ZONAL APPROACH TO MODELING THERMALLY STRATIFIED ATRIA

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ABSTRACT

Thermally stratified atria and similar spaces present challenges for building thermal-comfort and energy modeling. This work tests a zonal modeling method for dynamic thermal and energy simulation of a heavily glazed and thermally stratified atrium cooled by displacement ventilation. The goal of the study was to explore the extent to which this method offers any improvement over simpler methods with respect to assessing thermal comfort and energy consumption.

This paper describes a thermal and bulk-airflow zonal modeling strategy that appears to capture the some of the principal effects of thermal plumes generated when glazed façades and other interior surfaces are heated by solar radiation. This approach may be applicable to a relatively broad range of projects with similar characteristics. A CFD tool running the same model of the space, but without the zonal subdivisions, was used to tune the dynamic thermal/bulk-airflow model and to assess the degree to which the latter provides consistently appropriate results with variation in solar gain.

The zonal approach appears to have some advantage with respect to predicting thermal comfort as a function of heat removed from the interior of glazed façades; however, a comparison with a simpler method that does not use bulk-airflow modeling suggests that this simpler method may provide much of the same benefit with respect to assessing energy consumption.

INTRODUCTION

Heavily glazed atria and similar spaces are increasingly common features of modern architecture. In cases for which only a fraction of the atrium is occupied, conditioning the entire volume of such spaces as a well-mixed zone can be an energy intensive approach to maintaining thermal comfort. This is a potentially significant consideration with respect to space cooling, particularly when only a small fraction of volume at the bottom of the space is occupied, as conditioning the remaining volume above may require a relatively large input of cooling and/or fan energy while providing limited benefit with respect to thermal comfort.

There is ample evidence, including results from this study, to suggest that displacement ventilation systems designed to allow thermal stratification and focus cooling in the occupied zone at the base of such spaces have potential for significant energy savings. For many projects, however, adopting this strategy for space conditioning will hinge upon the ability to reasonably predict relative energy savings while maintaining a desired level of thermal comfort.

Computational fluid dynamics (CFD) offers suitably accurate modeling of such spaces, particularly with respect to thermal comfort, but for practical reasons is limited to modeling a set of conditions representing a particular moment in time. Dynamic simulation, on the other hand, is limited to fully mixed zones with the option of using bulk-airflow modeling to represent pressure-driven inter-zonal air movement through defined openings, and cannot actually model localized thermal plumes and similar air movement in thermally non-homogeneous spaces.

With this study, therefore, we sought to explore the feasibility, consistency, and practicality of one possible approach or methodology for modeling a thermally stratified atrium conditioned by displacement ventilation. The aim of this study was not to drill deep into the accuracy of this approach, as it can only approximate the dynamic effects of thermal plumes over time, but to assess the general potential and possible usefulness of the approach as a tool to be used in practice.

MODELING METHODS

Hypothesis and Tools to Test It

The central hypothesis to be tested was that using an expanded set of distinct zones or subdivisions to model large, contiguous, thermally stratified spaces might yield more accurate energy simulation results, and therefore provide a potentially more useful analytical tool for design. Because they tend toward thermal stratification, energy savings may be most significant for tall, heavily gazed spaces located in hot climates and having excessive solar gain. Thus we examined and compared modeling methods for a tall, mostly glass atrium or “winter garden” in a hot climate.

Fundamental to testing this hypothesis is the ability to model airflow between zones not separated by physical partitions. Some high-fidelity simulation programs include or can be coupled with bulk airflow models with this capability. The IES Virtual Environment thermal simulation program includes a bulk airflow modeling module called MacroFlo that can be used to model airflow through building openings, either internal or external. These are most typically openings in vertical surfaces with sizes small relative to the surface on which they reside—*i.e.,* windows, doors, etc., but can also be vertical or horizontal interfaces between volumes without physical partitions.

The MacroFlo module calculates pressure associated with wind, mechanical system airflow, or temperature differences to determine airflow between two volumes where a pressure difference exists. Buoyancy effects are thus accounted for in the pressure force determination. This is broadly similar to other bulk-airflow modeling tools, such as CONTAM (Walton, 1997) and COMIS (Pelletret and Keilholz 1997), which are employed in related studies of zonal modeling (Axley 2001, Mora et al. 2003, Wurtz et al. 1999). Because it runs in conjunction with detailed models of building envelope and HVAC systems—interacting with these at each simulation time step—MacroFlo was particularly well suited to this study.

