Improving Comfort and IAQ

Ups and Downs Of Stair Towers

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Designs of stairways are highly code-regulated for life-safety reasons. Today, for improved environmental sustainability as well as better personal health, popular advice says to use the stairs instead of an elevator whenever practical. However enclosed stair towers often suffer from poor temperature control and "stuffiness," are uninviting in appearance, or are inconveniently located. For new buildings there is opportunity to make stairways attractive choices for occupants to use regularly. This article discusses a study[1] concerning thermal comfort and indoor air quality (IAQ) in enclosed stair towers and looks at the effect of placement of HVAC terminal units to test a popular design rule-of-thumb.

Vertical transport of occupants and materials in modern multistory buildings is via stairs, escalators, and elevators. Flights of stairs are either in open stairways or enclosed in stairwells. These stairwells, and the staircases they contain, are often called stair towers, but all of these terms are often used interchangeably. In low-rise multistory buildings stairways are usually the primary, or are often the only, means of vertical transport, but in high-rise buildings elevators are used extensively. However, for improved public health and reduced energy consumption, regular use of stairways by occupants without mobility impairments should be encouraged via designing the stairways to be convenient, attractive, safer, and comfortable. In this research enclosed stair towers of moderate height and with frequent daily-use were of primary interest. Yet most research on and design-guidance for stair towers are for their use during extreme events such as fires. In these events occupant egress and stair towers' tenability are of primary importance. For example, doors are to swing

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in the direction of egress and have automatic closers, and, generally, only noncombustible materials can be used in stair towers' interiors.

Depending on local code adoption, design of tall buildings' enclosed stair towers for egress safety is governed by at least the International Building Code (IBC), NFPA 101 Life Safety Code®, and NFPA 92 Standard for Smoke Control Systems. For example, the IBC defines minimum tread and landing widths, NFPA 101 sets maximum door opening force, and NFPA 92 and ASHRAE's *Handbook of Smoke Control Engineering*[2] cover design, installation, and testing of stair tower air pressurization systems. If fire protection concerns conflict with thermal comfort measures, designers are wise to err to the side of life safety. For example, stair towers' ventilation systems are usually required to be physically separate from the buildings' general ventilation systems as was learned through difficult lessons from the 1980 Las Vegas MGM Grand Hotel and Casino fire and other tragedies.

John L. Bryan and many others have studied stairways and egress, particularly on smoke or occupants' flows, and, via improved building codes and enforcement, tall buildings are now much safer during fire events. Pressure-compensating ventilation systems are often specified to reduce smoke intrusion into stair towers so that occupants can leave and then emergency responders can move vertically through the buildings. From a life-safety point-of-view, enclosed stair towers, that benefit from fire protection design's compartmentation principles, are preferred over using open stairways in all buildings.

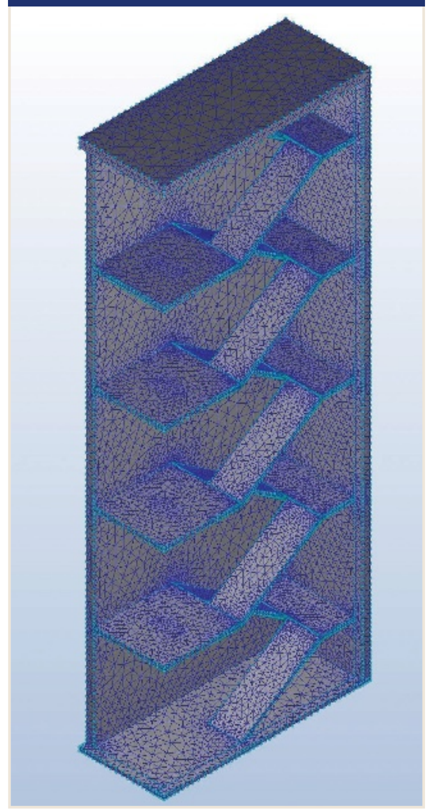
While enclosed stair towers' design and construction varies, common are masonry enclosures with either steel or concrete staircases, or wood-frame or steel enclosures with multiple layers of "Type-X" gypsum board and steel or wooden stairs. Typically, two- or three-hour fire-resistance ratings are required for these enclosures, and penetrations of stairwells should and usually do get close scrutiny by their code-compliance inspectors.

