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Multizone Modeling Approaches to Contaminant-Based Design

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ABSTRACT

Indoor air quality is currently addressed in the design process primarily through prescriptive building codes based on specified flow rates. However, a contaminant-based design approach opens the door to design innovation, offering opportunities for improved indoor air quality, energy conservation, and reduced environmental impact. This paper discusses current design approaches and some possibilities for the future of contaminant-based design. Techniques and modeling approaches that could be used today are demonstrated using examples from a case study building. A multizone network airflow model is used to simulate airflow rates, pressure relationships, and contaminant transport to support the design. These simulations are utilized to specify minimum ventilation rates to control non-occupant-related contaminants for a system with carbon dioxide demand control. Contaminant buildup during an overnight shutdown is also studied, and strategies for a pre-occupancy purge are developed. The model is also used to size an exhaust fan to negatively pressurize an enclosure housing a biological process. The design is then re-evaluated based on experimental measurements of envelope airtightness and contaminant emissions that were conducted in the building. The case study identifies the critical, or "design," conditions that must be addressed, discusses strategies that could be used to meet them with contaminant-based design, and considers the role that available measurements can take.

INTRODUCTION

Indoor air quality is currently addressed in the design process primarily through prescriptive building codes that specify minimum outdoor air ventilation requirements and ventilation standards on which these codes are based (ASHRAE 2001). These ventilation requirements are intended to control indoor air contaminants to minimize health impacts on building occupants as well as to provide for comfortable conditions in terms of odor levels. While ventilation rates based on these requirements are generally successful in achieving these goals, there may be circumstances in which these rates are insufficient to control the contaminant sources in a given building or in which the rates are higher than needed to achieve acceptable indoor air quality. In addition, these prescriptive design approaches do not allow one to take credit for filtration and air cleaning or efforts to reduce indoor source strengths or other innovative technologies for improving indoor air quality. The use of prescriptive ventilation rates also does not account for poor outdoor air quality.

As an alternative to the prescriptive approach, design ventilation rates can be determined based on target contaminant levels, contaminant source strengths, and the capabilities of contaminant control technologies. Such "contaminant-based" design methods would be analogous to thermal control where the designer attempts to control temperature and humidity using target levels based on thermal comfort objectives, heat and moisture generation rates, and the performance of space conditioning equipment. Contaminant-based design methods would allow designers to incorporate new technologies for indoor air quality control and presumably ensure better indoor environments in the process. These design methods will require data on contaminant source strengths and the establishment of target concentration levels, and the availability of both will not occur until some point in the future. Nonetheless, limited application of contaminant-based design is possible now, for example, to control carbon monoxide in parking garages, and the development of the design methods

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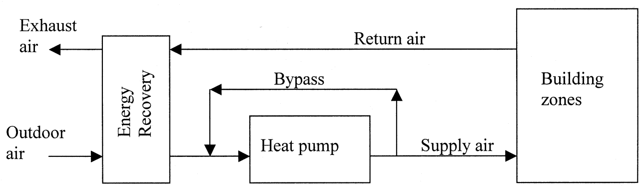

Figure 1 *Schematic of air-handling system serving the main building.*

can and should proceed before all the required data are available.

Contaminant-based design methods are likely to take several different forms. Single-zone calculation methods have already been developed (Walton and Persily 2002), but some design applications will require the use of multizone airflow and contaminant dispersal modeling. Analysis methods with various capabilities have been developed already (Dols et al. 2000; Feustel and Smith 1997; Sparks et al. 1989) that enable one to calculate contaminant concentrations based on ventilation rates, contaminant source strengths, and, in some cases, filter efficiencies. The contaminant-based design methods being discussed would reverse this process, enabling one to calculate ventilation rates, filter efficiencies, and other design parameters based on target concentrations and source strengths. This paper presents several examples of the application of multizone modeling, specifically the CONTAMW model (Dols et al. 2000), to a case study building to illustrate how contaminant-based design could be implemented. As part of this effort, the program was used to specify and modify control strategies for carbon dioxide demand control and to size a depressurization fan to isolate odors from a wastewater treatment facility in the building.

