Smoke and fire in building Atria

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ABSTRACT: Atriums are popular elements in large buildings and skyscrapers because they provide imposing, environmentally controlled and often daylight lit spaces. They are also inherently part of sports arenas, conference halls, shopping centers, botanical gardens, and airline terminals. Such spaces require special treatment by fire protection engineers to assure smoke abatement or containment while assuring adequate evacuation routes. Engineers draw on physical, zone, node and network or field (CFD) models to design fire management systems in such situations. The wind environment outside such buildings can critically affect the behavior of smoke and fire plumes within the structures, yet few fire codes consider such factors. A combination of physical and computational modeling techniques provides a means to deal effectively with such phenomena.

KEYWORDS: Smoke, Fire, Wind engineering, Building atria, Hazards.

1 INTRODUCTION

An atria was originally the grand entrance space or focal courtyard at the center of a Roman house or villa. [1] In 1806 the British architect, John Nash, included a roofed over picture gallery with natural lighting in the stately home of Attingham Park, Shropshire, UK. Then John Paxton designed the Crystal Palace Exhibition Hall for the Great Exhibition of 1851 to celebrate the industrial, military and economic superiority of the British Empire. The Crystal Palace included over a million square feet of glass and over 800,000 square feet of open space...a giant for its time. In the late 19th century the Rookery Atrium was constructed in Chicago in 1886 as part of the city restoration after the Great Chicago Fire. But it was really Frank Lloyd Wright who popularized the use of open space in commercial buildings when he created the Larkin Building in Buffalo, NY, in 1905. This was the first commercial building to include an atrium with natural lighting, air-conditioned and filtered air, integrated design of chairs, windows, furnishings and desks, and a recreation ground and gardens. Subsequently, Wright included atria in the Johnson Wax Headquarters of Racine, Wisconsin, 1936; the V.C. Morris Store in San Francisco, CA, 1949; the Guggenheim Museum in New York City, 1959; and the Ford Foundation Headquarters, Detroit, MI, 1967.

Today, the inclusion of a large interior space in the design of any tall building or skyscraper seems to be automatic. The Hyatt Regency Hotel, Atlanta, GA, 1968, designed by John Portman was the first building to formally call its covered central court an “atrium”. This concept has now been copied in skyscrapers worldwide. Modern atria are contained in the Hong Kong Shanghai Bank Tower, designed by Sir Norman Fosters & Partners, 1985; the Hong Kong Bank, 1989, and the Bank of China, Beijing, PRC, 2001, designed by E.M. Pei. When one includes open spaces associated with sports arena, shopping malls, and airline terminals; thus, buildings which include atria space number in the thousands. Such spaces, however, present a safety challenge for fire protection engineers because their height (typically greater than 20 m) decreases the effectiveness of conventional fire control systems such as automatic sprinkler systems. [2]

Conventional fire and smoke control systems use pressure differences across small openings and cracks in physical barriers as a means to restrict smoke propagation from one space to another and water-spray curtains to diminish or eliminate fire and smoke. Most USA fire codes depend upon the National Fire Protection Association (NFPA), guidebooks [3, 4]. In turn these propose the use of simple zone models that solve conservation of mass and energy in a control-volume sense for each zone. One weakness of zone modeling is that momentum conservation is only captured through use of loss coefficient at openings. The strength of zone or multi-zone models is that they are very fast compared with computational fluid dynamics (CFD) based models (e.g. ASMET, AZONE, CFAST, or CONTAM96 and CONTAMW) [5, 6].

Atria are examples of large spaces for which these conventional zone-model approaches are not always effective [7]. CFD, sometimes called "field-modeling" in the fire community to distinguish it from zone-modeling, has an unparalleled potential as an engineering estimator of fire consequence in atria since it permits specification of momentum conservation as well as much finer spatial and temporal resolution of the fire physics [8]. In addition CFD approaches provide a link between outside building weather conditions and fire and smoke development. This paper will consider a comparison of the results of calculations for an example building atrium based on zone (ASMET [9]) and field (FLUENT [10] and FDS [11, 12] CFD)-based models.

2 PRINCIPAL CONCEPTS

2.1 *Smoke Management Strategies*

Since atria do not have the compartmentalization that has traditionally been a major contribution to fire protection, smoke management rather than elimination by water sprays is of particular importance. The three management methods available are smoke filling, gravity venting, and smoke exhaust. The goal of smoke management is to provide for a tenable environment for the evacuation or relocation of occupants. Typically, the approach is to restrict any smoke spread to a plume rising from the fire and to a smoke layer just under the ceiling of the large space. The idea is to maintain a lower "smoke-free" layer for some specified time in which occupants can safely exit and fire fighters can see to contain and eliminate the fire. Design issues include pre-stratification preventing smoke from reaching ceiling mounted detectors or vents, smoke detection and number and placement of exhaust vents. The U.S. Uniform Building Code (UBC) specifies constraints on smoke barriers, pressurization methods, and equipment characteristics, but the choice of equipment must depend upon the actual dynamics of the fire, kinematics of the smoke plume, and specific geometry of the atrium.