Depending on the climate, the owner's choices, and the intention for a particular stair tower to serve for routine use or only during emergencies, stair towers may have only nominal heating capacity installed, and not cooling, dehumidifying, or, rarely, humidifying capabilities. Filtration may be minimal or nonexistent. Except for the fire-related smoke management systems, stairwells often have no mechanical ventilation and instead rely on infiltration or transfer air.

Use of their doors for passage, and the stack effect, moves some air through towers, but their enclosures are intended to be very tightly sealed. As such, infrequently used stair towers often have a "stuffy" concrete, gypsum, or moldy odor to them, and internally generated contaminants from materials off-gassing, as well as from occupants, are often not rapidly removed.

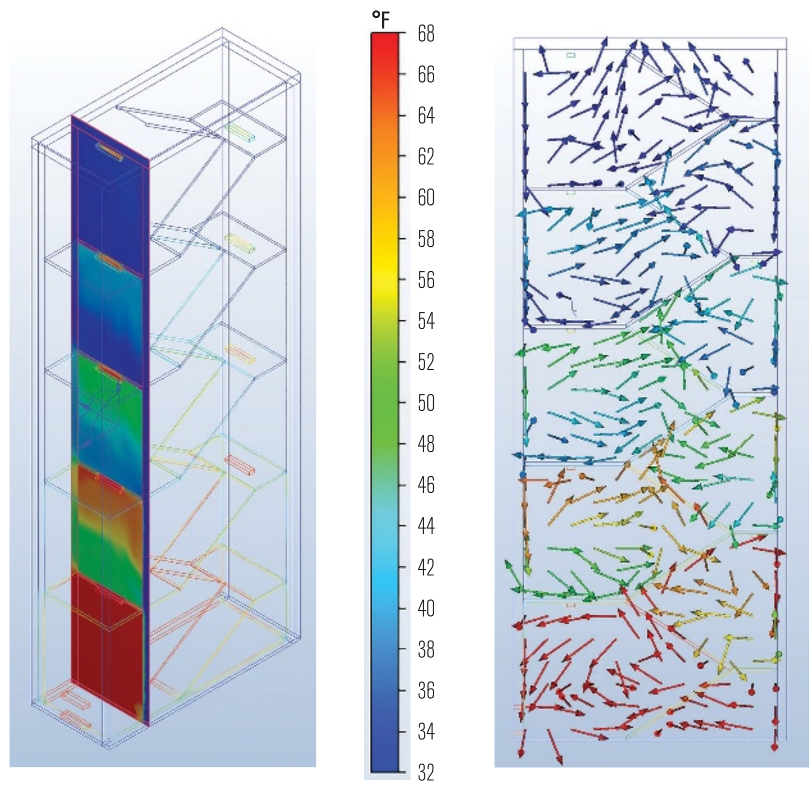
If attached to parking garages or near other places with high airborne contaminants such as kitchens, smoking areas, driveways, or loading docks pollutants can enter stair towers. Poorly sealed stair towers, like elevator shafts and floor penetrations, can transport pollutants between floors. With high-mass, heated-only stairwells especially, another problem can occur, typically in the spring, when very humid outdoor air enters towers and, at times, condenses moisture on their cool, below-dewpoint surfaces, usually toward the bottom of the towers. Groundwater intrusion or leaky pipes also can cause odor or mold issues as well as slip-and-fall hazards. Proper design, construction, and maintenance of the enclosure, as well as having dedicated, effective HVAC systems that provide thermal comfort in all seasons, and that dilute airborne odors and pollutants, can make stair towers more

FIGURE 1 A cut-away isometric showing the five story stair tower's three-dimensional CFD model's surface elements. Low-sidewall fan coil units were then added at 1) the bottom-only (heating) or top-only (cooling), 2) on every other floor, or 3) on every floor to predict temperature distributions in the tower. Fluorescent luminaires were mounted under each landing.



desirable for everyday use, as well as safer.

FIGURE 2 Heating-mode base case with only one FCU located on the lowest level. Note the significant temperature stratification (left) with the coolest air at the top due to envelope heat loss. On the right, via a perpendicular 2-D slice, is shown that the air circulation is complex; on-screen 3-D views show that the buoyancy-driven airflow is in a corkscrew-like manner up and down the stairway. The temperature scale's full range is 36°F (20°C) for the heating cases.