CASE STUDY BUILDING DESCRIPTION

A two-story classroom/office building located on a college campus in Ohio was used for the case study. This building was intended to demonstrate innovative technologies and design techniques for reducing the environmental impacts of buildings. Some of its unique features include operable windows for natural ventilation, CO_2 demand-controlled ventilation, HVAC system heat recovery, and low-emitting building materials.

A primary air-handling system supplies ventilation air to the main building. A second system can be switched between an auditorium and a large, glass atrium that is occasionally used for public functions. Each of these systems is designed to provide pre-conditioned outdoor air in quantities modulated based on measured carbon dioxide concentration. Thermal control in individual rooms is accomplished using localized heat pumps, so that ventilation is decoupled from thermal conditioning and recirculation is not needed. However, return air is routed back through the mechanical room for energy recovery before it is exhausted.

Figure 1 shows a schematic drawing of the air-handling system that serves the main building. Because the ground-source heat pump that preconditions the supply air requires constant flow, a bypass is installed to allow the supply flow rate to vary.

Another design feature of this building is an onsite biologically engineered wastewater treatment facility. These biological processes are housed in an attached, semi-conditioned glass enclosure. Because of the possibility for odors, the design also includes an exhaust fan to maintain this space at negative pressure with respect to the adjacent building atrium.

DEVELOPMENT OF THE BUILDING MODEL

In CONTAMW, buildings are represented as networks of connected zones (e.g., rooms) that are modeled as having uniform contaminant concentrations. Zones are connected to one another and the outdoors via paths that represent building component leakage. The air-handling system fans and ductwork are also specified in the model. A mass balance calculation determines the flow between zones and concentrations of contaminants distributed by this flow.

One of the most difficult aspects of defining such a model during the design phase is estimating building leakage. This was addressed using a hybrid approach in which easily identified leakage paths were specified directly, with a distributed leakage component added to produce an expected mean overall exterior envelope leakage. The leakage of components such as doors and windows that were easily visible from the building plans were estimated using published data (ASHRAE 1997; Persily and Ivy 2001). The distributed leakage was then chosen to produce a conservatively "tight" building based on previously published studies.

A recent review summarized pressurization test results from 79 office and school buildings in the U.S., Canada, and U.K., reporting mean overall exterior envelope leakage ranging from 0.7 to 2.4 cm^2 per m^2 of wall area in office buildings and from 0.6 to 1.9 cm^2/m^2 in schools (all leakage areas given for a 10 Pa pressure difference and discharge coefficient of 0.6) (Persily 1999). Based on this information, a distributed leakage area of 0.75 cm^2/m^2 was specified for the exterior walls. Coupled with the leakage specified at doors, windows, and other known sites, this produced an overall mean exterior leakage area of 1.1 cm^2/m^2 in a simulated fan pressurization test. Interior partitions, ceilings, and floors were modeled with twice the leakage of the exterior walls. By developing a model that was at the lower end of the "average" range for schools and office buildings, we felt that infiltration would be realistically but conservatively predicted. Direct specification of the obvious leakage paths was intended to fine-tune the model as much as possible to the actual distribution of leakage on the building envelope. Figure 2 shows inputs for a portion of the model in graphic form.

Once developed, a few simple tests were applied to determine whether the model was realistic. As mentioned previously, a simulated fan pressurization test was conducted to