The IES Virtual Environment simulation program also includes a basic CFD module called MicroFlo that was used for the tuning and validation of the thermal, bulk-airflow, and HVAC energy model. Because this CFD tool can use geometry, surface temperatures, and other data from a selected simulation timestep in the dynamic thermal, airflow, and energy simulation, it facilitates an iterative "ping-pong" process, using CFD to repeatedly inform and test validity for iterative experimental simulation runs.

Acknowledging that, in practice, energy modelers may not have access to a CFD tool or sufficient project resources for iterative tuning and validation of zonal bulk-airflow models, this study seeks to advance an understanding of how zonal modeling methods compare to simpler methods that may have broader practical applications.

Methods for Modeling Thermal Stratification

There are at least three common methods for modeling thermally stratified spaces:

1) A model with two air nodes—one for the occupied zone and one for the stratified zone—or an equivalent pair of stacked zones wherein airflow from the HVAC system can be supplied to the occupied zone and extracted from the stratified zone. In this method the two zones are each fully mixed and the volume of air forced to flow between the two is determined by the HVAC supply flow rate.
2) Bulk-airflow network models that expand upon the first method to include infiltration, exfiltration, operable windows or vents, air movement between rooms, and/or air movement between the occupied and stratified zones.
3) Zonal models that further subdivide the thermally stratified space to determine some aspects of air movement in keeping with pressure differentials.
4) Computational fluid dynamics (CFD).

The first three of these provide no means of actually modeling thermal plumes and other local airflow effects; however, the third (zonal) method is an attempt to partly overcome this limitation.

The first two of these methods treat each space as an instantaneously and fully mixed volume. Mora et al. (2003) state that the "assumption that the building can be defined as a set of well-mixed volumes or zones of homogeneous composition…can be acceptable for small rooms or zones, [but] becomes unacceptable when modeling large indoor spaces such as atria and auditoria, regarding modeling of phenomena based on local airflows…"

Without some form of zonal subdivision or CFD model to get beyond the assumption of such spaces as thermally homogenous, a building simulation will fail to represent thermal stratification. The first of the methods listed here approximates thermal stratification via the simple subdivision of the space into occupied and stratified zones or volumes. This is a really the most basic form of zonal model. For this paper, however, these will be referred to as "two-node" models and the term "zonal" will be reserved for models that further subdivide the thermal zones to include multiple airflow paths through a single space.

The second method introduces a bulk airflow network. So long as air is supplied by a mechanical system, the addition of the airflow network affords an advantage only when there are multiple possible paths that the air might take, including between occupied and stratified zones, between these and adjacent zones, through operable windows or vents, and/or as infiltration and exfiltration through the building façade. When there is only one possible path, the mechanical system will simply force the flow of air from occupied to stratified zones, as in the first method (without a bulk-airflow network). While bulk airflow tools such as MacroFlo include algorithms to represent turbulent bi-directional flow associated with a sharp-edged orifice or relatively small punched opening between two large volumes (such as an operable window), it would be inappropriate to apply this to the virtual subdivision of a space that is not actually partitioned.

The limitations of bulk-airflow models with respect to large openings between zones can be further understood by considering a fully enclosed space divided into upper and lower volumes with warm air beneath the virtual boundary and cool air above it, and assuming no forced supply or extract to or from either volume. This condition is inherently unstable, resulting in buoyancy driven fluid motion—the Rayleigh instability—which cannot be directly modeled by bulk airflow networks. The model underlying bulk airflow networks predicts that no air will flow between the two volumes, as it assumes uniform pressure across the opening. In practice, however, warm air will rise through one side of the opening while cool air descends through the other. A zonal approach can account for some aspects of the Rayleigh instability based on the behavior of thermal plumes; however, the fidelity of this approach is quite limited with respect to the actual complexity and variability of local airflows in a large atrium.

Computational fluid dynamics (CFD) methods are able to model these situations with considerable accuracy. The computational cost of CFD models with typical mesh densities, however, renders this tool infeasible and impractical for annual or even seasonal building energy simulation. This suggests a possible role for bulk airflow modeling to represent buoyancy driven airflows in atria. In this study, we have attempted to use these two methods in a complimentary manner. We use a zonal bulk airflow model to simulate vertically stratified spaces within an atrium and use CFD to test, validate, and tune the zonal model.

Mora et al. (2003) describe a less computationally intensive "course-grid" approach to CFD modeling that may be both desirable and practical in some cases. This study, however, is focused on discerning the relative merits of methods that do not directly rely upon a CFD model for the simulation of building energy consumption as required to maintain a desired level of thermal comfort over an extended period of time.

The zonal method described in this study subdivides the space both vertically and in close proximity to glazed façades. This is an attempt to roughly approximate the pool of cool air on the floor provided by true thermal displacement ventilation diffusers, the thermal plumes rising up the façade from that pool of cool air as a result of the hot inside surface of the glazing, and the tendency for the hottest air in the space to collect in another pool adjacent to the ceiling surface.

