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TECHNOTES
ISSUE NO. 13

ATRIUM SMOKE MANAGEMENT SYSTEM DESIGN

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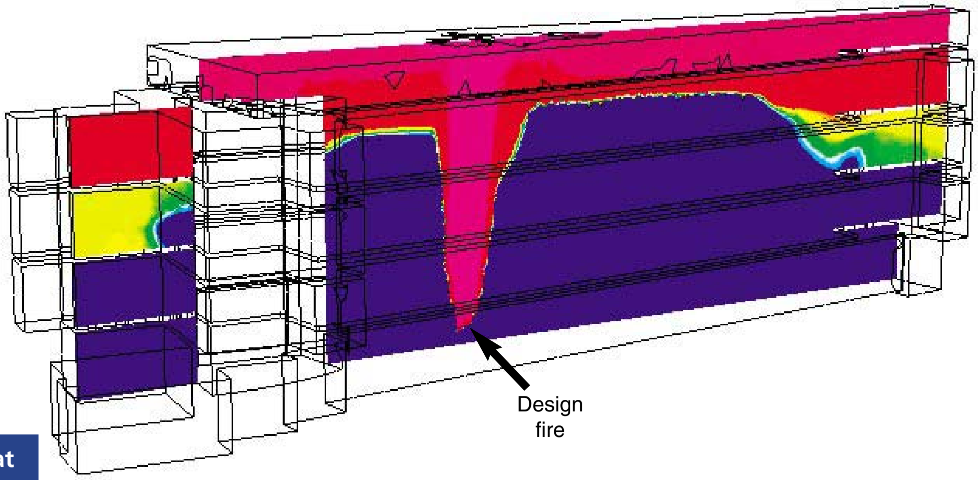
In large-volume spaces such as atria and covered malls, smoke management systems are often an important aspect of fire protection, with their primary goal being to ensure that the impact of smoke and heat on occupants is not life threatening (NFPA 92B[1]). This involves keeping the height of the smoke layer above the highest level of occupancy for a defined period, longer than the expected time to evacuate the building.



Impact of hot smoke shown at ends of a narrow atrium

Atrium smoke management relies on the buoyancy of hot smoke rising above a fire. As it rises, relatively cool ambient air is entrained into the plume decreasing the temperature and increasing the mass flow rate of contaminated air. Upon reaching the ceiling, the momentum of the plume is diverted into a jet which spreads the smoke over the ceiling area. Long travel distances and architectural features can cause further entrainment of air, adding to the smoke filled volume. Once the ceiling jet has covered the ceiling, the depth of the smoke layer increases until either the atrium fills with smoke or the rate of smoke entry into the layer is balanced by the rate of exhaust.

This article examines the usefulness of code-type calculations in providing initial estimates of smoke exhaust rates, even though there is a degree of uncertainty. Computational Fluid Dynamics (CFD) computer simulations are discussed as an alternative method of proving the capacity and performance of proposed smoke management systems.

DESIGN FACTORS

Sinclair[2] lists several aspects of the atrium smoke management problem that make it challenging to design and potentially costly to build. The paper notes that the height of the atrium and the architectural complexity are the most significant considerations. Also, having an unoccupied volume at the top of the atrium is essential to store smoke prior to the activation of the emergency ventilation system. This also ties into the need for a rapid detection and response of the smoke management system, plus the need for careful planning of make-up air locations and flow rates.

Make-up air must be introduced below the smoke layer and should not generate turbulence in the vicinity of the plume or smoke layer, since this would tend to increase the required exhaust rate. This often means that make-up air should be provided from a wide distribution of supply points over the lower levels of the building to keep air speeds below 200 feet per minute within the atrium. In some situations, make-up air can be used to provide a degree of protection for egress routes.

PRELIMINARY CALCULATIONS

The design of an effective smoke management system requires calculation of smoke mass flow rates and rate of descent of the smoke layer. It is particularly important to consider the time from ignition of the fire until detection, after which the system would be expected to control further growth of the smoke layer.

A starting point to estimate quantities of smoke from a fire is the empirical formulae listed in applicable building or fire codes, or the NFPA 92B[1].

Design fires may be located far from walls and other obstructions or under balconies. In NFPA 92B, these two situations are described as axisymmetric plume or balcony-spill plume scenarios, respectively. The following summarizes some key factors that affect the quantity of smoke predicted from a postulated fire scenario.