Actual Stair Tower

The five-story tall, approximately 10 ft wide and 24 ft long (3.1 m by 7.3 m) stairwell that initiated this study is in a many decades-old education building in the central United States, and is constructed of masonry, a few metal-framed windows, and metal doors to each floor. On one of its landings there is a double-door to the outside. These two doors' seals are in poor condition; their weatherstripping is replaced infrequently, but the very high use of these doors wears the seals out quite rapidly. As such, infiltration through these doors is very apparent in the extreme seasons. Typical of that building's era, and still somewhat common, is that the walls, roof, and foundation of this stairwell are uninsulated; designers considered stair towers to be "transiently occupied spaces" so thermal comfort within them was not expected to be important. The winter thermal resistances (R-values) of the high-mass walls and roof of this particular stair tower are only 2.45 and 1.39 $h \cdot ft^2 \cdot °F/Btu$ (0.4315 and 0.2448 $m^2 \cdot K/W$) with the significant difference being an air space within the masonry walls vs. the solid, cast-in-place concrete roof deck.

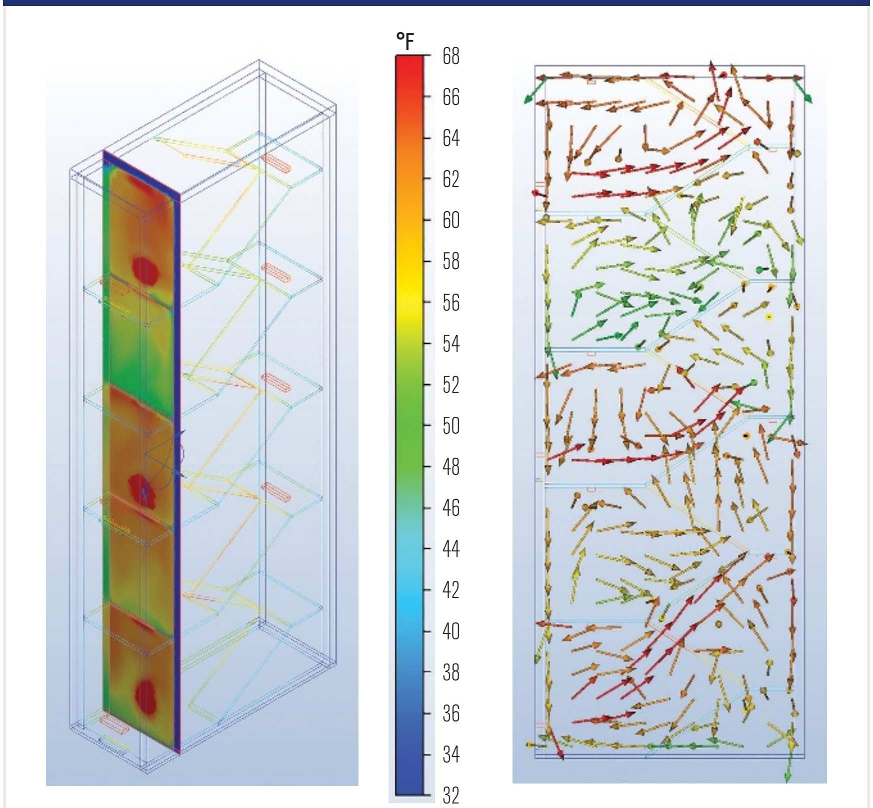
In stair towers there are most often two stair flights and two landings per floor-level, also known as "half-turn" or "U-shaped" stairs. Over each landing in this study's such stairwell are about 80 W of operating-continuously fluorescent lamps and their ballasts; they provide a consistent heat gain. There's no interior wall between the two flights of stairs for each floor of this tower, but there is a 7 in. (178 mm) wide air gap between. This geometry allows buoyancy-driven flow to move vertically both via this open gap and also in a corkscrew-like manner over the flights of stairs. These flows are usually bidirectional, up and down, as the researchers observed in a similar staircase nearby where cold air very noticeably rippled down the steps in a thin, higher-velocity layer, and replacement warm air rose slowly above it, both buoyancy-driven flows only.