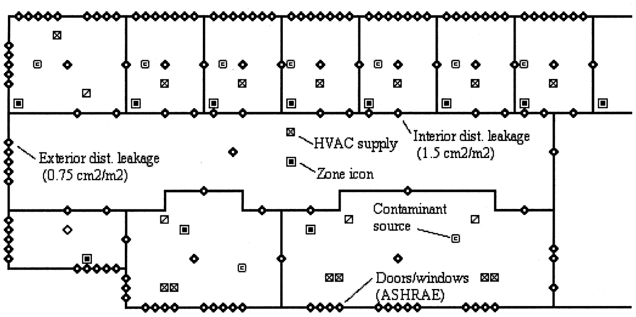

Figure 2 *CONTAM model of representative floor and modeling assumptions.*

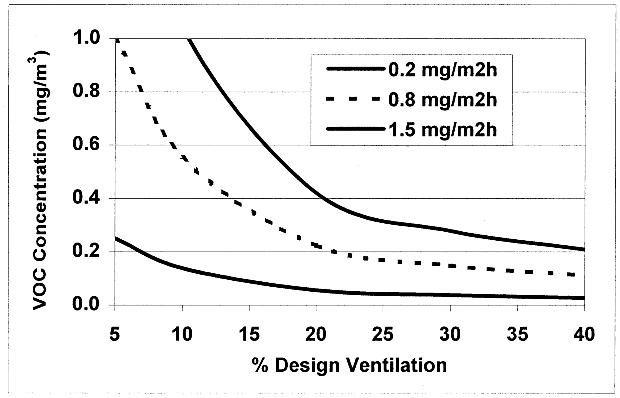

Figure 3 *Design calculation—minimum ventilation setpoint.*

verify that the mean exterior envelope leakage area was 1.1 cm^2/m^2. Additional pressurization tests to isolate door and window leakage showed that these account for roughly 35% of the total building leakage. This fraction has been reported to be about 15% in residences and between10% and 20% in commercial buildings (Persily and Grot 1986; ASHRAE 1997). Although by these standards this percentage seemed somewhat high, it was not adjusted downward due to the unusually large number of operable windows.

DESIGN FOR DEMAND-CONTROLLED VENTILATION

The building ventilation system can deliver 100% outdoor air in quantities that satisfy ASHRAE Standard 62-2001 for the design occupancy (ASHRAE 2001). A carbon dioxide demand-controlled ventilation strategy is installed in most intermittently occupied zones to adjust the ventilation rate based upon actual occupancy. An official interpretation of Standard 62 requires that designers consider the possibility for buildup of non-occupant-generated contaminants, particularly during unoccupied hours. The model was used to investigate the impact of this requirement on the design and control of a representative classroom.

The classroom design occupancy is 25, and 200 L/s of outdoor air is needed to satisfy the 8 L/s per person requirement of Standard 62. The model was used to set minimum supply air volumes to control estimated building-related contaminant sources and specify appropriate time periods for purging after a night setback. Transient analysis can also be performed with varying operating schedules and weather conditions to demonstrate the off-design performance with respect to building and occupant-related contaminants.

Indoor air contaminants from building materials, furnishings, processes, and the outdoors may not be well controlled by a CO_2 demand-controlled ventilation system since they may not coincide with occupancy. The outdoor air was not of specific concern, and the wastewater treatment facility described earlier was the only unusual process present. Therefore, the primary group of non-occupant-generated contaminants of concern was volatile organic compounds (VOCs) from building materials, furnishings, and activities.

VOC source strengths in buildings have been estimated from ventilation rates and measured contaminant concentrations. Average source strengths have been measured between 0.2 and 1.5 mg/m^2h (Levin 1987). One option for the designer is to consider this range of source strengths as well as the materials, occupants, and owner in analyzing the building. Modeling steady-state conditions over a range of likely source strengths provides a range of ventilation rates likely to maintain acceptable contaminant levels. This much-simplified approach ignores both the time-dependent nature of the contaminant sources and adsorption/desorption effects, but it allows the designer to estimate a minimum ventilation rate.

Steady-state simulations were performed with the classroom receiving between 5% and 40% of its design ventilation rate with no additional wind or stack-driven infiltration. Since the system supplies 100% outside air at all times, this means that the outdoor air supply was reduced to between 5% and 40% of that required for the maximum number of occupants. This range was chosen as representative of what a designer might specify and because it ultimately produced results within the desired range. Three levels of VOC emission were considered: low (0.2 mg/m^2), average (0.8 mg/m^2), and high (1.5 mg/m^2). Since the architect made an effort to choose building materials with low VOC emissions, actual source strengths in the building were expected to fall between 0.2 and 0.8 mg/m^2. The higher emission level was modeled to demonstrate the impact of design and operation for low VOC emission on minimum ventilation rates. Computed VOC concentrations are shown in Figure 3 for outdoor levels assumed zero.