2.1.1 *Smoke Filling*

This method only applies to very large volume spaces where the filling time is sufficient for evacuation, including time for fire detection, alarm and the movement of people to exits. It is presumed that smoke will not lower below a specified height above any evacuation route during a reasonable evacuation time (10 to 30 minutes). The presence of an unoccupied volume at the top of the atrium is essential to store smoke. Fire researchers have performed numerous experiments in open rectangular spaces to study the relative filling rates for different size fires using various fire sources and strengths [e.g. Poly U/ASTC Atrium in Hefei, PRC (30 x18 x 30 m high); or the Full Scale Fire Test Laboratory of the Japanese Building Research Institute (24 x 30 x 26.3 m high)]. Data produced by these facilities provide valuable opportunities to test alternate calculation methods and mitigation strategies.

The design of an effective smoke management system requires calculation of smoke mass flow rates and rate of descent of the smoke layer. A starting point might be the formulae found in NFPA 92B [3] or Klote [5]. For an axisymmetric plume scenario,

$$m = 0.071\ Q_c^{1/3}\ z^{5/3} + 0.0018\ Q_c\ , \tag{1}$$

where: m = mass flow rate in plume (kg/sec); Q_c = convective heat release rate of the fire (kW); and z = height from the base of the fire to the bottom of the smoke layer (m). This smoke will result in a descent of smoke from the ceiling at a rate specified by,

$$Z/H = 1.11 - 0.28\ \ln\{t\ Q_c^{\ 1/3}\ H^{-4/3}/(A/H^2)\}\ \text{and} \tag{2}$$

$$t = (A/(H^{2/3}\ Q_c^{\ 1/3})\ \exp[\ 3.57\quad (1.11 - Z/H)], \tag{3}$$

where: Z = height of the first indication of the smoke above the fire surface (m); H = ceiling height above the fire (m); t = time (s); and A = cross-sectional area of the atrium (m^2). This simple expression is for a fire whose strength does not vary in time, a plume that has no contact with the walls, and for a constant cross-sectional atrium area with respect to height. It is appropriate for A/H^2 from 0.9 to 14 and for Z greater than or equal to 20% of H.

Note that the mass flow production of smoke is not very sensitive to the convective heat release rate of the fire; hence, for a 50 m plume height and a nominal 2 MW design fire, a fire 1 MW smaller or larger would generate 22% less or 16% more smoke, respectively. But the smoke generation rate is a strong function of the total height of the plume (this is caused by enhanced entrainment rate of air as plume rises); thus, in a 15.2 m high atrium an atrium 5 m shorter or 5 m taller would have a predicted smoke generation rate 50% less or more, respectively.

The descent rate of the smoke filled zone is also a weak function of the fire strength. For a nominal 2MW design fire in a 50 m high atrium with A/H^2 equal to 1 after a time of two minutes a fire 1 MW smaller or larger would descend only 8% further or remain 12% higher at the same time after ignition. Yet, for the same fire strength, geometry and time if the atrium height is increased by 25 m or decreased by 25 m, then the smoke level above the ground varies from 50 m to 6.5 m, respectively. The latter situation would be unacceptable.

2.1.2 *Mechanical Exhaust*

If the smoke descends below a desirable height, then one mitigation strategy would be to use mechanical exhaust fans to remove a portion of the smoke filling the atria. Simplifying assumptions might be that the only mass flow into the smoke layer is the fire plume and the only mass flow from the smoke layer is the smoke exhaust, the exhaust is only removing smoke and not clean air, no heat transfer occurs to the atrium walls (adiabatic) and the exhaust rate applied holds the smoke layer height constant. In this case simple expressions would be:

$$dm/dt = 0.071\ Q_c^{1/3}\ Z^{5/3} + 0.0018\ Q_c \qquad \text{for } Z > Z_F \quad \text{and} \tag{4}$$

$$dm/dt = 0.032\ Q_c^{3/5}\ Z \qquad \text{for } Z < Z_F, \quad \text{and} \tag{5}$$

$$Z_F = 0.166\ Q_c^{2/5} \tag{6}$$

where dm/dt = mass flow exhaust (kg/s) and Z_F = mean flame height (m) [5].

Thus, to maintain a smoke layer height of Z = 50 m for a 2 MW fire would require a mass exhaust rate of 610 kg/s (or for air at ambient temperature) a volumetric exhaust rate of 500 m^3/s. For a fire 1 MW stronger or smaller, the exhaust rates would be13% higher or 20% lower, respectively.

Of course, the fire may be unsteady (growing or decreasing in intensity), spreading, radiating and convecting heat to the walls, and the exhaust fan may not exhaust immediately after fire ignition. In some cases the fan may result in "plug holing" or the removal of clean air from beneath the smoke layer actually aggravating the smoke situation. The location of the exhaust fan will also affect the symmetry of the plume depending on where it is located on the ceiling or sidewalls. The effectiveness of the fan may also be modified depending on the wind conditions outside the building. Wind impacting against the fan exhaust can inhibit fan efficiency significantly.

