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Chapter 1

SMOKE AND FIRE DYNAMICS IN ATRIA AND LARGE ENCLOSURES: AN OVERVIEW

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ABSTRACT

The proliferation of atria within modern large buildings is relatively recent. An atrium can be defined as a large open space connecting two or more storeys. Atria are important architectonical features since the 60's and can be found, among others, in shopping centres, office buildings and high-rise buildings, airports, stations and sports centres. However, the atrium represents an innovative, complex and non conventional architectonical element that can lead to fire environments diverging significantly from those in conventional compartments used in the development of current codes and standards. They are a source of discussion in the fire safety community because smoke can easily spread from one floor to another making the traditional methodologies for compartmentation of little or null effect. The design of smoke management in atria has been based on prescriptive codes since the 70's. It was not until the mid 80´s that the phenomena started to be the objective of both experimental and numerical studies. It is because of the subsequent improved understanding on fire dynamics and smoke management together with the increased computing power available nowadays, that there is a progressive movement from prescriptive-based to performance-based codes which is

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also chaning the way atria are designed. The aim of the present work is to provide a broad overview of the current state-of-the-art of fires in atria. A brief introduction to the characteristics and types of atrium structures is presented first. Then, a description of the fire dynamics as well as the main safety problems that arise in case of fire are considered. A historical discussion of the research, including experimental and numerical studies, is presented, and current design methodologies and fire safety strategies are discussed. The final part of the overview addresses the international tendencies towards the introduction of performance-based fire protection codes. This overview highlights the need for further experimental studies and validations of numerical simulations for a wider range of fire conditions.

1. INTRODUCTION

The atrium form was originally used in ancient Greece and Rome where it was an uncovered internal roof opening [1]. The atrium was open towards the sky with inward sloping roof pitches and incorporated a central pool, the "implivium", to which the rain water was drained. Its function was that of a central meeting space coupled with passive moderation of the building's microclimate. The opening to the sky provided ventilation and allowed daylight to enter the building. In addition, the central pool provided evaporative cooling in the hot Mediterranean summer. This uncovered form was extended in traditional Arab architecture to create a layer courtyard space. Courtyard spaces were covered with glass in wrought-iron frames during the 19th century, when these materials became widely available as a result of the Industrial Revolution. In the 19th and 20th century, the possibility of creating glazed surfaces led to an alteration of the atrium concept allowing the central space to be made weather proof and habitable in less favourable climates.

The modern origins of the atrium can be traced back to the construction of the Hyatt Regency Hotel in Atlanta in 1967 by John Portman [2]. In the 80's the typical atrium was positioned in connection with a shopping centre or the like and the function was primarily to act as a circulation area and to form the basis of a recreational area for the customers with green plants, fountains and cafes. In the 90's it became more and more common to build atria in connection with other kinds of buildings like office buildings, libraries, hospitals, etc.