The designer could use Figure 3 to select minimum settings for the demand-controlled ventilation system to limit VOC levels during periods of low occupancy. While specific guidelines have not yet been developed, we know that average VOC concentrations of 1 mg/m^3 have been measured in residences, while concentrations in commercial buildings tend to be lower (Brown, Sim et al. 1994). For example, if a designer

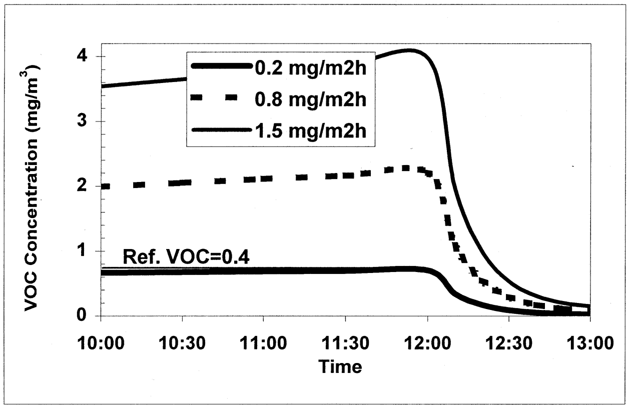

Figure 4 *Design calculation—specification of purge time.*

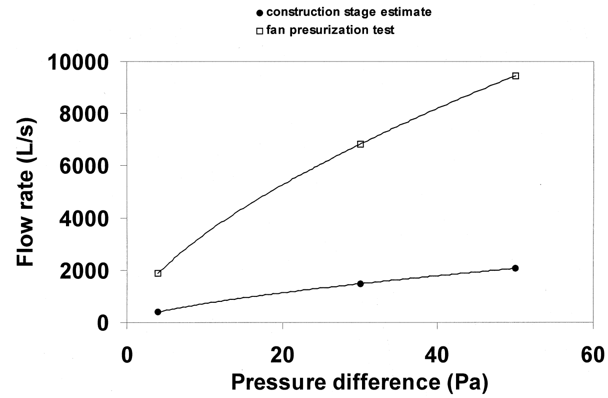

Figure 5 *Measured and predicted fan pressurization test results.*

chose to limit VOC concentration to 0.4 mg/m^3 above the outdoor level, Figure 3 specifies minimum setpoints of 20%, 13%, and less than 5% of the design ventilation rate for source strengths of 1.5 mg/m^2h, 0.8 mg/m^2h, and 0.2 mg/m^2h, respectively.

Over longer unoccupied periods, such as nights and weekends, the ventilation systems in many buildings are shut down completely. The model can then be used to specify a strategy for purging the building of contaminants following such a shutdown. If the ventilation system were shut down for a twelve-hour period each night, the classroom might experience a buildup of VOC, particularly if weather conditions were mild and infiltration limited. A "worst case" scenario would occur if the classroom ended the day with a VOC concentration of 0.4 mg/m^3 and very little infiltration occurred over the following twelve hours.

Average annual weather data for a nearby weather station were used to determine the infiltration design weather condition. Indoor-outdoor temperature difference and wind speeds were averaged for each twelve-hour overnight period and sorted from lowest to highest. The "infiltration design day" was chosen as the lowest fifth percentile temperature difference and wind speed, applied from the prevailing wind direction. In this case, a 2.4°C indoor-outdoor air temperature difference and a 2.5 m/s wind speed were applied. This produced a very low air change rate of 0.02 air changes per hour.

The model was then used to simulate the VOC concentrations, with the classroom having an initial condition of 0.4 mg/m^3, and allowed to build up overnight with no mechanical ventilation and the infiltration conditions noted above. After twelve hours, the ventilation system was activated at 100% of its design ventilation rate. The resulting contaminant profile, shown in Figure 4, can be used to specify the time necessary for this purge process. The time scale in this figure begins at the start of shutdown, with the mechanical system coming back on in the hour twelve. If the designer would again like to limit the VOC concentration to 0.4 mg/m^3, purge times of 35 min, 25 min, and less than 10 min are required for source strengths of 1.5 mg/m^2h, 0.8 mg/m^2h, and 0.2 mg/m^2h, respectively.