In this stair tower, a water-filled fire protection standpipe passes up through one corner of each floor's landing, as also occurs in many other buildings. Wall-mounted recirculating fan-coil units (FCUs) are located on each floor-level's landing; these FCUs are in a variety of maintenance-states, so may not be fully functional. There's no mechanical ventilation; instead, infiltration and transfer air, driven largely by wind and buoyancy, provide some air exchange. This stairwell has remained dry, fortunately, so the primary complaint is the lack of thermal comfort within it, especially in the winter on the lowest level with its poorly sealing exterior doors. An infrequent complaint is when tobacco smokers are outside, but are too close to the exterior doors, so some smoke enters the tower.

Field Measurements

While formal complaints about thermal comfort or IAQ in stairwells seem to be rarely given to building operators, the researchers themselves noticed that at least the temperatures in the stair tower of interest varied widely throughout its height, as well as with weather conditions. To document one such instance, transient temperature measurements were taken early on a cold winter day; 3 a.m. to 5 a.m. on a Sunday was selected as the best time span for when the tower had least use so that its doors would remain closed as much as possible. The outdoor air temperature was fairly constant at about 25°F (–4°C) and there were no solar heat gains due to the early time. Thermocouple temperature sensors were placed on the first, second, fourth, and fifth levels. Confirming perceptions, the first level's temperature was very low at about 42°F (6°C). The second level was about 62°F (17°C), the fourth 64°F (18°C), and the fifth 61°F (16°C). The first floor's low temperature was expected due to infiltration, but, because of buoyancy, the slight temperature decrease at the top of the tower was unexpected. A high rate of heat loss, through the uninsulated masonry roof and exterior walls, explains the temperature decrease at the very top of this tower.

FIGURE 3 Heating mode case with FCUs on every other floor. Note the much more uniform temperatures and per-floor flow fields than the prior base case.