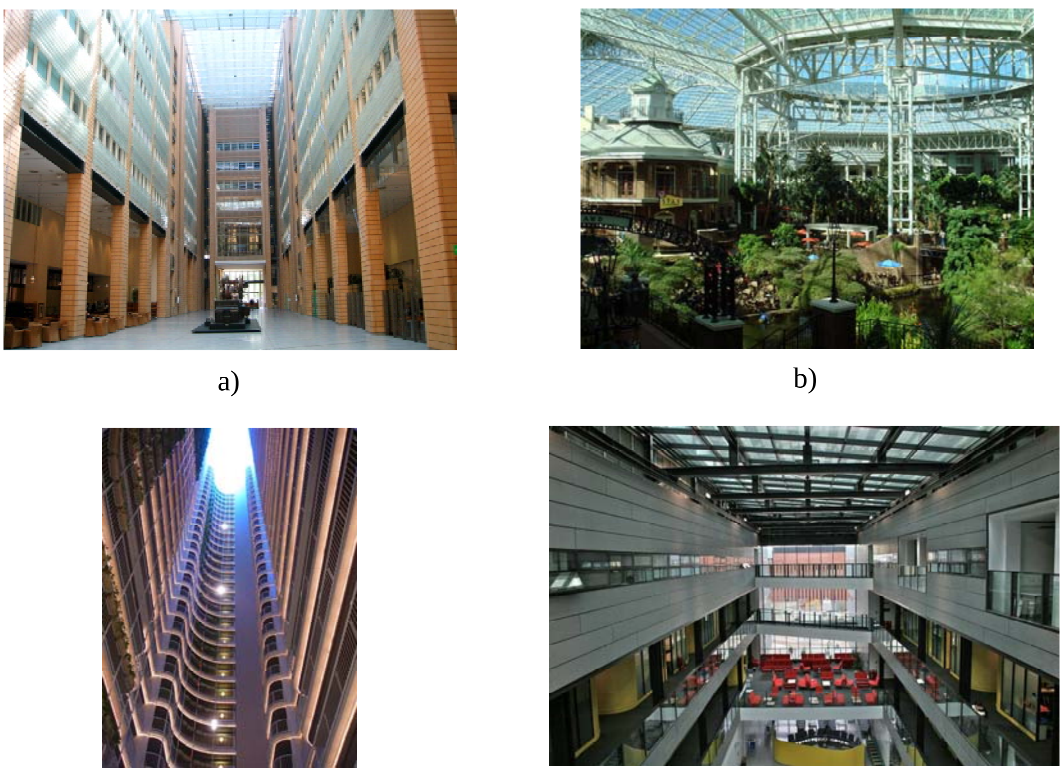
Nowadays, an atrium is a pleasant, all-weather gathering place that provides shelter from the more extreme climate conditions outside. Its use has significantly extended, becoming a common feature in modern constructions and can be generally found in hotels, commercial buildings, shopping centres, office blocks, mass transport stations, airport terminals and auditoria, among others.

Modern atria, see Figure 1, are designed with the aim of providing an indoors environment that feels like a visually and spatially external environment [3], reviving the indoor space by admitting natural light, simulating the outdoors and increasing people interaction. Atria have been reported to increase the marketing values of many buildings.

A good atrium building design could effectively reduce the overall energy consumption of the building and enhance the quality of the indoor environment [4, 5]. They provide good daylight penetration to the adjacent rooms, with increased visual comfort and could reduce electrical power for artificial lighting as the consequences. They could help to reduce the heat losses from the building because of the compact design. There is also an energy consumption reduction for ventilation due to the use of the stack effect for natural ventilation.

Atrium buildings appeal to people not only technically and aesthetically but also psychologically by providing an indoors connection to the outside. By bringing natural light into the interior, atria offer larger, more efficient floor areas than conventional buildings. Atria provide more desirable work environments by providing more space with a connection to natural daylight and the outside environment. Many believe that access to natural full spectrum lighting could create a more healthful and productive environment [6, 7].

The aim of this work is to present an overview of the state-of-the-art of the main topics in atrium fire safety. Specifically, it introduces the characteristics and types of atria, the threats to safety when a fire takes place and the strategies to control smoke. It is beyond the scope of this overview to be exhaustive on the details of the atrium fire dynamics or the discussions of fire safety features. The reader interested in these details can find further information in references [8-16].



a) b) c) d)

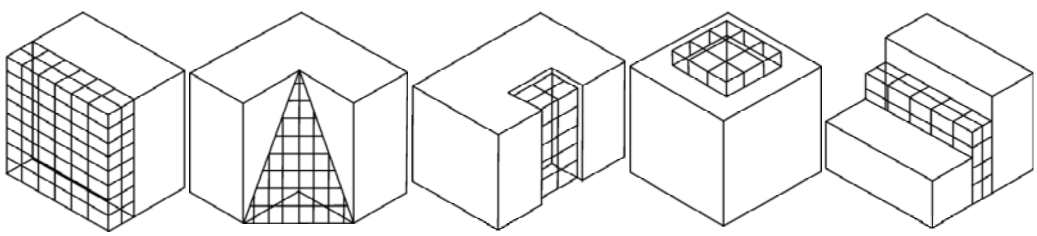
Figure 1. Examples of modern atria: Debis-Haus (Berlin)(photo of Public Domain) in a; Gaylord Opryland Resort & Convention Center (Nashville)(GNU Free Documentation License) in b; The Grand Doubletree (Miami)(Creative Commons (CC)) (photo taken by Marc Averette) in c; Alan Turing Building (Manchester) (photo by Mike Peel)(Creative Commons (CC)) in d.