POST-CONSTRUCTION ANALYSIS OF VOC LEVELS

Some of the most difficult quantities to estimate in the preceding sections were the building leakage, the resulting infiltration design condition, and VOC emission rates. After construction is complete, it is possible to conduct measurements to verify or fine-tune these assumptions. This process allows the performance of the system to be verified and may present an opportunity for further energy savings if the design is conservative. In this case, the building was the subject of an extensive 14-month monitoring project that included fan pressurization testing and automated tracer gas decay measurements. Several week-long VOC monitoring studies were also conducted during this time period. This section compares the measured conditions to the design assumptions and describes how these results might be used to fine-tune system operation.

The fan pressurization tests indicated that the exterior envelope of the building was roughly four times leakier than was originally assumed. Figure 5 compares the measured leakage with that which was originally estimated. Based on this result, the leakage of the exterior envelope was increased to 4.3 cm^2/m^2 to match its measured value. This increase was accomplished by proportionally increasing all specified leakage paths. Under the previously predicted "design" infiltration condition, this model predicts an air change rate of 0.09 air changes per hour.

Tracer gas decay tests were also performed to obtain building air change rates under realistic operating conditions. For these tests, sulfur hexafluoride (SF_6) tracer gas was injected at the air-handling unit fan and distributed throughout the building. Concentrations were then monitored in several rooms over two-hour periods, and a building average air change rate was calculated. Because an injection was only made when the fan was operating, many more data are available for periods in which the air-handling unit was on. However, 301 data points were collected for periods in which the fan was turned off after the injection and the tracer gas

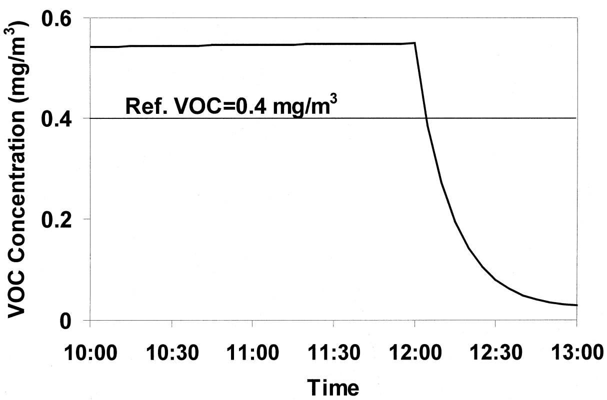

Figure 6 *Overnight concentration and purge process.*

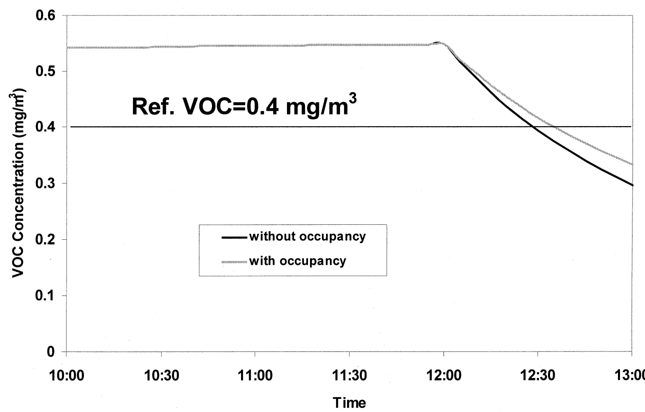

Figure 7 *Overnight and morning concentrations with no purging.*

decay took place under infiltration conditions. During mild weather, six hours sometimes elapsed before the tracer gas concentrations had decayed and three two-hour periods would be analyzed. Therefore, mild weather conditions tended to be over-represented by the data.