Model Setup and Assumptions

The model was kept relatively simple to facilitate understanding of fundamental characteristics. The atrium is a rectangular enclosure with glazed surfaces on three sides and roof (Figure 1). The model was oriented with the largest glazed façade facing south to be exposed to maximum solar gain variations during a summer day. The glazed façades are assumed to have 10% frame area constructed of thermally broken aluminum mullions with wetted-to-projected frame area ratios of 3.0 outside and 5.0 inside. The double glazing represented in the model is PPG Azuria with SolarBan 60 low-e coating on the second surface and a clear inner pane (center-of-glass SC 0.32, SHGC 0.28, U-value 0.29; ASHRAE U-value with frame 0.34).

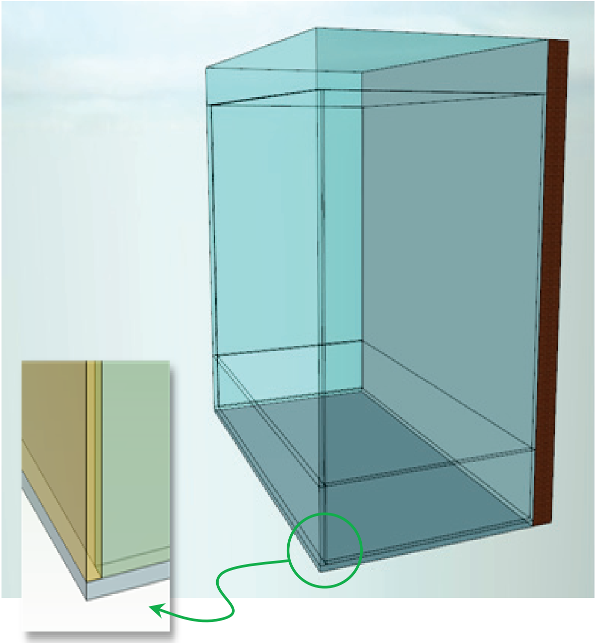

Figure 1 Atrium model with zonal subdivisions to represent both vertical stratification and thermal plumes adjacent to the glazed façades.

The remaining opaque north wall was modeled as adjacent to a separately conditioned zone (brick textured in Figure 1) representing the building and adjacent spaces to which the atrium would be attached. This adjacent zone was separated by a continuous wall of typical interior construction and maintained between 68 and 75 °F. This was an intentional simplification of the influence that fully conditioned adjacent spaces would have if there were openings to the atrium.

The 20-ft deep, 40-ft wide, 40-ft tall atrium volume was then subdivided into the following zones:

- 6-in Cooling air zone covering the entire floor area to represent the shallow pool of cool supply air provided by displacement ventilation diffusers
- 7.5-ft Occupied zone above the cooling air pool
- 28-ft Lower stratified zone
- 4-ft Upper stratified zone against the ceiling
- 6-in Façade zones to concentrate heating of room air by the glass surfaces on each orientation.

The façade zones were subsequently subdivided at the same height as the top of the occupied zone (8 ft above the floor) to form upper and lower façade zones. These were defined as sitting on top of the cooling air zone and meeting the underside of the uppermost stratified zone. Bases of the lower façade zones were adjacent to the cooling air pool and the top of the upper façade zones were adjacent to the uppermost stratified zone.

The purpose of the façade zones was to model localized heating of air adjacent to the facades and paths for that buoyant hot air to rise to the top of the atrium without significantly mixing with the main air volume. The façade zones were, over several modeling iterations, variously extended inward six to eighteen inches from the hot glazed surfaces to determine the zone depth that was best suited to mimicking results obtained with the CFD model.

The occupied zone was assumed to be the location of the thermostat and the only region of interest with respect to thermal comfort. In the zonal model, however, cool air was supplied to the displacement ventilation cooling air zone at the floor level and hot air was extracted from the uppermost stratified zone. It was therefore left to MacroFlo to determine how much of the cooling air would be drawn up through each of the façade zones *vs.* up through the occupied zone.

The study sought to discern whether or not there was any advantage to this relatively simple and intuitive approach to zoning the atrium as a potentially more accurate means of modeling the energy requirements for conditioning the space.

For comparison purposes, the model was also run in two other configurations. For these configurations, the MacroFlo bulk airflow model was simply turned off, as it would have nothing to add to these cases:

- One fully-mixed zone for the entire atrium.
- Separate occupied and stratified full-plan zones (the 2-node or 2-zone method), with the occupied zone being the first 8 feet above the floor and the stratified zone filling the remaining 32 feet up to the glazed roof of the atrium.