2. Atrium Definition

In general terms, an atrium within a building is a large open space created by an opening or a series of openings connecting two or more floors. Other definitions of atria can be found in different codes and regulations. For example, the NFPA 92B [9] defines an atrium as a large volume space created by a floor opening or series of floor openings connecting two or more stories that is covered at the top of the series of openings and is used for purposes other than an enclosed stairway; or other mechanical and utility service to the building. The International Building Code (IBC) [10] defines it as an opening connecting two or more stories other than enclosed stairways, elevators, hoist ways, escalators, plumbing, electrical, air-conditioning or other equipment, which is closed at the top and not defined as a mall.

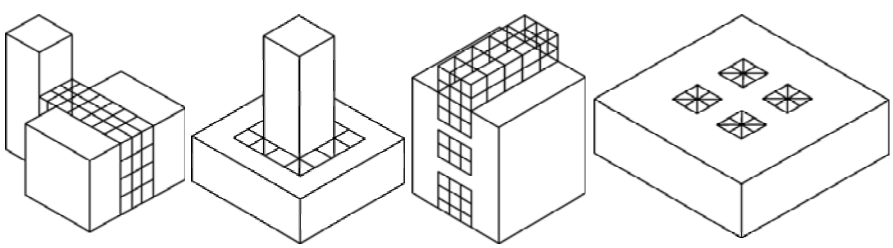
3. Atrium Typology

There are many different designs of atrium buildings. They could be classified, e.g., by their configuration, their construction or their use.



a) Single sided b) Two sided c) Three sided d) Four sided e) Linear

Figure 2. Typology of simple atria [17].



a) Bridging b) Podium c) Multiple lateral d) Multiple vertical

Figure 3. Typology of complex atria [17].

The shape and geometry of an atrium are both the products of and reasons for the adjoining occupied portions of the building. The atria' configurations can be divided into simple and complex [17]. Five main simple configurations could be defined, see Figure 2:

- Single sided: atria that adjoin one side to the occupied portion of the structure.
- Two sided: atria that adjoin two sides to the occupied portion of the structure.
- Three sided: atria that adjoin three sides to the occupied portion of the structure.
- Four sided: atria that adjoin four sides to the occupied portion of the structure.
- Linear: atria sandwiched between two occupied portions of the structure.

Four main complex configurations could be, then, defined, see Figure 3:

- Bridging: when the atrium connects several occupied portions of structure.
- Podium: when the atrium sits at the bottom or below an occupied portion of structure.
- Multiple lateral: when atrium spaces are scattered throughout plan on single or multiple stories.
- Multiple vertical: when atrium spaces are scattered throughout the height of the tower structure.