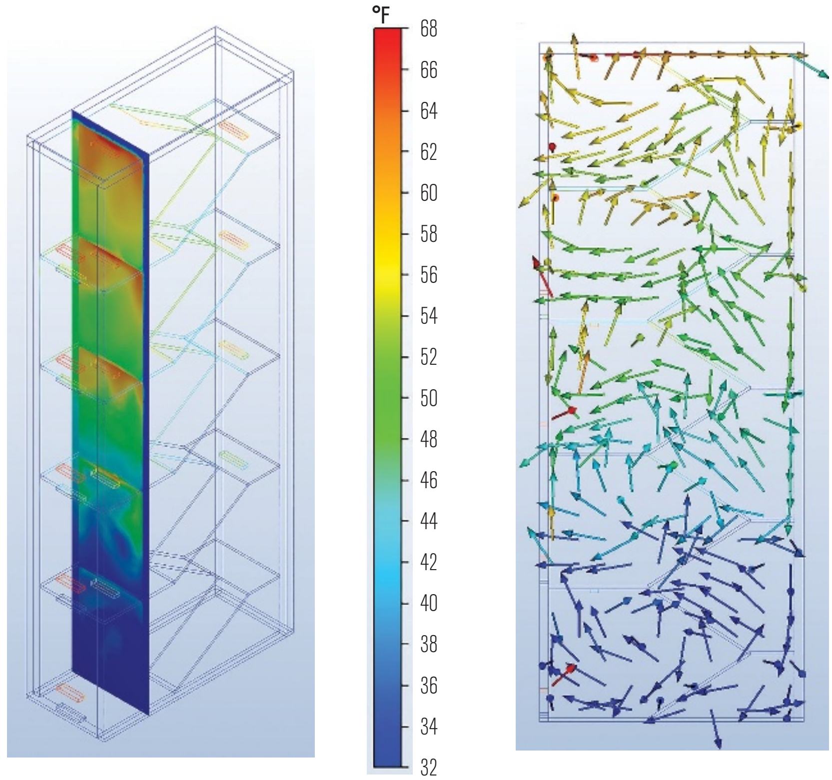


With the central U.S.'s winter outdoor air temperatures often falling much lower than that of this test-period, the measurements confirmed the suspicion that the water-filled fire protection standpipe in the stair tower could be exposed to subfreezing conditions despite being in a "heated" location; whether the water inside this steel pipe could freeze requires further study due to its high mass and its extension to warmer locations both above and below. Better insulated and sealed exterior doors, and installation of a vestibule, should raise the temperature of this lowest level of the tower significantly. Adding insulation to the walls and floor slab is likely not practical, unfortunately, but insulating the pipe itself might if done with durable, nonflammable material. When the roofing is replaced, adding board-type insulation there would be easy, but would not likely help the lowest level. Increasing the space-heating capacity is another possible, energy-intensive corrective measure. But how big, how many, and where such heating, and possibly cooling units should be placed in a new tall, single-zone space for optimal performance and economics are challenging design questions, and such units cannot decrease the minimum required egress path's widths. One at least locally utilized rule-of-thumb, for short- and moderate-height towers, is to put an out of the way, large heating unit on the lowest level of the stairwell, and to let buoyancy move air vertically through the tower. It was desired to test the effectiveness of this rule-of-thumb.

Modeling Needed

To study the question of interest – the effect of size and placement of the FCUs upon vertical temperature distribution – a three-dimensional computational fluid dynamics (CFD) model was created that was simpler but similar to the actual stair tower; it was different from

FIGURE 4 Heating mode case with an FCU on every floor, similar to the actual stair tower studied. Note how negative buoyancy, and likely floor slab heat losses, cause cold air to "pool" at the bottom. With the total design supply airflow rate divided equally among the FCUs in each case, having an FCU on every floor reduces the momentum-driven flow that enhances mixing.



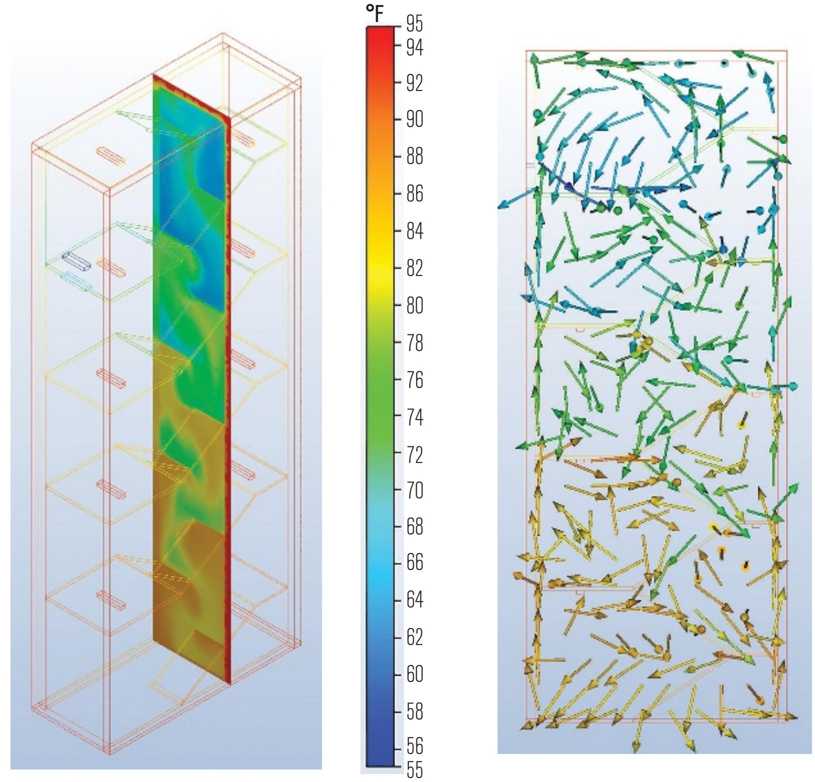
the real tower by having no windows and a slightly different floor shape, for example. The CFD model was not intended to match precisely the temperatures in the real tower at its off-design winter conditions, but instead to characterize a more-generic tower's performance at winter and summer design conditions. The commercial CFD software used has a finite-element approach, and its default κ-ε turbulence model was utilized. The program also solves for heat conduction through the tower's envelope as well as thermal radiation exchange within. Ergin, et al.,[3] Mokhtarzadeh-Dehghan, et al.,[4,5] and Peppes, et al.,[6] compared experimental tests to CFD models for two-story stairwells, and Peppes, et al.,[7] extended their research to three stories; all found good agreement when care was used in creating the models.