The lowest measured infiltration rate was 0.09 h^{-1}, and the lowest five percent included rates of 0.14 h^{-1} and less. These compare favorably with the 0.09 h^{-1} air change rate predicted under the infiltration "design" condition for the CONTAM model with the measured exterior leakage value. By comparison, the significantly tighter building envelope that was originally assumed produced a much lower infiltration rate and a very conservative design scenario for predicting contaminant concentrations during an overnight shutdown.

VOC measurements were also conducted in the building for several weeklong periods. This information can be used to reassess the assumed VOC emission rates. Predicting emission rates from measured data can be very difficult, particularly when the data are not collected under "steady-state" conditions (Persily 1996). Transient mass balance analysis methods, to be described in a future publication, were used to estimate baseline emission rates associated with the building and episodic sources associated with occupancy. This analysis estimated emission rates associated with "building" sources between 0.3 and 0.4 mg/m^2h for a similarly furnished and finished room in the building. In addition, episodic sources from the occupants ranged from 0.2 and 1.2 mg/m^2h.

The 0.3 to 0.4 mg/m^2h measured as the building-related emission rate falls between the "low" (0.2 mg/m^2h) and "medium" (0.8 mg/m^2h) emission rates that were modeled in the design phase. This verifies the low-emitting nature of the building design, and a baseline ventilation rate between 10% and 15% of design might be selected based on Figure 3. Because Figure 3 was generated from a model with only mechanical ventilation, it is not significantly affected by the change in building leakage. Figure 4, however, does depend on infiltration to predict contaminant buildup during an overnight shutdown, so a new simulation must be performed to account for both the measured emission rate and the measured building leakage.

This simulation, the results of which are shown in Figure 6, shows that the increased infiltration caused by the leakier building envelope and the low baseline emission rates of the constructed building lead to lower VOC concentrations during shutdown than were predicted during the design phase. Using the same "infiltration design" weather condition, the VOC concentration during the night shutdown remains less than 0.6 mg/m^3. Purging with the design flow rate brings this concentration down to a reference level of 0.4 mg/m^3 in less than five minutes. Therefore, a designer might conclude that a purge is not needed for this application or that a much lower flow rate could be used. Since it is likely that the ventilation system would begin to operate before most occupants entered the building, the minimum "baseline" ventilation rate may be enough.

This question can be investigated by adjusting the purge ventilation rate in the CONTAM model to 15% of design. This was done with just the "building related" emission rate of 0.4 mg/m^3 and also with a low occupant-related emission component of 0.2 mg/m^2h, beginning at the same time that the ventilation system is activated. Figure 7 shows the results of these simulations, again with the time scale showing the results of a twelve-hour shutdown in which the mechanical system is activated at hour twelve. If no occupant-related VOC is present when the ventilation system is activated, the VOC concentration will reach 0.4 mg/m^3 in 30 minutes. If a low occupant-related component of 0.2 mg/m^2h is present, this level will be reached in 35 minutes.

SIZING A DEPRESSURIZATION FAN

Exhaust fans can be used to isolate pollutant sources, such as the attached biologically engineered wastewater treatment facility, from the remainder of the building. This facility was not expected to produce indoor air pollutants or odors at levels that might be harmful or irritating to building occupants. However, due to its nature and the possibility that odors might

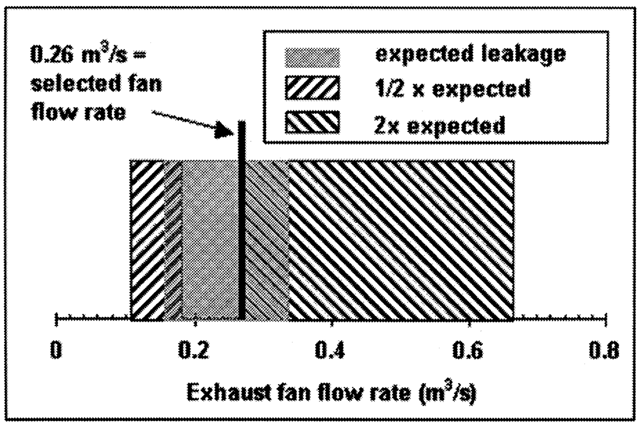

Figure 8 *Required exhaust fan flow rates.*

be generated in the case of malfunction, the capability to maintain a negative pressure relative to adjacent building spaces was desired.