HVAC Systems

Heating Ventilation and Air-Conditioning (HVAC) systems were set up, autosized for the Phoenix, AZ climate, and modeled in the IES Virtual Environment's ApacheHVAC module. Figure 2 shows the thermal displacement ventilation system for the zonal model. The floor-level cooling supply air zone, occupied zone, and uppermost stratified zone are included on the HVAC network. Controllers are used to eliminate the flow between zones on the network (controlled to zero cfm) such that all inter-zonal flow during the simulation must be determined by MacroFlo.

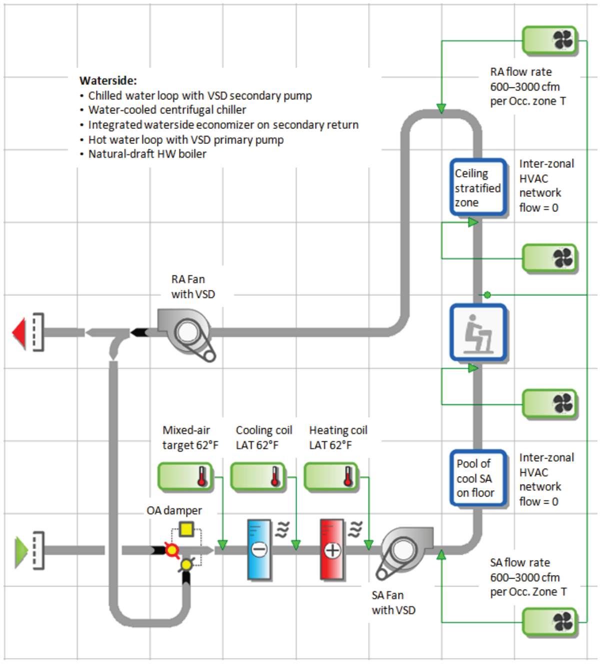

Figure 2. Thermal displacement ventilation system airside network as represented in ApacheHVAC.

Cooling air was supplied into the cooling air zone or "pool" for the zonal configuration and supplied directly to the occupied zone for the two-node and fully mixed configurations. The cooling supply air temperature was 62°F for the zonal and two-node configurations and 55°F for the fully mixed configuration. Airflow was modulated as required in all cases to maintain the 75°F cooling setpoint in the occupied zone.

The system initially prepared for the zonal model was reused for the other two configurations, with the only modifications being removal of the cooling supply air zone and removal of that plus the stratified zone for the 2-node and fully mixed configurations, respectively.

Cooling airflow rates, fans, coils, and plant equipment were then autosized for each of the configurations to ensure that none of the systems were significantly undersized or oversized with respect to maintaining the cooling setpoint in the occupied zone.

As noted previously, the occupied zone was assumed to be the only region of interest with respect to maintaining thermal comfort. Equivalent performance was achieved by tuning system controls to match both the peak design day temperature in the occupied zone (within 0.1°F) and the temperature profile as a function of system responsiveness for each of the systems.

Model development and simulations

Thermal displacement cooling airflow requirements were based upon maintaining a 75°F setpoint in the occupied zone with a 62°F supply air temperature (55°F SAT for the case of the fully mixed configuration). The thermal and energy simulation model also provided surface boundary conditions for the complimentary CFD model.

The CFD model of the atrium was configured using geometry and boundary conditions from the simulation model (the IES Virtual Environment allows for these conditions for a particular thermal simulation time step to be transferred, along with the geometry, directly from thermal simulation results to the CFD module). The very large supply air diffuser at the base of the opaque north wall and a similar outlet at the top of the north wall were added within the CFD model and assigned flow rates as calculated by the initial 3-zone thermal model. Since CFD provides a spatially dense, conservative computation of fluid properties, there were no "zones" in the CFD model. However, due to computational cost, each CFD run provided solutions for only a single set of conditions or point in time.

When testing for agreement between the thermal/bulk-airflow simulation and CFD model, we held cooling air temperature and flow rate constant and then extracted three sets of boundary conditions from the solar, thermal, bulk-airflow simulation for 10:00 AM, 1:00 PM, and 4:00 PM. These conditions were then the basis for three separate CFD models using the same constant cooling air temperature and flow rate to test agreement of occupied zone temperatures at these times of day, and thus across a range of insolation levels and outdoor temperatures.

Testing of 2-ft and 6-in depths for the cooling supply air zone adjacent to the floor in the zonal model indicated that the deeper zone resulted in excessive cooling airflow requirements. Airflow requirements in the zonal model with 6-in deep cooling supply air zone adjacent to the floor were aligned with the CFD model.