2.1.3 *Gravity Venting*

Smoke self ventilation or natural venting is common in many parts of the world (especially where external wind flows are expected to be minor). Natural venting relies on the buoyancy of the hot smoke to force smoke out of open vents at the top of the atria. The rate of venting will depend on the temperature difference between the smoke and the ambient outside air as well as the discharge coefficient of the exit. Mass venting will increase with increasing smoke temperature, exit vent size, and initially with lower outside temperatures. An appropriate expression would be:

$$(dm/dt)_n = C\ A_v\ \Delta_o\ [2\ g\ d_b\ (T_s - T_o)(T_o/T_s)]^{½}/[T_s + (A_v/A_i)^2 T_o]^{1/2} \qquad (7)$$

where: $(dm/dt)_n$ = natural mass flow through vent (kg/s); C = discharge coefficient; A_v = vent area (m^2); A_i = inlet vent area (m^2); d_b = depth of smoke layer below the smoke vent (m); and T_o and T_s are outside and smoke temperatures, respectively (°K) [5].

Given typical ambient air conditions, C= 0.6, a smoke layer 25 m deep beneath a 75 m ceiling, vent areas $A_v = A_i = 16\ m^2$ and $T_s - T_o$ = 20 °C, then $(dm/dt)_n$ = 45 kg/s. Notice this would not be sufficient to maintain a smoke layer height of 50 m height for the atrium considered initially! Indeed to achieve a mass exhaust rate of 610 kg/sec would require an exhaust vent area of about 220 m^2 or about 10% of the cross-sectional area of the atrium. For a fire larger than the design fire, the smoke temperature goes above the design value, and the mass flow rate automatically increases. On the other hand for air-conditioned atria, it is possible that the smoke temperature may be less than the outdoor temperature; in which case downward outside airflow could occur through the atrium smoke vents, which would aggravate the smoke hazard.

Often, a hot layer can form directly under an atrium ceiling due to solar radiation on the roof, or even radiation interacting directly with the air layer beneath a glass roof or wall. Temperatures in these regions may exceed 50 °C. In such a case a smoke free region may exist directly beneath the ceiling, which reduces the effective atrium volume available for smoke filling. This clear air region may also inhibit the operation of thermal or optical smoke detectors.

2.1.4 *Tenability Systems*

The systems discussed above have the goal of not exposing occupants to smoke at all during evacuation. This may not be realistic due to cost or other operational reasons; hence, a recent development in smoke management permits some smoke exposure as long as it does not decrease visibility below that needed to seek an exit or permit exposure to smoke and heat to exceed physiologically acceptable levels. A tenability system approach requires much more detailed information about temperature, smoke and velocity spatial distributions; hence, the volume averaged values acceptable for zone methods would not be adequate. This approach lends itself to the use of CFD calculation procedures [15].

2.2 *Modeling Methodologies*

Predicting smoke and flame behavior can be based on full-scale field experience, analytic integral approximations that capture the gross flow behavior, fine-scale numerical modeling and/or physical modeling at reduced scale...these methods are typically called full-scale, zone, field (numerical), and physical modeling, respectively.

2.2.1 *Zone modeling*

This method predicts the vertical descent of a well-mixed smoke layer continuously supplied from a fire plume. The method assumes there is a large volume available in which turbulence and relatively small lateral velocities distribute the heated gases into a homogeneous mixture. The analytic relations used are based on laboratory and field scale fires for a limited range of volume configurations typically unimpeded by interior stairways or other architectural elements. The fire initial condition relations used are specified by code stipulation. Popular codes provided by NIST include ALOFT (Smoke Plume Trajectory Model), ASMET (Atria Smoke Management Engineering Tools), CFAST (Compartment Zone Model), AZONE (Atrium Zone Fire Model), and the node net-work codes CONTAM96 and CONTAMW [5, 6].

Many factors can make a zone model prediction unrealistic. Special consideration must be given to situations where irregular atria cross-sections, balconies, walkways which bridge the atrium space, and make-up air vent locations deflect the fire/smoke plume causing it to contact atria walls or bathe balconies and walkway evacuation routes. High speed impact of the plume against a ceiling can result in lateral wall jets which may be deflected back down nearby side walls resulting in greater downward smoke penetration than anticipated from the well mixed approximation. Fire plumes deflected by makeup air may even produce fire whirls (fire tornadoes) within the atria. The generation of a fire whirl can increase the rate of combustion by factors of ten or more, and move the smoke plume erratically about the atrium volume [13, 14].

2.2.2 *Field Modeling*

CFD provides a design technique to examine the relative merits of various exhaust schemes and alternative locations of gravity vents or exhaust fans.[16, 17] Such programs can inherently consider irregular atrium geometry, heat transfer due to variable wall properties and radiation, time varying fire strength, affect of sprinkler operation, and time delays in vent or mechanical fan operation. While CFD represents a significant improvement in the predictive capability of smoke control modeling, uncertainties in the predictions remain. The smoke layer boundaries suggested by CFD simulations, just like those of the zone models, are best estimates, and as such have no conservativeness or "safety factor" built in. It is prudent to examine solutions to ensure that they are robust, that is that the flow patterns predicted are insensitive to small changes in boundary conditions such as at the makeup air supply openings, external wind environment, fire strength, and even fire location.

2.2.3 *Physical Modeling*

Another option to simulate smoke movement is physical modeling at reduced scale [19-24]. Froude modeling using either air or saltwater is probably the most common kind of physical modeling used for smoke transport, and NFPA 92B recognizes it as a method of analysis of smoke management systems for atria. Smoke movement away from the vicinity of a flame can be reproduced, but chemical kinetics, flame dynamics, and heat transfer scaling is not preserved. Unfortunately, due to scaling constraints it is difficult to simultaneously simulate buoyant plume movement within a building and wind induced pressure distributions about the external building envelope.

