2 sources such as air exchange with the occupied portion of the building. Referring to Figure 5, the auditorium CO2 level was 500 ppm above ambient when measurement began at 11AM. Until 11 AM, the windows had been closed and the mechanical ventilation system had been in operation.

One of the assumptions implicit in the CONTAM model was that the CO_2 level measured 0.76 m (30 in.) off the ground at the mid point along the east and west façades of the auditorium ¼ and ¾ of the way across the room was representative of a constant CO_2 level seen throughout the zone; CONTAM assumes that contaminants are well mixed in each zone. It was strongly suspected that in fact the auditorium zone was not well mixed if for no other reason than that the two CO_2 meters displayed quite different readings, particularly while the room was being filled. At attempt was made to mix the zone air during the filling process as can be seen in Figure 5 between 12:00 and 13:00. Periodically, the reading of one or the other CO_2 meter spikes only to then come back closer to the average fill rate over the time period. Mixing in the zone was achieved by experimenters walking around the CO_2 canister and nozzle (in about a 5 m diameter circle) holding a jacket as a sail - if only we had thought to bring a fan with us. Presumably, if CO_2 measurements were taken at a high concentration point, then the measured decay rate would be faster than simulated since the high concentration would dissipate naturally as it mixed with the air nearby, particularly at the start of the simulation. If, on the other hand, measurements were taken at a low concentration point, then the measured decay rate would be slower than in the simulation since again, mixing would serve to keep the measured rate higher, longer. The above relies somewhat on the idea that air mixes naturally without being forced. During the experiments, however, some form of cross flow occurred whenever windows were open and the sensors were on that cross flow path. If the room was not well mixed and cross flow caused in essence a jet of air (above and below which, air movement was significantly less) then that too could explain the higher measured rate of CO_2 expulsion (Murakami, 1991). Without exception, the simulated CO_2 dispersal rate was lower than measured indicating according to the above, either that the actual CO_2 level in the zone was higher than was measured or that initial mixing was taking place or that cross flow ventilation caused an air jet in the middle of the space. In order to clarify the situation, a “fill test” simulation was performed in which all of the CONTAM open windows were closed and a source was defined as adding either 0.0001554 or 0.00031081 kg/s of CO_2 into the auditorium space. These values correspond to the lowest and highest maintainable rates of fill achieved during the experiment (0.283 m^3/hr (10 ft^3/hr) and 0.556 m3/hr (20 ft^3/hr)). The simulated results are plotted along with average measured results for the Auditorium fill between Experiments 2 and 3.

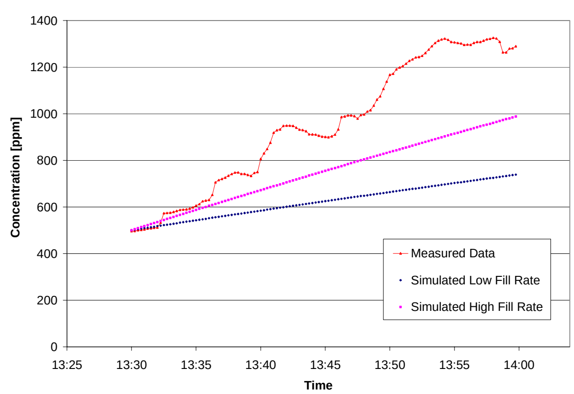

Figure 17: Fill Test

It seems quite clear from Figure 17 that the auditorium was not well mixed in terms of CO_2 concentration at the start of each experiment. According to CONTAM, the highest fill rate obtained without the CO_2 regulator beginning to freeze up would have resulted in a concentration level that was 60% of the value measured at the end of the half hour fill period. If that is true, then clearly, mixing is a factor, especially early in each of the experiments and perhaps the initial curvature of the decay plots is due more to air mixing than it is to ventilation of the space by outside air. Unfortunately, since CONTAM assumes that the zone is well mixed, it is hard to know how best one could simulate the effect of mixing. The latest version of CONTAM (2.4) offers the ability to define one dimensional diffusion axes within a zone, along which the concentration of a given contaminant (whether CO_2, water vapor or another) can vary. Unfortunately, that feature was not available at the time of the simulations carried out in this project.

The possibility of jetting (a high velocity air stream flowing across the sensors), seems slightly less likely given the fill test result. Jetting can certainly explain the higher CO_2 removal rates of Experiments 1 – 3. However, the same effect (comparatively slower simulated change in CO_2 level) was seen during the two cases in which the zone was entirely closed up (natural decay and fill tests.)

It is interesting to note that the fill test simulations, like the natural decay test simulations, are quite linear. It is hard to tell whether the measured fill test was linear or not given the short period over which values were measured. Presumably in both the simulation and in the measurement, the CO_2 concentration would level off since low CO_2 concentration air is always infiltrating the space from outside.

CONCLUSIONS

The preliminary work carried out at UEC and SANC arguably suggest that natural ventilation systems bear significant promise for providing adequate fresh air supply and that existing simulation tools are well capable of modeling their performance to within a reasonable degree of accuracy. Measurements at the UEC building show that interior space CO_2 levels are similar on naturally vented cool days when the mechanical heating has been turned off and on days when the air conditioning system is on. During mild weather, interior space CO_2 levels are lower than when the building was mechanically ventilated. Natural ventilation, when designed properly, has a proven potential to provide higher quality indoor air than does mechanical ventilation. Simulations on the SANC auditorium show promise that if indeed a zone is well mixed when it comes to CO_2 concentration, then currently available tools can be used to predict likely concentrations of contaminants under natural ventilation driving forces.

There is evidently more experimental work that should be done in support of both the UEC and SANC building natural ventilation systems. It would be advantageous to be sure that the measured zones are indeed well mixed and it would be advisable to have more than just two CO_2 level measurement points. It is equally important to investigate whether simulation results are acceptable under more adverse wind conditions (extremely low wind, gusty wind, wind from a more variable direction, etc.) and to carry out simulations and measurements on occupied zones during normal building use.

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