We then added one full-height façade zone to each glazed orientation of the zonal model, testing agreement with the CFD model for 6, 12, and 18-inch façade zone depths. As we were seeing further discrepancies between the airflow requirements in the zonal *vs.* CFD models for all three of these façade zone depths, we then went on to explore the effects of subdividing the façade zones into lower and upper zones adjacent to the occupied and stratified zones at the core of the space. This provided improved agreement with the CFD model in terms of the air temperature at the geometric center of the occupied zone for a given cooling air flow rate.

Having achieved a reasonable level of agreement between the zonal and CFD models in terms of occupied zone temperatures for a given cooling airflow rate and temperature, we then went on to compare the results of the zonal model with simpler methods for thermal and energy modeling that did not include the use of the MacroFlo bulk-airflow network.

Façade Zones Development, Testing, and Discussion

As described earlier, the use of façade zones to capture boundary layer buoyant effects makes intuitive sense; however, there are several parameters that might affect the results of such a model. To characterize the parameters introduced in the zonal model, we tested several sets of boundary conditions for the CFD model, airflow rates, façade zone depths (dimension perpendicular to the glazed façade), and both full-height and vertically split façade zones.

Results from initial runs indicated significant dependence on boundary conditions and sizing of airflow rates when attempting to determine the correct façade zone depth. Using inappropriate boundary conditions and cooling airflows could readily lead to incorrect determination of the façade zone depths. For example, if we used a *fully-mixed* model to obtain boundary conditions and cooling airflow rate for the CFD model, and then ran the zonal model using the same airflow rate, the results suggested that a 2-ft façade zone provided the best agreement with the CFD model and 1-ft façade zone was on par with no façade zones.

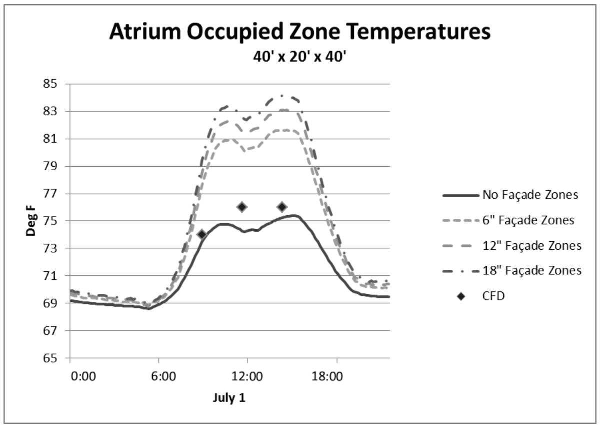

Figure 3. Occupied zone temperatures for three façade zone depths using boundary conditions and airflow from the zonal model prior to addition of façade zones.

When we first added the facades zones to the model, all three façade zone depths tested showed much worse agreement with the CFD in terms of predicted occupied zone temperature than for the case with no façade zones (Figure 3). While we anticipated that a substantial portion of the airflow would be draw to and then up the façades via the façade zones, the significant increase in occupied zone temperatures for these cases was not expected.

Air flows in the zonal model indicated that more cooling airflow was being diverted around the occupied zone than was predicted by the CFD model, resulting in higher occupied zones temperatures.

To see if this was consistent across changes in atrium geometry, we tested atria height. As shown in Figure 4, the relative affect of the façade zones was reversed for a 20-foot tall atrium *vs*. the 40-foot tall atrium.

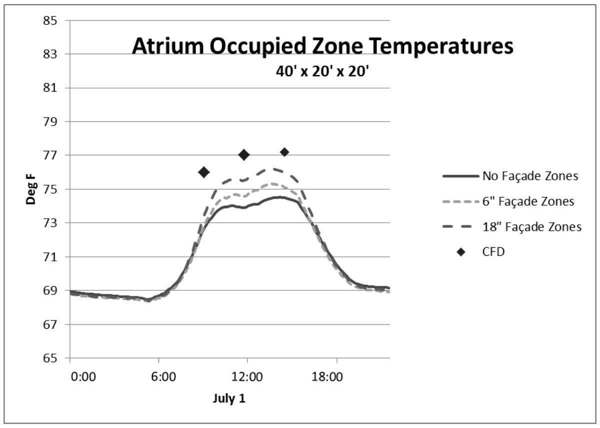

Figure 4. Initial CFD and zonal model occupied zone temperatures for a shorter, 20-ft tall atrium.

Vertically Stratified Façade Zones

We further refined the zonal model by vertically subdividing the façade zones to match the height of the adjacent occupied zone and stratified zones at the interior of the space. This approach provided better agreement with the CFD model (Figure 5), with the smaller 6-inch depth, vertically split façade zone yielding results closest to the CFD model.