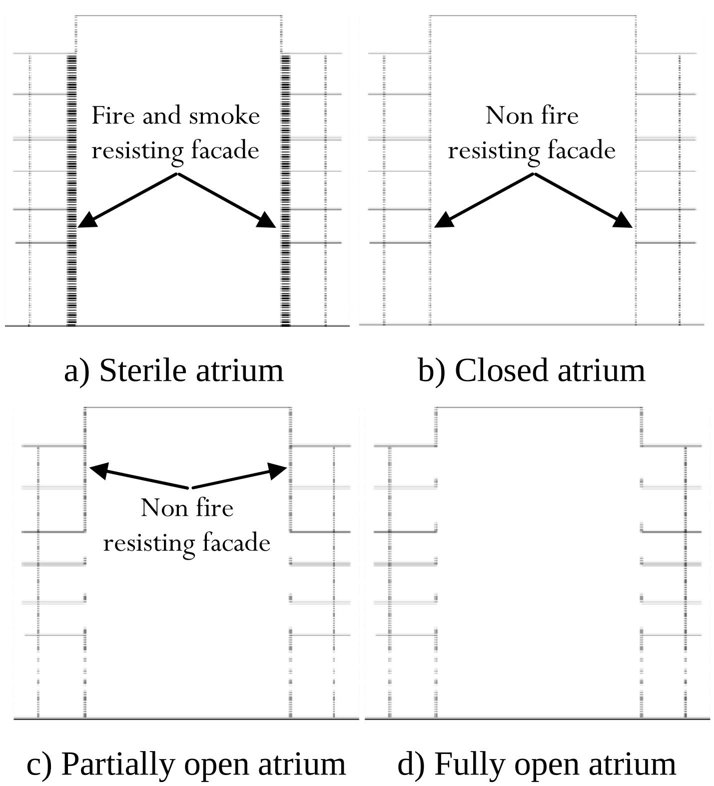


Figure 4. Atrium typology according to the enclosure.

By their use and type of occupants, atria could be classified into different categories [18]:

- Category A. Occupants who are awake and predominantly familiar with the building. This includes office buildings.
- Category B. Occupants who are awake but unfamiliar with the building. This includes shopping centres and most public assembly buildings.
- Category C. Occupants who are likely to be asleep. This category includes flats, halls of residence and hotels.
- Category D. Occupants requiring nursing or medical care. This includes hospitals.

Taking into account the type of enclosure and fire safety, see Figure 4, Morgan et al. [11] categorised atria into:

- Sterile tube atrium, that is, an atrium in which its space is separated from the remainder of the building by a façade which is both fire and smoke resisting. In this case, the façade acts as a barrier to fire and smoke spread between the atrium and the adjacent spaces. The ideal sterile tube atrium would contain no flammable material on the atrium floor. The atrium space would generally have no functional use apart from as a circulation area for the occupants of the building.
- Closed atrium, that is, an atrium separated from the remainder of the building by a non fire resisting façade. This façade may not necessarily be smoke resisting. The atrium space may possibly have a functional use (e.g. restaurants).
- Partially open atrium, that is, an atrium in which there are communicating spaces between the atrium space and the adjacent areas on some of the lower storeys. A non fire resisting façade provides separation between the atrium and adjacent areas on the upper storeys.
- Fully open atrium, that is, an atrium that contains large openings between the atrium and adjacent areas on all storeys.

In general, the atrium design can be very complex and innovative; however, the basic configurations remain recognizable.

4. Atrium Fire Dynamics and Safety Problems

The use of atria has become a common feature of modern architecture. However, such spaces present a challenge for the fire protection engineers because their height decreases the effectiveness of automatic sprinkler systems and because they lack the floor-to-floor separations that can limit the likelihood of fire and smoke spreading from the floor of fire origin to other areas of the building. Furthermore, evacuation routes in atria are of greatest concern because they become vulnerable to spreading smoke.

When a fire takes place in an atrium or a large enclosure, hot gases rise above the fire forming a plume [19, 20]. The internal openings and heating and ventilation systems allow the fire and smoke to spread towards other parts of the building and into the surrounding atmosphere. Thus, the smoke can travel large vertical distances, affecting multiple floors simultaneously. The hot smoke emitted from a fire will rise up due to buoyancy. As the plume rises, it entrains air from the room so that the diameter and mass flow rate of the plume increase with elevation. Air entrainment has the effect of increasing the mass flow of gas but also dilutes the smoke and lowers the smoke temperature. The fire gases from the plume flow up to the ceiling. Upon reaching the roof, a ceiling jet is formed. Smoke will then spread radially from the fire axis, eventually giving a smoke layer. The building concerned is then divided into two layers: an upper hot smoke layer and a lower cool air layer. The hot gases can also flow through openings in walls to other spaces.