For the axisymmetric plume scenario, NFPA 92B equation (8) is:

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

where: m = mass flow rate in plume (kg/sec); Q_C = the convective heat release rate of the fire (kW); and, z = the height from the base of the fire to the bottom of the smoke layer (m).

The form of this equation indicates that the predicted mass flow rate of smoke is not very sensitive to the convective heat release rate of the fire (Q_C). In fact, it is proportional to the 1/3rd power of Q_C. This means, for example, that compared to a nominal 2 MW design fire, a fire 1 MW smaller or larger would generate approximately 22% less or 16% more smoke, respectively.

The NFPA equation (8) also has the smoke generation rate strongly proportional to the height z, being a 5/3rds power relationship. Compared to a 15.24 m (50 ft) high atrium, an atrium 5 m shorter or 5 m taller would have a predicted smoke generation rate approximately 50% less or more, respectively.

These trends may be useful to architects and engineers who look for ways to reduce the required smoke exhaust rate. If the architecture can be modified to allow the smoke layer to descend to a lower level there are potentially greater savings in the required smoke exhaust rate than trying to re-engineer the design fire to a lower heat release rate.

The NFPA equation (10) predicts the smoke mass flow rate for a fire located under a balcony, a situation that can generate significantly more smoke than the axisymmetric plume situation. This balcony-spill-plume equation has the following form:

$$m = 0.36\, (Q\, W^2)^{1/3}\, (Z_b + 0.25H)$$

where: Q = the total fire heat release rate (kW); W = width of the plume as it spills under the balcony (m); and Z_b is the height above the balcony (m) to the base of the smoke layer.

The plume width parameter W, affects the predicted plume mass flow rate by a 2/3rds power. This means that if W is doubled in size then the smoke mass flow, m, will be about 60% greater. In practice, it is difficult to estimate W. Usually the best one can do is estimate a range of values of W to use in the calculations. This introduces a high level of uncertainty in the predicted exhaust rates.

DETAILED DESIGN CALCULATIONS

Although code-type calculations are useful early in the design of the system, their level of uncertainty is often unacceptable to the design team because of significant capital cost impacts on sizing the emergency ventilation system. Designers and the authority having jurisdiction are also concerned about whether the smoke management system will perform as expected, since most atria are not simple shapes. No one wants delays in receiving acceptance of the design or occupancy permit, or the potential for costly retrofits.