Splitting the façade zone vertically provided lower façade zone with reduced homogenous temperature, and this resulted in less pumping action at the façade and a larger portion of the cooling air flowing through the occupied zone. This partial shift in flow from façade zones to the occupied zone, thus lowering the occupied zone temperature for a given cooling airflow rate, provided the improved agreement with the CFD model. Examination of airflows in the zonal model revealed that the façade pumping action was now drawing cooling airflow from the "pool" of cooler air on the floor in a proportion of total flow that approximated the thermal plumes in the CFD model. It is worth noting that the zonal model with vertically stratified façade zones was really not very different from either the zonal model without façade zones or the even simpler 2-node/2-zone model without any bulk-airflow network in terms of predicted occupied zone temperature at a given cooling airflow rate.

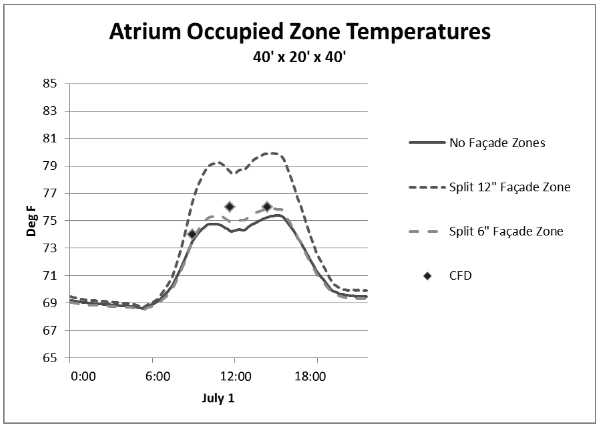

Figure 5. CFD and zonal model occupied zone temperatures with a fixed airflow rate after vertically subdividing the façade zones.

RESULTS ANALYSIS

Thermal performance

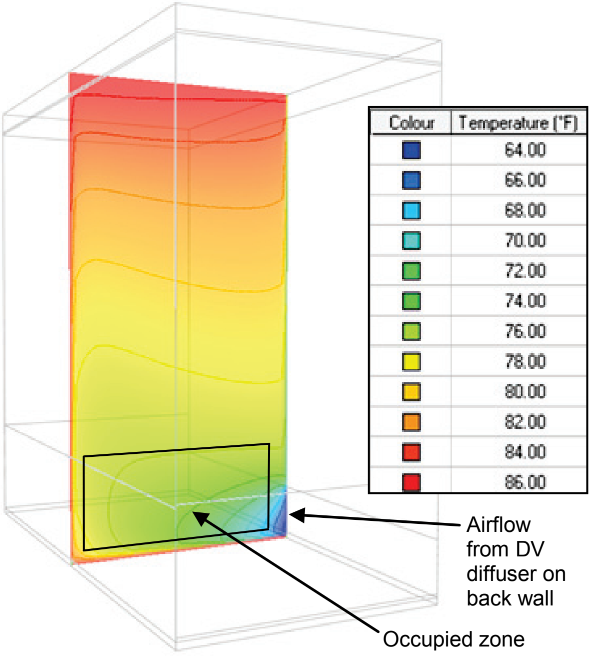

Figure 6. CFD model using boundary conditions from the final version of the zonal model.

Results for the zonal model (Figure 7) had strong agreement with the CFD model (Figure 6) in terms of predicted occupied and stratified zone temperatures at a given cooling airflow rate.

Airflow through the lower façade zones (Figure 8) indicate that stack-effect flows are responding to diurnal variations of interior glass surface temperature as a function of absorbed solar radiation.

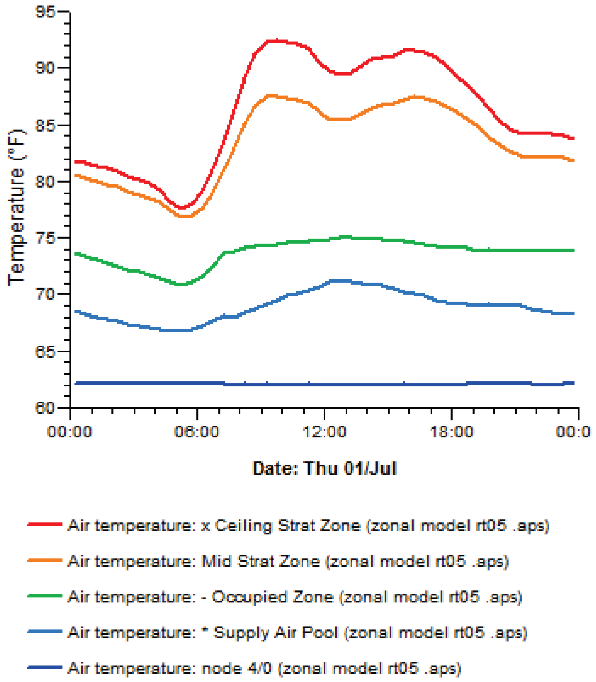

Figure 7. Temperatures for cooling supply air (node 4) the lowest zone as virtual pool of cooling supply air on the floor, the occupied zone, stratified zone above that, and finally the uppermost stratified zone at the ceiling.