As commented before, as the atrium layout intrinsically does not allow for vertical compartmentation, fire and smoke could spread to interconnected floors making their control really difficult to achieve. Moreover, detection, control and extinction of fires in atria differ significantly from those in small enclosures. Thus, a proper understanding of fire dynamics and smoke movement at this kind of structures is essential for providing the scientific understanding required for the design of fire-safe structures. Specific requirements have been included in building codes for atria [21-23]. Besides, many approaches to smoke management in atria have been developed and provided in standards and engineering guides [9, 11, 24]. However, it is still needed to continue studying all the phenomena that appear in case of a fire within an atrium or an adjacent space affecting the atrium to close some gaps that the knowledge on this subject presents nowadays.

There can be many different fire scenarios, see Figure 5. Depending on these variables the smoke production rate will vary. They could be grouped into three main categories of fire scenarios:

The first fire scenario considers a fire located in the floor of the open space. Within this fire scenario, there could be three different sub-scenarios of smoke plumes. The first is the axisymmetric plume. This is the plume of a fire located near the centre of an atrium floor. This type of plume is typically remote from any walls and air is entrained around all sides of the plume. Entrainment of air will occur over the full height of the plume until it reaches the interface with a smoke layer which may have formed above. Morton et al. [25] developed a classic analysis of the time averaged flow of plumes. The analysis of axisymmetric plumes for turbulent plumes due to fires in buildings has been studied by different authors like McCaffrey [26], Heskestad [27] or Cetegen [28]. The second kind of plume is the wall plume. This is a plume generated from a fire against a wall of the atrium. Wall plumes can only entrain air from half of their perimeter. Zukoski [29] developed a wall plume entrainment correlation based on entrainment of each mirror symmetry. Poreh and Garrad [30] have studied this more recently. Finally, the third configuration of smoke plume is the corner plume. This is a plume generated from a fire located in the corner of an atrium. Zukoski [29] treated corner plumes in a similar manner to a wall plume with the use of double mirror symmetry.

The second fire scenario considers a fire located in a space adjacent to the atrium or pedestrian space. In this case, the smoke flows horizontally through a compartment opening and subsequently under a balcony before entering the atrium space and then rising at a spill edge forming a plume. This phenomenon is known as a spill plume [31]. In case of fire in an adjacent sprinkled retail space in which the fire does not spread out of it, three different phases will be observed [32]: fire growth and sprinkler activation, steady fire and decay. During the fire growth phase, the sprinklers will be activated and hot smoke will flow into the atrium space. During the steady phase, hot smoke will continue to flow into the atrium forming a smoke layer at the top. During the decay phase, the smoke temperature will decrease to near or below ambient temperature. This cool smoke will be mixed throughout the fire compartment and spilled through the opening and descended into lower areas of the atrium.

The third fire scenario considers a ventilation-limited fire that is located in an adjacent space and the smoke enters the atrium through a window (which could have been broken by the fire) or doorway. In this case, a plume which flows from the opening into the atrium space [33] is formed. This plume is known as window plume. Typically, window plumes are generated from post-flashover fires [34]. An entrainment correlation was developed by Heskestad, by comparing the air entrainment for a window plume with that of an axisymmetric plume. Klote and Milke [33] obtained as well a correlation for window plumes. This fire scenario can be reduced to a spill plume case.

For further information on fire dynamics see [19] and [20].

5. Fire Strategies and Design

Protecting the occupants of a building during a fire is the primary objective in the design of a fire protection system. As an atrium is an open design linking many floors, a fire started on one floor could lead to smoke spreading to other parts of the building via atrium.