Figure 1 (Page 13), of this current study's computational mesh for the stair tower's interior surfaces and stairs, shows the five-story, 3D geometry used. Three of the stair tower's walls and its roof were to the outside air, but one abuts the interior of the building. The floor-to-floor height was 12 ft (3.7 m). The geometry of the stair tower was created in a popular building information modeling (BIM) software package and then exported to the CFD program. Due to time and computer memory constraints, the flights of stairs' geometries were simplified, slightly, to be ramps instead of many small treads and risers, but the automesher still suggested that about 640,000 elements were needed. The CFD program's momentum as well as energy equation solvers were activated so that both the steady-state flow fields and air temperature distributions could be predicted. Each final run required from three to 12 hours on a PC; one test run of the heating base case with a tighter convergence criterion took much longer, but didn't change the results noticeably.

Cases

HVAC load calculations, via a widely used software package, predicted that the tower's peak cooling load would be about 43,600 Btu/h (12.8 kW). The peak heating load of about 77,100 Btu/h (22.6 kW) was determined by hand calculations. Because the real stair tower is somewhat old, and great thermal comfort within such was not expected then, 60°F (15.6°C) winter and 78°F (25.6°C) summer indoor design conditions were assumed; where needed, standard outdoor air design temperatures for its location were used and were 4°F (–15.6°C) and 99°F (37.2°C).[8] Supply air temperatures of 55°F (12.8°C) and 100°F (37.8°C) were then used to determine the total constant air volume (CAV) air flow rate of 1750 cfm (826 L/s) for the one or more FCUs. As mentioned earlier, in this region of the U.S. for low- and moderate-rise stair towers that are heated only, often there is just one FCU at the bottom of a stair tower and it has been assumed that buoyancy would adequately spread heat to the entire tower. This was desired to be tested, so the CFD model's heating-mode base case was just that. Similarly, the cooling-mode base case was one FCU at the top of the tower, only. The other cases studied were with FCUs placed on the first, third, and fifth (highest) floors, and with FCUs on every floor, for heating and cooling modes, separately. The design air flow rate was 1,750 cfm (826 L/s) for the cases with only one FCU, 583 cfm (275 L/s) each for three FCUs, and 350 cfm (165 L/s) each for when five FCUs were installed.

FIGURE 5 Cooling mode base case with one FCU at the top floor. The lowest level is the hottest; buoyancy-driven flow is not enough to mix the air well vertically. The scale's temperatures vary by 40°F (22°C) from coldest to hottest for the cooling cases.