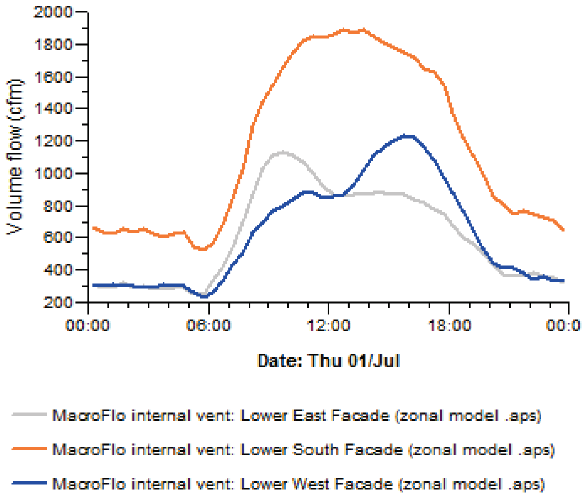

Figure 8. Interzonal flow for East, South, and West lower façade zones in the zonal model.

Results for the much simpler 2-node/2-zone model (Figure 9) were very close to those of the more detailed zonal model (Figure 7): Temperature profiles are similar and peak occupied zone temperatures were in both cases just under 75 °F at cooling airflow rates that differed by just 1.3% —a difference that is well within the uncertainty of the relatively coarse zonal method.

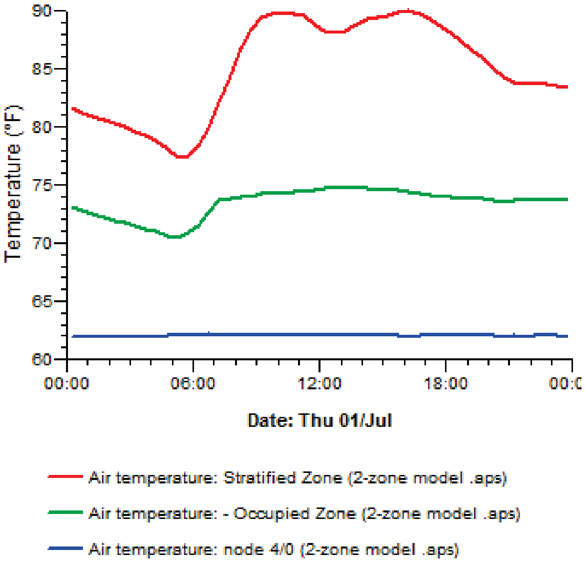

Figure 9. Temperatures for cooling supply air, occupied zone, and stratified zone in the simple two-node or two-zone model without bulk-airflow network.

The one clear difference between these models is radiant temperature as seen from the occupied zone, contributing to a lower dry resultant temperature in the zonal model (Figure 10) than in the 2-node model.

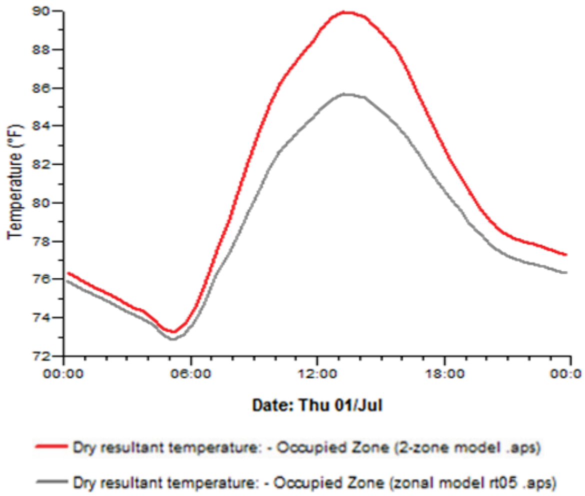

Figure 10. Occupied zone dry resultant temperature for the zonal model (gray) and 2-node model (red).

A comparison of return air temperatures (Figure 11) shows that that the zonal model is removing more heat from the façades (thus the lower radiant temperatures). Both models have a 62 °F supply air temperature and the occupied zone temperatures and associated supply air flow rate profiles are so closely matched as to almost completely hide behind one another on a graph.