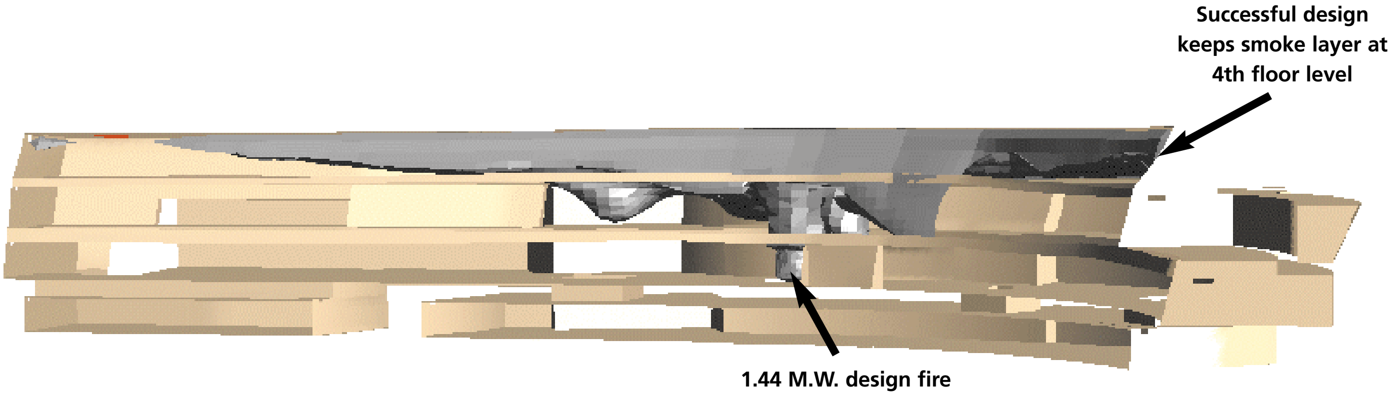


Figure 1: CFD predicted smoke impact in a 400 foot long atrium

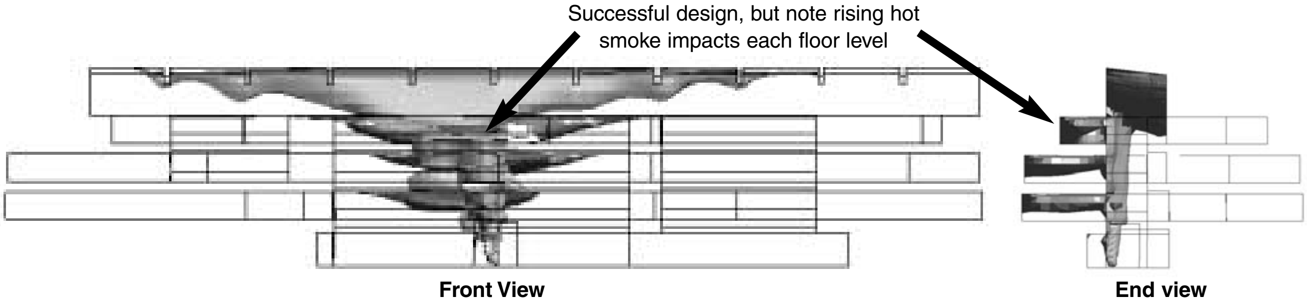


Figure 2: Narrow atrium 12 minutes after ignition of the design fire

One of the best tools to evaluate smoke management system performance more accurately for large-volume spaces involves computer simulations based on Computational Fluid Dynamics (CFD). With a CFD model, the geometry of the space is divided into thousands of brick-like cells over which the fundamental equations of fluid flow and heat transfer are solved. The actual combustion process is not as important as predicting the effects of smoke and heat in the space and how to best manage it. Therefore, CFD models usually represent the fire as a volumetric heat source with a soot emission rate. It is common practice to ignore radiation heat transfer from the fire and conduction heat transfer through all surfaces, but it is important for the modeller to develop methods to correctly predict plume growth rates.

EXAMPLES OF CFD SMOKE ANALYSES

This section presents the application of CFD smoke modelling in three office building atria. The three are similar in height, but the shapes are different. All three have either balcony walkways or floor slabs open to the atria.

LONG ATRIUM

Figure 1 shows part of a large office complex with a 4-storey atrium and attached gymnasium. The curved atrium is approximately 122 m (400 ft) long, 11 m (36 ft) wide and 17.7 m high (58 ft). It has a glass front facade and balcony walkways at Levels 3 and 4.

The unusual shape and size of the atrium raised concerns about the smoke management system. The code did not adequately address: balcony spill plumes occurring at the openings in the Level 2 floor slab; turbulence generated in the smoke plumes by the Level 3 and Level 4 balconies; the impact that the geometry has on smoke filling at the ceiling/roof; and the ability for fans located at the opposite end from the fire to provide useful exhaust capacity.

Early feedback from RWDI allowed the design team to easily modify their design to ensure that the fourth floor walkway was declared unoccupied space, since it was essential to have a smoke reservoir at the top of the atrium. As well, this lowered the target height of the base of the smoke layer which lowered the required exhaust rate.

A second recommendation provided early in the design was that the nominal designed capacity of the emergency ventilation system was too low when based on a code-minimum level of 6 air changes per hour. An initial CFD simulation confirmed the design team's concerns since the entire atrium filled with smoke in minutes. This lead to the revised design shown in Figure 1, based on a balcony spill-plume fire condition. The exhaust system was designed with 11 smoke exhaust fans of 28,000 cfm each and the gymnasium was given a total of 96,000 cfm. Make-up air is provided through the front facade windows at the lowest level of the atrium and some distributed mechanical supply.

The final design was proven successful in keeping the average smoke layer height at or above the unoccupied 4th floor walkway.

NARROW ATRIUM

In this example, the architecture of the building presents a 5-storey atrium, again long and narrow. The atrium is about 91 m (300 ft) long and 6 m (20 ft) wide, with open connections to occupied office space.

The smoke management system has an exhaust capacity of 200,000 cfm uniformly distributed along the atrium skylight with mechanical make-up air supplied on all floor levels through the normal supply diffusers. The system is assumed to be activated within 45 seconds of the ignition of the design fire, based on the proposed detection systems.