Hybrid physical/analytical/numerical methods are possible during which physical modeling can be used to define the external flow and pressure conditions outside a building, which specifies pressure coefficients at prospective building inlet and outlet vents. This data may then be used to set boundary conditions for zone or field model calculations. Meroney et al. demonstrated how this might be done to determine external heat transfer coefficients [19] or flow through permeable walls, cracks and finite wall openings during infiltration or exfiltration [20]. Such information would be extremely valuable for smoke mitigation situations where large external winds may negate the mitigation advantages of mechanical or natural venting.

3 NUMERICAL MODELING OF SMOKE AND FIRE

CFD models the airflow in an atrium by dividing the volume of the atrium into thousands of smaller spaces, called cells, and solving discrete approximations of the equations of fluid motion between each cell. Accurate solutions require cell sizes small enough to capture the flow phenomena being investigated, as well as the use of a suitable model for the turbulent mixing that takes place in the fire's plume and near obstructions. The use of CFD in smoke control modeling is described in more detail in Chapter 16 of Klote and Milke [19].

3.1 *CFD Codes Used for Fire and Smoke Modeling*

There are many general-purpose commercial CFD models that have typically taken tens of thousands of man-years to develop. These general models often contain features that permit solution of two phase flows, compressible flows, chemical reactions, discrete particle tracking, etc. These full-featured codes include attractive pre-processors to construct grids, specify chemical reaction expressions, and apply initial conditions, processing algorithms that permit segregated or coupled, steady or unsteady state flows and a variety of turbulence models, and post-processors that display results in a manner that enhance interpretation. Typical packages include CFD2000, CFX-4, CFX-5, CFD Taskflow, FLOW-3D, FLUENT, PHOENICS, STAR-CD, etc. (A list of currently available commercial packages can be found at http://www.icemcfd.com/cfd/CFD_codes_c.html).

There are also CFD models developed specifically for fire applications. The FDS (Fire Dynamic Simulator) model is a product of the U.S. government agency NIST (National Institute of Standards and Technology) [11, 12]. It is well documented and is in the public domain so that it can be obtained at no cost. Because it has been specifically developed for fire applications, it does not require that the user write computer code in order to make routine simulations. (Available at http://www.fire.nist.gov/fds/). Another fire specific CFD code called SMART-FIRE is maintained and licensed by the Fire Safety Engineering Group, Univ. of Greenwich, UK. (Available at http://fseg.gre.ac.uk/smartfire/index.html)

3.2 *Current limitations of CFD Codes*

Perhaps the most severe limitation of current CFD codes is associated with the complete simulation of the fire chemical dynamics over the range of scales that exist in a flame. Flame kinetics occurs over scales ranging from the microscopic molecular mixing and soot sizes 9-10 nanometers to the macroscopic 100 m fuel source scales encompassing 9-10 orders of magnitude. Currently large simulations, ~10^6 grid points, capture only about two orders of magnitude [8].

In addition a flame moves unsteadily and burning gases can rise buoyantly and continue to combust even though they are separated from the original fuel source. For example, during a fire whirl combustion flames are seen extending 10 to 20 times as high as in no swirl cases. Swirling suppresses the fire pulsations until much higher in the fire. The whirling tightens up the fuel core, stretches it, and limits the amount of oxygen available to consume fuel. On a coarse grid fuel and oxygen will mix purely because the coarse interface between fuel and oxygen smears out, and too much combustion occurs down low. To avoid such numerical diffusion a tight fine-resolution grid is required that would follow a long unsteady flame. Radiation dynamics can also be significant as heat is transported between gaseous volumes and nearby fuel surfaces. In many cases the associated errors are small, but in some situations they are not. A universal solver is not yet available.

In so far as is possible any CFD code should be verified for conditions close to the specific application. It is easy to achieve flow and temperature distributions which "look" quite reasonable, but which can be quantitatively in error. Small deviations in the geometry of a window opening have been known to change the discharge coefficient of the opening and the direction of the inlet flow sufficiently to completely change the motion inside a room [25].

4 BUILDING ATRIUM CASE STUDY

A case study has been chosen that considers an actual atrium that includes an exposed interior staircase, suspended walkways, open lateral hallways and lobby, ceiling skylights and wall exhaust fans, and other architectural features which made the problem more complex than a simple box-shaped volume. As atrium size goes the case study was small (~17 m cube), but it was within the range typically evaluated as atrium spaces. Continuous fire sources of 5276 kW and 2100 kW were considered as suggested by the NFPA 92B guide. Fire sources were placed alternatively in the lobby, basement and first floor regions of the atrium (see Figures 1 and 2). Steady state and temporal calculations were performed to determine fire kinematics, temperature distributions and smoke descent levels.

The ASMET zone model provided by NIST was used to initially calculate the mechanical venting required to clear smoke from the atrium [7 (Appendix E), 9]. The FLUENT CFD suite used during the authors' calculations provides an structured/unstructured mesh building pre-processor and a control volume based solver containing a variety of turbulence model options [10]. The gridded volume used during the Fluent calculations is displayed in Figure 3. The NIST-FDS program is also a control volume based solver with large eddy simulation (LES) turbulence models, but it uses a structured grid mesh [11] as shown in Figure 6.