The fan sizing technique for this type of application using a multizone model is similar to that which is used to size stairwell pressurization fans for smoke control (Milke 2000). However, very different sets of constraints govern the selection of target pressure differences and fan sizing.

The pressure difference generated by stairwell pressurization fans must be high enough to prevent smoke from entering the stairwell but not so high that it interferes with door operation. Doors opening against the pressure can become more difficult to open, since the opening force must overcome both the door closer and the pressure force. Conversely, doors opening outward from a pressurized space can be pushed open if the pressure force becomes larger than the door closer force. Door opening forces are determined from door properties and forces that can be applied by most occupants (Klote and Milke 1992). Because these fans are used only in the event of a fire, designers can conservatively size them for a leaky building envelope and make use of dampers for pressure relief if needed.

In this case, the depressurization must be sufficient to achieve odor control and low enough that door opening is not affected. Since the system will operate most of the time, the designer must also consider any effects on pressure relationships or supply/return balance in the remainder of the building. Specific guidance for appropriate pressure differences was not available for this application, so a minimum recommendation of 12 Pa for smoke isolation in sprinklered applications (Klote and Milke 1992) was used in the design calculation. The doors to this space open inward, so one upper limit is established to prevent pressure forces from pulling them open. For a 90 N door closer force, this produces a maximum depressurization of 85 Pa. The multizone model was then used to select an exhaust fan to maintain depressurization between 12.4 Pa and 85 Pa.

Actual operating pressure differences in the constructed building vary depending on weather, operation of the HVAC system and local exhaust fans, and operation of doors and windows. The building leakage characteristics are also uncertain. Therefore, a constant speed exhaust fan must provide acceptable depressurization for a variety of operating situations over a range of exterior leakages. Eight operating conditions were investigated: demand-controlled ventilation fan operation (minimum and maximum settings), operation of restroom and other local exhaust fans (all on and all off), and outdoor temperature (38°C and –23°C). These conditions were modeled for the expected building leakage, half that amount of leakage, and twice that amount of leakage.

The range of acceptable exhaust fan flow rates for the eight operating conditions and three leakage scenarios are shown in Figure 8. For the expected building leakage distribution, fan flows of at least 0.15 m^3/s and at most 0.33 m^3/s satisfy the above pressure criteria. For half the expected leakage, flows between 0.10 and 0.16 m^3/s would be appropriate, and flows between 0.26 and 0.67 m^3/s would be needed for twice the expected leakage. Since the three areas in Figure 8 do not overlap, one fan flow rate cannot satisfy all three leakage scenarios. Therefore, a designer might choose a fan flow rate of 0.26 m^3/s, which would be appropriate for up to twice the anticipated leakage. Using CONTAM to calculate the pressure rise, an appropriate fan could be selected. If the constructed building turned out to have less envelope leakage than expected, the fan speed could be adjusted.

Unfortunately, it was not possible to conduct an isolated pressurization test on this part of the building. We do know from the whole-building tests that the mean exterior leakage was four times higher than was originally assumed, and this underscores the need to be conservative in design so that fans are not undersized. However, the fan that was originally installed was several times larger than was needed for this analysis, and it was large enough to blow the doors open. This problem was solved by installing variable-speed capability and controlling the fan to maintain 12 Pa negative pressure with respect the neighboring atrium. However, after several months of operation, concerns arose regarding the supply/return balance of the building's main air-handling systems. Because the exhaust for this space lowered the overall system return volume, the heat recovery at the main air-handling unit was less than expected. This development underscores the importance, in this application, of not oversizing the fan. Since variable-speed capability was available, the fan was simply adjusted to maintain a lower pressure difference.

Another possible alternative to this approach would have been to select the fan after the building envelope construction was complete. Then a pressurization test could have been conducted and a fan selected to maintain a target pressure difference under the expected range of operating conditions. With the building leakage no longer unknown, the model predictions would cover a much smaller range of conditions and a single fan flow rate could be specified.