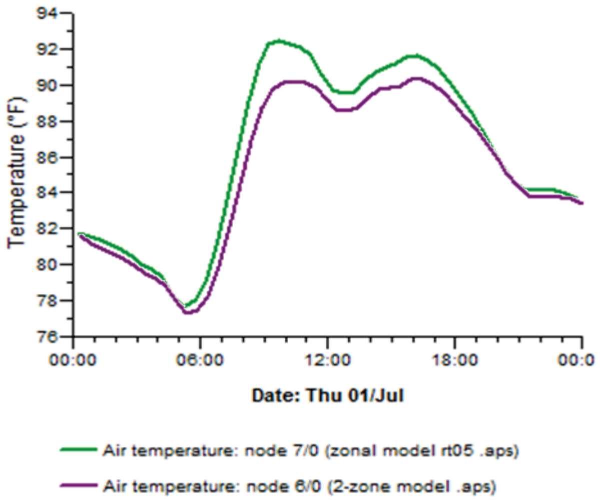

Figure 11. Return air temperature for the zonal model (green) and 2-node model (purple).

System Energy Results Comparison

Month of July	Chillers energy (MWh)	Fans energy (MWh)	System energy (MWh)
Zonal model	2.71	0.86	5.60
2-node mode	2.37	0.93	5.20
Fully mixed	3.60	1.42	7.09

The added removal of heat from the facades contributes to roughly 14% higher chiller energy for the month of July. While fan energy is 7.5% less for the zonal model, overall HVAC system energy for the month of July, including pumps and cooling towers, is 7.7% higher in the zonal model than 2-node model.

CONCLUSIONS

This study set out to examine whether the use of vertically segmented zones plus special façade zones in a bulk airflow model for thermally stratified atria could provide greater fidelity in energy simulations.

The zonal model, including both a 6-in deep floor-level zone to represent the TDV "pool" of cooling air and a 6-in deep facade zone for each glazed orientation as an alternate path within the bulk-airflow network (split into upper and lower zones at the top of the occupied zone), appears to more closely match the CFD model with respect to removing heat from the interior façade surfaces while maintaining the occupied zone setpoint with very slightly *less* total airflow. The added removal of heat and associated requirement for additional cooling energy provide a more conservative and probably more realistic energy model as compared to the simpler 2-node/2-zone method.

Study results suggest that, relative to the CFD model, the zonal modeling method tested appears to yield more accurate simulation results than were obtained with the simpler models in terms of cooling airflow requirements, cooling of façade surfaces, and predicted temperatures in the occupied zone. The improvements with respect to accuracy of cooling airflow and chiller requirements are modest but still significant relative to a far simpler 2-node/2-zone model. The zonal model does, however, appear to have greater need for tuning via iterative CFD and bulk-airflow simulation runs, as there are more possible airflow paths—the added façade zones in particular—and these can either improve or detract from the model. The simpler method may provide much of the same benefit with respect to energy modeling as compared to a fully mixed baseline model. In practice, therefore, a zonal model may be justified on the basis of improved energy simulation results only when the climate is fairly extreme and the atrium represents a significant portion of the overall building project.

The zonal model, even without validation via CFD, may be also useful in providing enhanced representation and communication of the relative fluctuation of thermal plumes at each façade orientation as the levels of insolation on each change over the course of a day.

While the zonal model can provide a reasonable simulation of design conditions being maintained throughout the year, modeling of thermal comfort in the context of displacement ventilation (DV), requires a CFD model with thermal mannequins to represent thermal plumes and local cooling effects associated with each occupant. Therefore, the comfort conditions maintained in the zonal model are only a proxy for what would be provided by the DV system.

For practical energy modeling purposes, especially where the atrium is but a minor part of the building, simply dividing the atrium into fully mixed occupied and stratified zones (a 2-node or 2-zone model), with all HVAC cooling airflow supplied to the occupied zone and extracted from the stratified zone may be sufficient. Under relatively extreme conditions for a notably extreme design case, this far simpler method appears to overestimate benefits of DV for the atrium by only about 7% relative to that predicted by the CFD model. The tendency toward convergence of results for the simpler 2-node model with that of the zonal model when solar gain is reduced suggest that the simpler model would be on par with the zonal model in terms of matching the CFD results under less extreme conditions. The simpler method has the added advantage of low computational overhead, as it does not require modeling inter-zonal air movement as a function of temperature or pressure. This will hold true so long as there are no operable exterior openings (*i.e.,* no natural ventilation or mixed-mode operation) and no need for detailed infiltration modeling, either of which may call for the use of a bulk-airflow model.

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