It is generally known that smoke inhalation and suffocation are often the main causes of deaths in an indoor fire [35, 36]. Smoke is defined as the airborne solid and liquid particulates and gases evolved when a material undergoes pyrolysis or combustion, together with the quantity of air that is entrained or otherwise mixed into the mass [19, 33]. Thus, efficient smoke control systems are essential to preserve occupants' lifes and facilitate fire fighting actuations. Smoke control systems designs for atria are complicated due to the large number of factors affecting their performance. Five design objectives were given by Milke [37] for smoke control systems in atrium buildings:

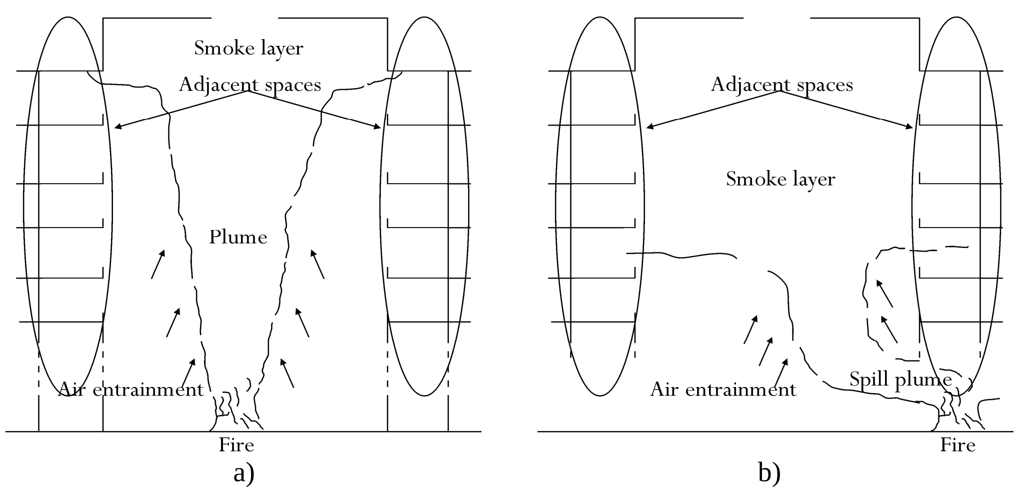


Figure 5. Main fire scenarios. Atrium fire, in a; spill plume, in b.

- Maintain a tenable environment in the atrium during the time required for evacuation. The smoke exhaust system should ensure that the height of the smoke layer is kept above the highest level of the occupants for a defined period of time, so as to allow sufficient time for evacuation from the building.
- Confine the smoke in the atrium to a limited region in that space.
- Limit the migration of smoke into adjacent spaces from the atrium.
- Provide tenable conditions for fire fighting [38] to assist the emergency response personnel in conducting search-and-rescue operations and locating and controlling the fire.
- Contribute to the overall protection of life and reduction in property loss.

Atrium smoke management systems have been included in some building codes since late 70's and early 80's. At the beginning, the requirements were based on air change rate methods, that is, based on the volume of the atrium. The smoke exhaust capacity for atria and shopping centres was stipulated by some codes to be 4 to 6 air changes per hour [39-41]. Later, requirements to restrict the descent of the smoke layer started to be specified. It became apparent that the volume-based air change per hour method of determining the smoke exhaust capacity did not relate to provision of steady and high smoke layer. In the 90's, new approaches for designing the capacity of smoke exhaust fans based on the necessity to prevent the descent of the smoke layer below a determined height, that is, maintain a certain clear height, were developed, e.g. in the first edition of NFPA 92B [42]. An overview of this technical guide was performed by Milke [37].

Approaches to smoke management in atria have been introduced into codes and engineering guides [33, 43-46]. For example, in 1994, Klote [47] presented different correlations that could be used to predict the smoke movement for the design of atrium smoke management systems, explaining the physical concepts behind the NFPA 92 [42]. These approaches have the zone fire model concept as a common foundation and consist of a collection of algebraic equations intended for design calculation. Klote warned about the limitations of the approach and the range of applicability of the equations presented. Klote also suggested the use of CFD analysis for design purposes.