Results

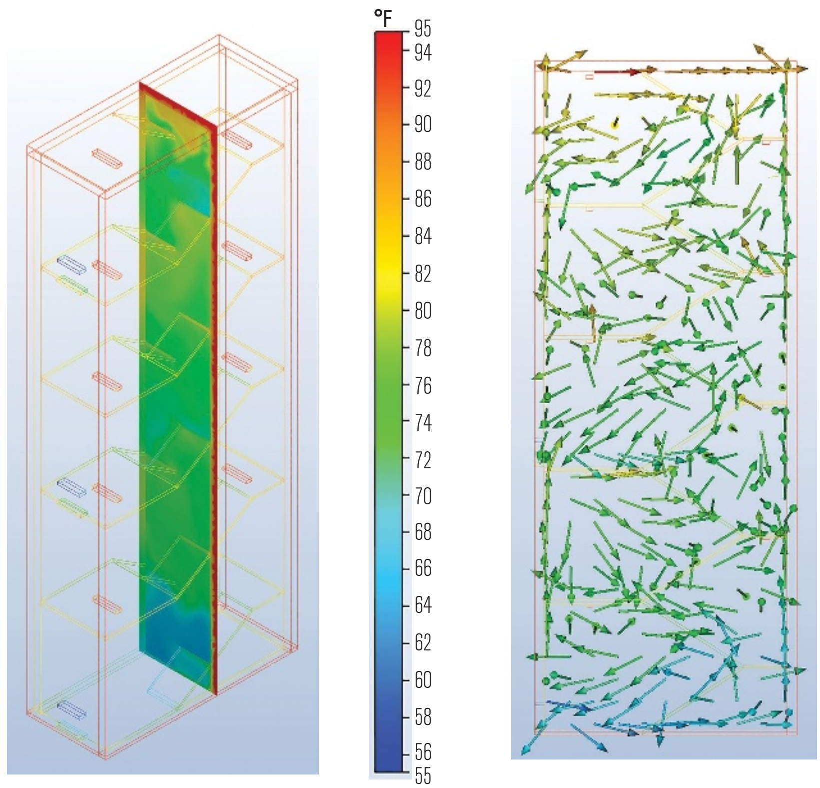
Figures 2 through *7* (starting on Page 14) illustrate the results of this study at the location's design conditions. *Figures 2, 3,* and *4* are for heating mode with, respectively, only one large FCU at the bottom, three mid-sized FCUs placed on alternating floors, and one small FCU installed on each floor. Similarly, *Figures 5, 6,* and *7* are for the stair tower in cooling mode, but the single-FCU case, in *Figure 5*, has the FCU at the top instead of the bottom. *Figure 2* shows that if the rule-of-thumb of using only one large heating unit, placed at the bottom, is used, the top region of the stair tower can get too cold—even potentially below freezing—due to high heat loss rates on the lowest levels and geometry-limited buoyancy-driven flow. *Figure 3*, with mid-sized FCUs on alternating floors, shows very good temperature distribution vertically except at the second-highest floor; the extra heat loss of the roof likely is the cause, and insulating the roof might solve it. *Figure 4*, with small FCUs placed one per floor, has unexpected worse performance than the prior case, likely due to reduced mixing. The flow rate per FCU was decreased proportionally, so buoyancy forces became dominant in this third heating case.

When in cooling mode at design conditions, *Figure 5*, with one large FCU only and at the top floor, shows clearly that "negative" buoyancy dominates its flowfield. And that envelope heat gain at the top causes the indoor air toward the bottom to be too warm. Similar to the heating case with mid-sized FCUs on alternating floors, *Figure 6*, for cooling, shows very good temperature distribution with only the lowest level being too cool due to "pooling" of cold air by negative buoyancy. *Figure 7* shows that the FCUs' reduced airflow rates, by installing equally sized small units on every floor, gives worse temperature uniformity than using mid-sized FCUs on alternating floors. As with the heating-mode case, buoyancy forces dominate for this specific geometry because the FCUs can't adequately mix the air on each level. These cases assume that all units are operating continuously; with thermostats controlling each FCU, separately, the results likely would show even more stratification and more under-heating and cooling on certain floors; as units throttle-back on the thermally satisfied levels, they won't provide their extra capacity to other levels through increased buoyancy flow.

Conclusions

This study tested the rule-of-thumb regarding if a single heating unit at the bottom of a typical low- or mid-rise stair tower is sufficient, ostensibly to provide reasonable comfort and definitely to protect a "wet" fire protection standpipe from freezing. The single-FCU base case heating and cooling CFD models suggest strongly that significant stratification occurs, and that heat losses or gains can cause very cold or hot regions in a tower. The base case models show clearly that a stair tower, with a single fan-coil, does not behave as a single, perfectly mixed thermal zone. Somewhat unexpectedly, the CFD models showed that for both heating and cooling, dividing the heating or cooling capacity equally across units placed one per floor causes insufficient mixing and allows buoyancy to again create strong stratification. For the typical, poorly-insulated five story stair tower modeled, located in the central U.S. in a hot/humid as well as cold/dry climate, the best performance was when the capacity was spread across only three units on alternating floors: the first (lowest), third (mid), and fifth (top). Others are encouraged to develop CFD models for assorted stair tower configurations, and to use various solver routines to compare and then report how their results compare with this study's.

FIGURE 6 Cooling mode case with FCUs on every other floor. The temperature distribution is much more uniform than for the just-prior single-FCU case. Note the layer of hot air at the top due to high heat gain through the uninsulated concrete roof.