4.1 *Modeling Results*

Zone model calculations using ASMET suggests that an exhaust rate of 90 m^3/s (200,000 cfm) would be adequate to limit smoke descent to regions 3 m (10 ft) above any walking surface within the smoke zone. But both the FLUENT and FDS models demonstrate that smoke would descend significantly below safe levels due to impingement of the fire plume against the ceiling that produced lateral jets that were, in turn, deflected downward by the atrium side-walls (see Figures 4 and 5 for Fluent results and Figures 7 and 8 for FDS results). Consideration of a wide variety of conventional inlet ventilation, ceiling skylight, and wall exhaust fan alternatives did not reveal a safe solution for this dilemma! Architectural changes to the ceiling region including the use of hanging porous curtains to reduce lateral jetting can mitigate the problem.

4.2 *Wind Effects*

Typically, the wind field outside the building is not considered when specifying fire hazard systems. Moderate winds can produce sufficient pressures on a building envelope to overwhelm the expected buoyancy driven internal flow patterns. While this has been acknowledged in smoke control literature [26], and is tacitly incorporated into some state building code (e.g. Ohio Building Code Section 909.4.3 reads "The design shall consider the adverse effects of wind..."), no formal method of performing an analysis of these wind effects is prescribed.

A simple technique discussed in section 2.2.3 above involves the estimation of the mean pressure coefficient (Cp) at the building's openings based on either typical Cp patterns for buildings of simple shape, free of upwind or downwind obstructions or a specific physical numerical simulation of the unique building geometry and its environment. Combined with knowledge of the local winds, wind pressures expected on the building openings can be estimated. Even this approach will not fully consider the interaction of fire plume driven flow fields and the external winds.

The primary concern for a natural ventilation exhaust is that the wind will push the smoke back into the atria or excessive wind driven makeup air will augment the fire combustion rate. On the other hand if the smoke outlets are located in regions expected to experience wind induced suction forces, smoke removal may even be enhanced.

Separate calculations that included the presence of a simple wind field impinging on the case study building exterior reveal that such conditions can significantly alter the trajectory of the fire plume and internal circulations (Figure 9).

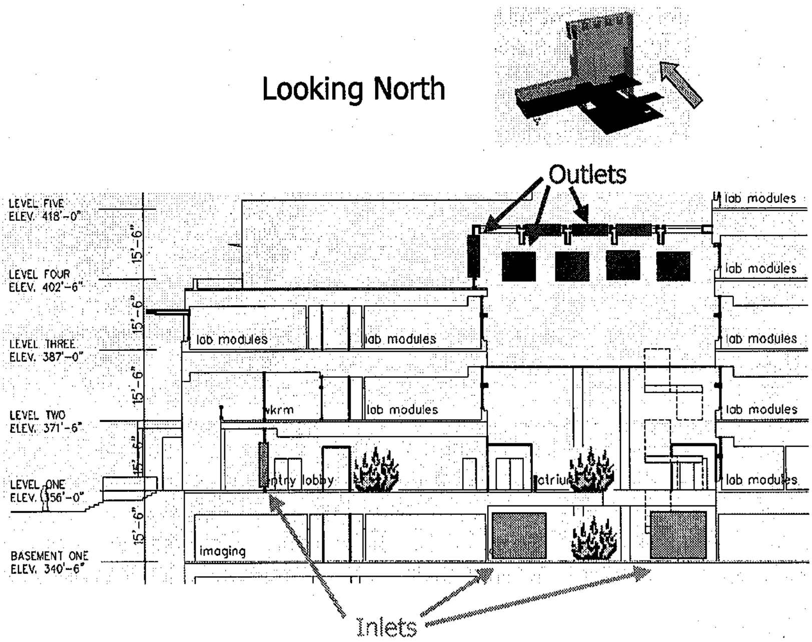

Figure 1. Model atrium viewed from north including fire locations in lobby, basement and first floor.

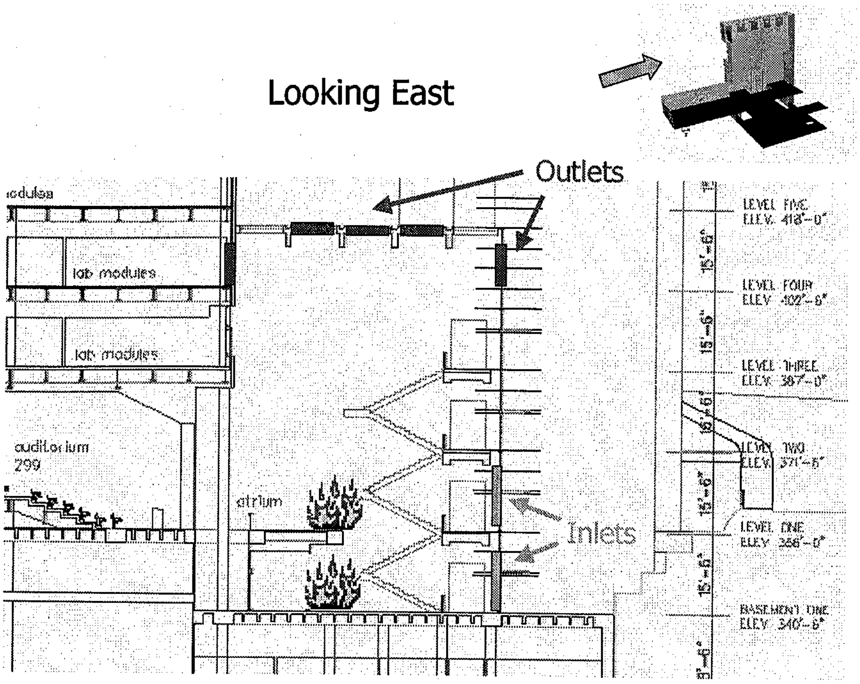

Figure 2. Model atrium viewed from east including fire locations in basement and first floor.