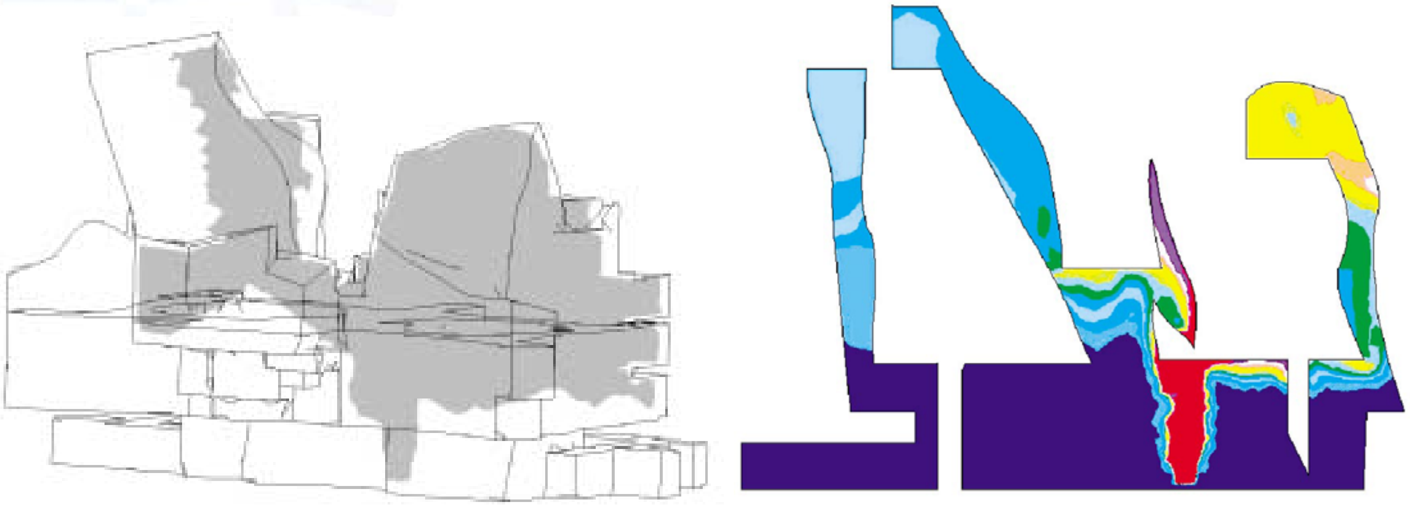
Figure 2 shows the predicted final position of the smoke layer, achieved at approximately 12 minutes into the unsteady simulation. This shows that the proposed smoke management system is acceptable. The success of this final design was valuable to the design team which had found the initial design did not pass.

During the CFD smoke study, the design team had benefitted from: establishing realistic goals for managing smoke, which included recognizing that there would be areas on each occupied floor level that would not be tenable; gaining agreement from the owner to restrict fuel loads at the base of the atrium; providing more rapid detection systems; providing a widely distributed make-up air system; and establishing a sufficient exhaust rate.

COMPLEX ATRIUM

Figure 3 shows the complex architecture of an atrium space that starts from a common footprint and evolves into two distinct, irregular-shaped towers, each equipped with its own exhaust fans. Unlike a typical atrium, the space has meeting rooms almost entirely encapsulated by the volume of the six-level atrium. Approximately 70% of the required make-up air is provided by supply fans bringing outside air into the lowest levels of the atrium with the remainder coming through door openings on the first floor or ground level.

The design fire of 2.43 MW was located at the base of the atrium, under a meeting room floor slab approximately 9.15 m (30 ft) above the base of the fire. Code-type calculations predicted smoke exhaust rates between 300,000 cfm and 500,000 cfm. The design team had serious challenges to accommodate such high exhaust rates, primarily because of the relatively high cost of the make-up air system and emergency power. CFD model tests were performed to determine if satisfactory performance could be achieved at lower exhaust rates. In the final design, Figure 3 shows that the CFD model demonstrated that an exhaust rate of 240,000 cfm could keep the average height of the smoke layer above the +8.22 m (+27 ft) design height. This resulted in significant cost savings over the design that had been based on code-type calculations.



Final smoke layer position **Predicted air temperatures in vertical cross-section**

Figure 3: Complex atrium

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1. NFPA 92B, 2000, Guide for smoke management systems in atria, covered malls, and large areas. Quincy, Mass.: National Fire Protection Association.

2. Sinclair, J.R., "CFD Simulation in Atrium Smoke Management System Design", presented at the ASHRAE winter meeting, Jan 27-31, 2001, Atlanta, GA.

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