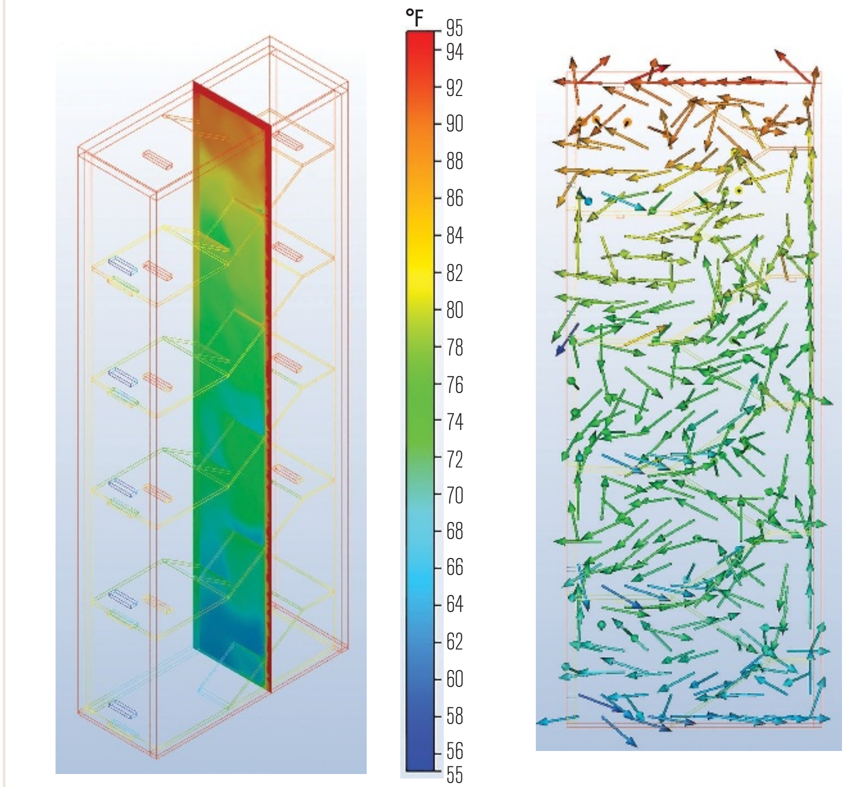


If units are placed on every other floor, every floor, or even on every landing, a practical, but as of yet untested design modification could be to double the capacity of the heating on the ground level, and if cooling is to be provided, to double the cooling and dehumidification capacity of the unit on the top level. This possible new rule-of-thumb would provide extra capacity to help overcome the buoyancy-driven pooling of air on those levels—cold at the bottom in winter, and hot/humid air at the top in summer. From psychrometrics, when at the same temperature and pressure, more-humid air is less dense than drier, so buoyancy should drive more airborne moisture to this topmost cooling unit; summer infiltration may also be highest at this top floor if a tower is air conditioned.

Instead of using a thermostat at each fan-coil, temperature and, if cooling capacity is specified, humidity sensors at each level could send data to a central controller that modulates the FCUs separately and optimally; research is needed to determine the best control scheme. For improved indoor air quality, use of unit ventilators or dedicated outside air units should be considered to provide some mechanical ventilation to dilute pollutants, but such would need to be coordinated carefully with the fire protection systems' designers to prevent smoke introduction. A slight positive pressurization, via outside air, might be beneficial not only for limiting infiltration during normal operation and diluting airborne contaminants, but also to reduce smoke intrusion somewhat before a separate stair tower smoke management system takes over after an extreme event is indicated. Tobacco smoking in or near a stair tower should not be allowed. Water intrusion must also be controlled to limit mold-growth and other hazards.

To improve comfort and reduce energy consumption, stair towers' enclosures should be well-insulated and doors well-sealed, and, if present, quality windows used. Vestibules can reduce pollutant introduction as well as reduce energy use. Because using stairs requires some physical exertion by people, especially when climbing, the setpoint temperature within them likely should be slightly less than that for the typical "seated, doing light

FIGURE 7 Cooling mode case with FCUs on every floor. Similar to the third heating mode case (*Figure 4*), the lower airflow rates per floor's FCU don't provide enough momentum for sufficient mixing, and buoyancy then causes significant stratification with the hottest air at the top. Heat gain through the uninsulated roof further heats the top layer of air.



work” activity level. ANSI/ASHRAE Standard 55 may already provide the answer to “By how much lower?”, but due to the short residence time within stair towers, further study may be needed to determine the optimal values.

Acknowledgments

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