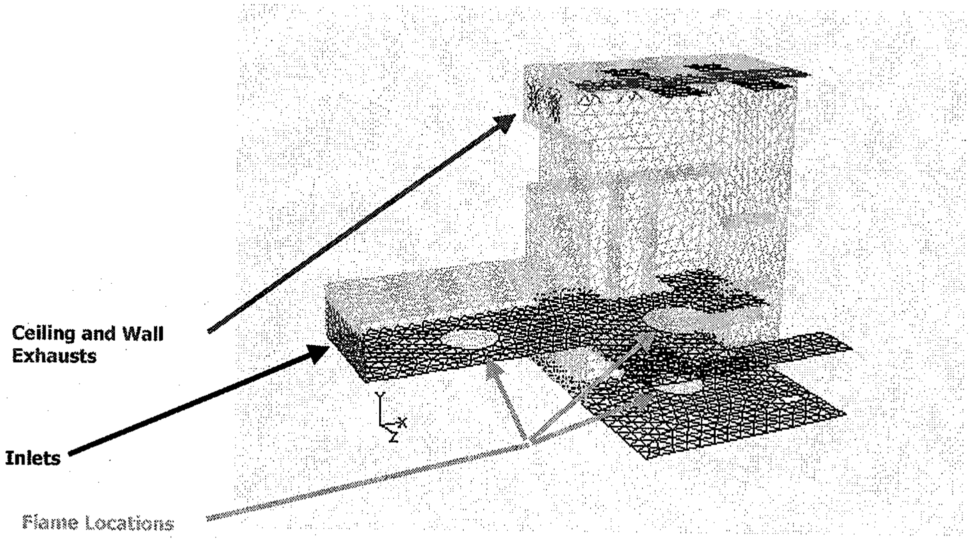

Figure 3. Differential volume used in Fluent, 36,817 unstructured tetrahedral cells. Turbulence model: kappa-epsilon RANS model

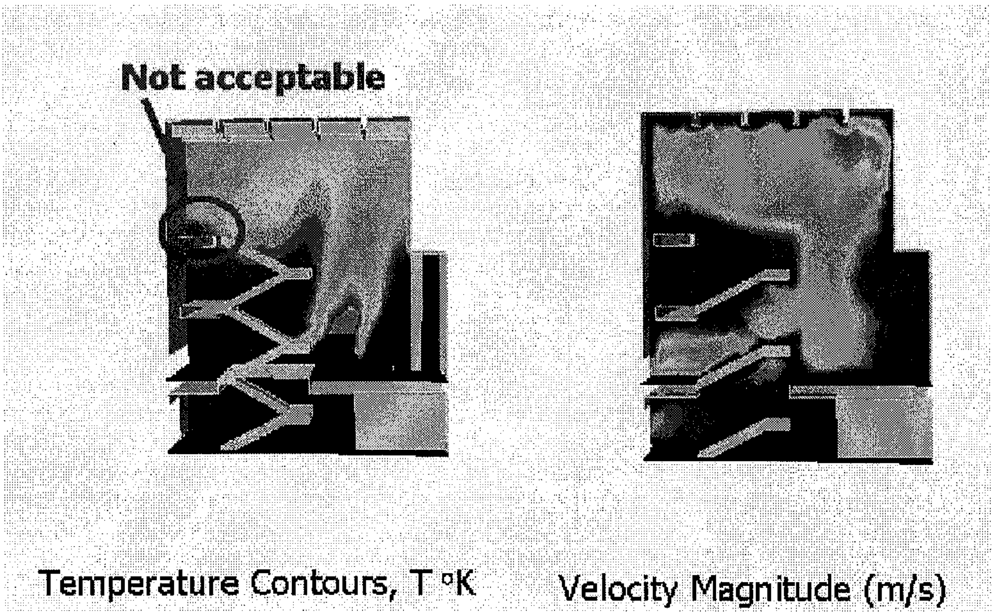

Figure 4. Fluent results for 5275 kW fire on first floor with 90 m^3/s (200,000 cfm) mechanical exhaust through ceiling fans.