DISCUSSION

The case study building has been used to illustrate indoor air quality design calculations that utilize a multizone network airflow model to develop a procedure analogous to that which is commonly used to design systems for thermal conditioning. The system is sized to deliver ventilation air for the maximum number of occupants, and CO_2 demand control adjusts this volume based on the actual occupancy. The multizone model is used to calculate minimum ventilation rates to limit VOC concentration during periods of low occupancy and no infiltration. Transient simulations of an overnight period with very low infiltration (an infiltration "design day" condition) demonstrate a method that is used to specify a pre-occupancy purge strategy for a case in which sorption effects are known to be unimportant.

This example illustrates the use of an available design tool and associated methods that could be applied to indoor air quality design. However, there are a few needs in terms of supporting data. A fairly comprehensive set of building leakage data are available for residential buildings, but the leakage of commercial building components has not yet been summarized in as convenient a form. It is also often useful to perform calculations for a range of leakages, since as this example illustrates, there can be significant variation between individual buildings. Features that make the assembly and adjustment of these models as fast and easy as possible would be very helpful to the designer.

Perhaps most important is the need for more research and guidance to assist designers in estimating sources and setting limits for pollutants such as VOCs in contaminant-based design. Contaminant sink effects and variable source quantities, while not included in this analysis, can have a significant impact in real buildings. The multizone model has the capability to model these in more detail if the behavior of pollutants and materials is well understood in the design phase.

The case study results show differences in both the minimum ventilation quantity and purge times required to control VOC levels for the different source strengths modeled. This highlights the need for the designer to be able to estimate source strength as realistically as possible, as well as the benefit of designing and operating buildings with low-emitting materials and processes. For the system modeled in the case study, these differences apply to operational techniques rather than system size. Therefore, these techniques may also offer an opportunity to reduce costs and improve operating conditions in buildings where source strengths can be verified.

The design method undertaken in this particular case study provides the means to size ventilation system components and specify operational strategies for critical "design-day" conditions to develop a preliminary design proposal. To further refine the design, annual simulations could be completed using the multizone model to estimate and minimize peak and annual energy demands and to assess operation under predicted occupancy profiles.

The generic VOC considered in this example is just one of several contaminants that would have to be considered with use of the indoor air quality procedure of ASHRAE Standard 62. This procedure could be adapted to many indoor contaminants that would be generated entirely or in part by the building or its occupants. Other contaminants, such as particulates, which may have an outdoor source, would require additional procedures. The necessary simulations could be performed with a multizone modeling tool, but the critical conditions and necessary control strategies would differ.

CONCLUSIONS

The procedure undertaken in this work involves some approaches to design and some new types of "design conditions." The design for demand-controlled ventilation perhaps focuses more on control strategies than equipment. In addition, the critical conditions under which these systems must perform are often not the same "design conditions" for which thermal conditioning equipment is sized. Minimum ventilation rates come into effect when the thermal or occupancy-based load is very low, and pre-occupancy purges are most needed when weather conditions are very mild and little infiltration occurs.

There are also opportunities to tune this design approach to the as-built behavior of a particular building. As was demonstrated by this case study, if actual measured background contaminant levels are low, the control strategy can be adjusted to provide lower background ventilation rates. Likewise, a pre-occupancy purge strategy can be adjusted based on the measured airtightness of the building envelope and background contaminant emissions rates if they are available. Both of these strategies make it possible for buildings to reduce ventilation-related operating costs in response to low-emitting design and construction practices.

Analysis of pollutant levels in the absence of mechanical system operation and the sizing of fans to maintain fixed pressure differences relies heavily on knowledge of the building leakage. Because this is difficult to predict in advance and can vary significantly between buildings, a conservative approach is the only viable option for buildings in the design phase. When infiltration during system shutdown is being considered, the conservative approach means a tight exterior envelope. In other cases, such as the sizing of depressurization fans, neither over- nor undersizing the fan is desirable, and it may not be possible to satisfy the entire range of possibilities with a single fan size. This can be addressed either by post-construction testing of the building envelope or by planning for some other means of adjusting fan speed.

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