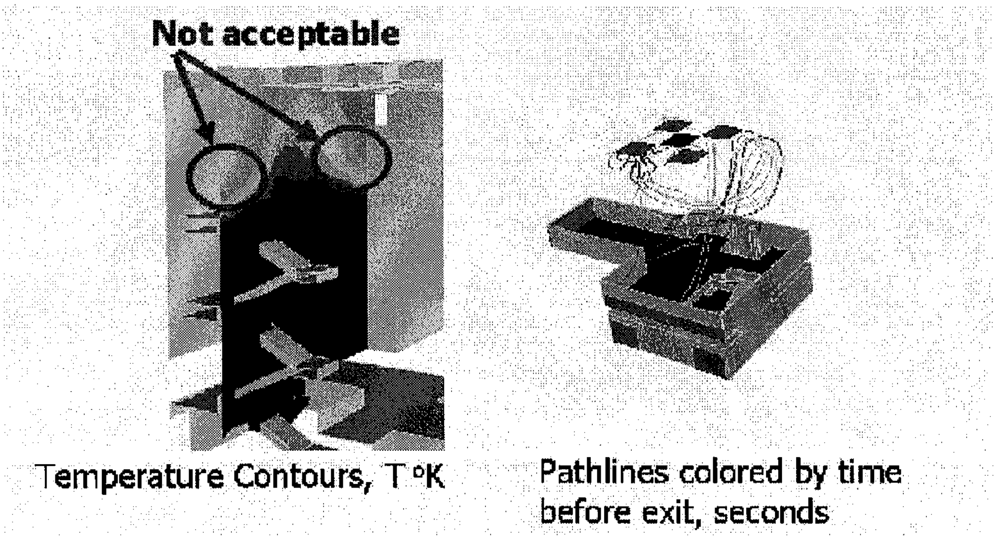

Figure 5. Fluent results for 5275 kW fire on first floor with 150 m^3/s (320,000 cfm) mechanical exhaust through ceiling fans.

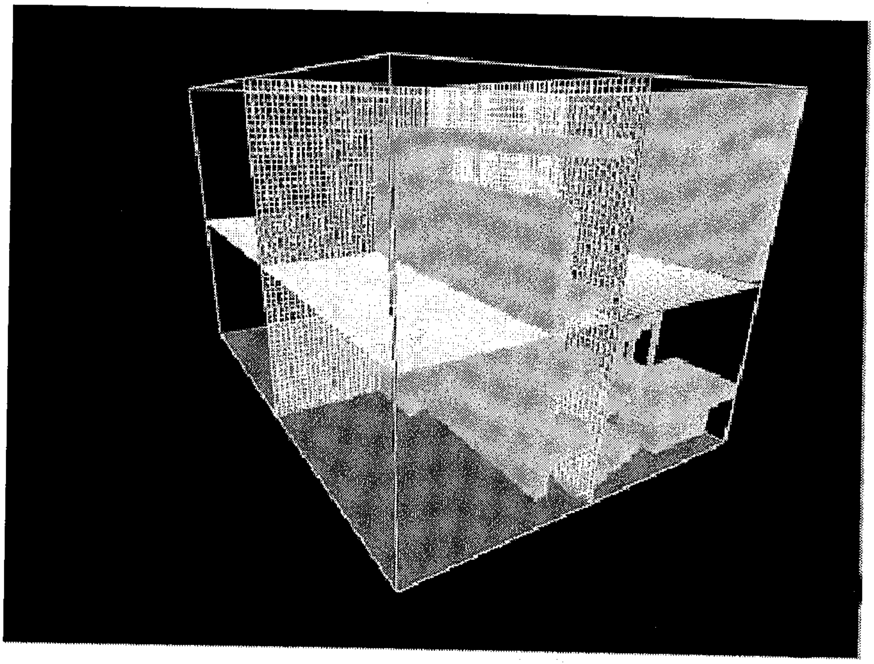

Figure 6. Differential volume used in FDS. 259,200 structured hexagonal cells on a rectangular grid. Turbulence model: Large eddy simulation.

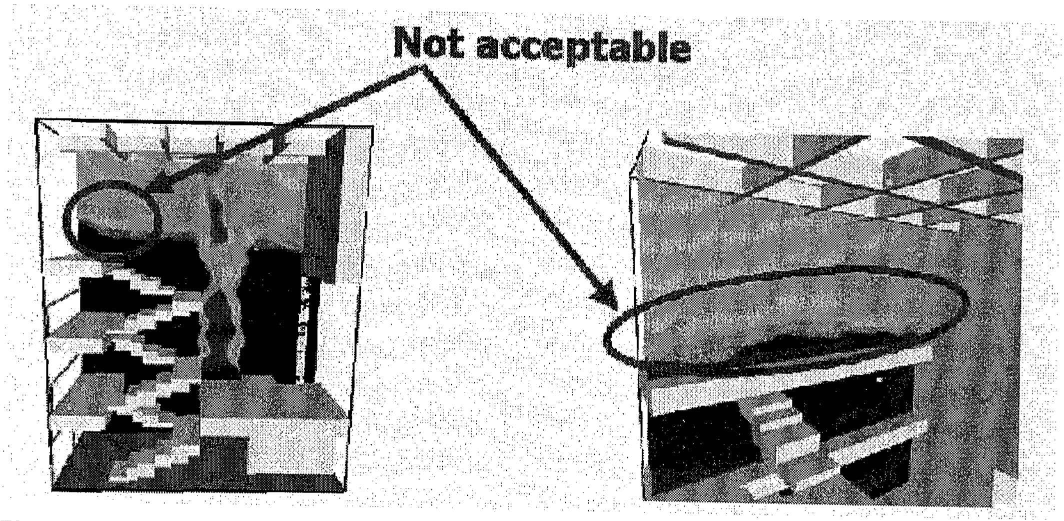

Figure 7. FDS results for 5275 kW fire on first floor with 90 m^3/s (200,000 cfm) mechanical exhaust through ceiling fans. Temperature contours °K.

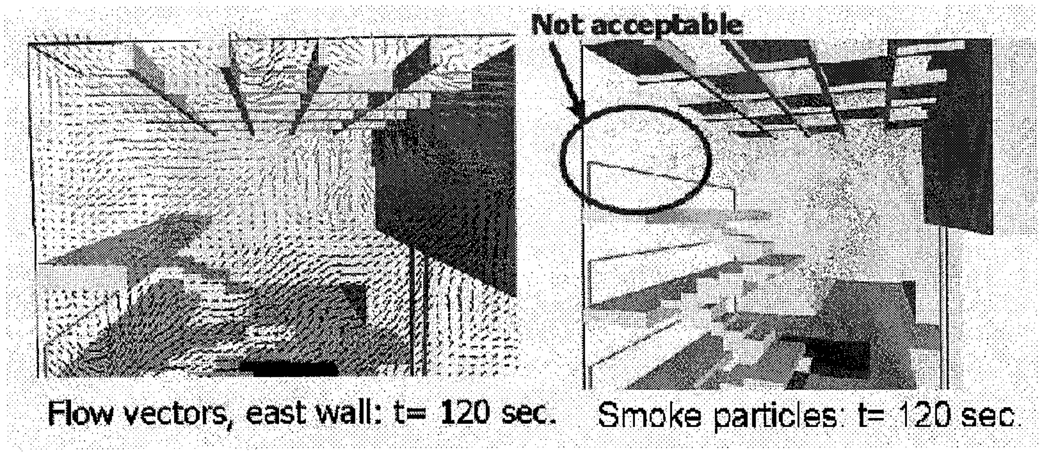

Figure 8. Velocity vectors and smoke particle distribution for FDS results for 5275 kW fire on first floor with 90 m^3/s (200,000 cfm) mechanical exhaust through ceiling and wall fans.

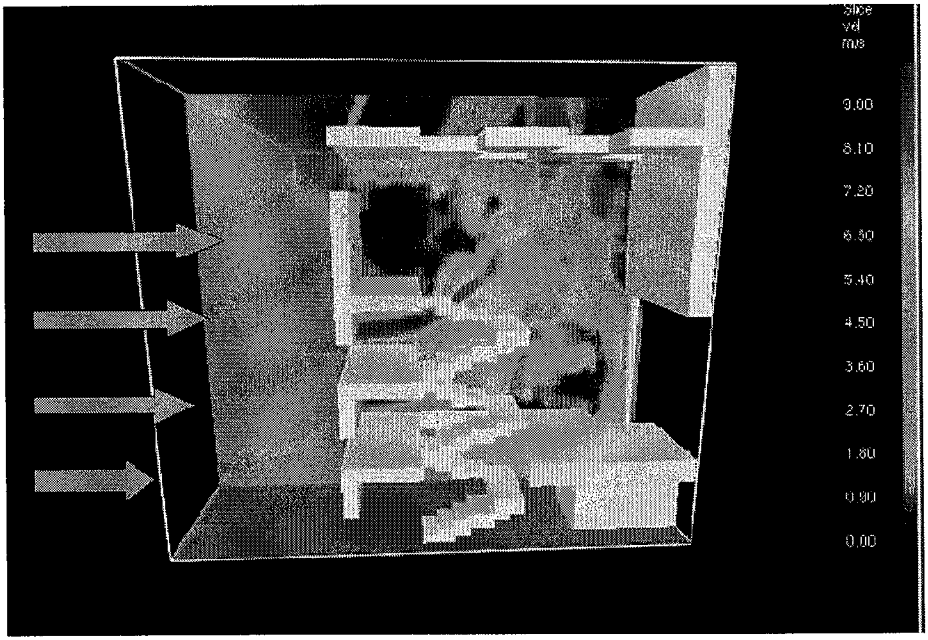

Figure 9. FDS results for wind effects on atrium circulation due to flow impinging on east face of model atrium No fire plume, but inlet and exhaust vents are active.

5 SUMMARY

Most fire-related deaths are attributed to smoke inhalation rather than burns. Also the reduction in visibility by smoke is a major hazard in atrium fires that needs to be considered in any smoke management design. Today fully enclosed empty space atriums (sterile tubes) are considered too restrictive from both design and use perspectives. In most modern designs the interior space is partially or fully connected to adjacent spaces, volumes are complex shapes, and cluttered with bridges, walkways, balconies and open elevators. Management decisions based on simple zone model approaches are no longer adequate; hence, field or numerical modeling is commonly applied. This review concludes:

- Simple zone models are not suitable for situations where smoke plumes can impinge on a ceiling and consequently produce wall jets downward,
- Simple zone models are not suitable for situations perturbed by inflow from external wind environments,
- Field modeling should include the study of the unsteady fire environment to detect any significant smoke plume instability such as a tendency to produce a fire vortex,
- Field modeling is not yet capable of modeling fire dynamics from the molecular to the macroscopic scales, and
- A hybrid combination of physical, zone and field model approaches permits the fire engineer to consider the influence of weather conditions outside the building envelope on a smoke mitigation strategy.

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