The clear height is the vertical distance between the level of the fire and the base of the buoyant smoke layer in the atrium. The design clear height will usually provide a layer with a safe height above the highest egress route. This clear height will provide a tenable environment for safe egress for the duration of the evacuation. The clear height can differ depending on the code. For example, the NFPA 101 [46] stated that "a clear layer height of 1.85 m must be achieved above the highest floor level of exit access open to the atrium for a period of 1.5 times the calculated egress time, or 20 minutes, whichever is the greater". The Building Officials and Code Administrators (BOCA) National Building Code [48] established as design criterion that the smoke management system had to keep "the smoke layer at or above 1.828 m" for not less than 20 minutes. More recently, some authors [49] have located the clear height as the bigger value of the 20 % of the atrium height and the common design figures of 3 or 4 m.

The approach of maintaining a minimum clear smoke height could be considered a conservative strategy as it is assumed that all smoke is inherently hazardous and needs to be avoided. In tall atria, the smoke exhaust capacity to maintain the smoke layer above a determined level for a safe egress can be very large if that level is near the top of the atria. The air entrained along the plume that increases the mass flow of smoke also dilutes it, decreasing the smoke concentration and temperature to a level that could not be a threat to safety. Thus, Milke [50] indicated that a cost effective design for an atrium smoke management system that causes people to be exposed to the dilute non-lethal smoke might be suggested. A maximum effective smoke exhaust rate could be identified by conducting a hazard analysis for people or contents immersed in the residual smoke layer. Milke listed the 'hazard parameters' to take into account when evaluating the design objectives of the smoke control system: Smoke layer depth, reduced oxygen levels, visibility through the smoke layer, carbon monoxide concentration and temperature rise in the smoke layer. Milke stated that an acceptable smoke control system was one which maintained the hazard parameters of concern to within acceptable levels. This methodology was based on the algebraic correlations included in NFPA 92B [51] for equilibrium conditions. It was found that the visibility reduction was the most demanding parameter for flaming, well-ventilated fires. The visibility depends on the combustible materials involved and the conditions of combustion (Chapter "Visibility and Human Behaviour in Fire Smoke" in [15]). There are two reasons for the decrease in visibility through smoke: first, luminous fluxes from a sign and its background are interrupted by smoke particles and reduce its intensity when reaching the eyes of a subject, and second, luminous flux scattered from the general lighting of corridors or rooms by smoke particles in the direction of a subject's eyes is superimposed on the reduced flux mentioned first. A reduction in visibility is not self-sufficient to cause harm but makes people more susceptible to tripping over obstructions or reduces their walking speed, thereby increasing the amount of time that they are exposed to the other effects of smoke [52, 53]. However, it has to be noticed that this analysis was based on strong simplifications as it was used a zone model approach which has limitations, e.g. the conditions in the upper layer are considered to be uniform. In addition, the analysis was performed assuming the entire fire involved a single fuel with a characteristic value for the parameters.

In terms of designing smoke control systems, there are a number of different smoke control strategies available for atrium buildings [11, 33, 51]. Morgan et al. [11] describe various alternative approaches such as:

- Smoke filling

  This approach consists of accumulating the smoke at the upper part of the atrium. It can be applied to atria which have large volumes, such that smoke ventilation may not be necessary. This strategy becomes viable when smoke can be safely contained away from occupants in a roof void for the duration of the required safe egress time for the occupants of the building.
- Smoke clearance

  This approach provides sufficient ventilation to remove smoke from the atrium after the fire has been suppressed. No action is taken during the fire. This can only be applied to smoke filling strategies.
- Smoke and heat ventilation

  This approach uses the buoyancy of the combustion products from the fire to form a layer above the occupants of the building, providing a safe means of escape. Smoke and heat will exhaust from the ventilators in the roof of the enclosure either by natural or mechanical means. For the smoke ventilation to be effective, it is necessary to provide an adequate amount of inlet air.

- Ventilation control by temperature

  This strategy can be applied when the height of the smoke layer above the floor is not a critical design parameter. The smoke exhaust is used to maintain the temperature below a given safe threshold. This approach allows the use of building materials which would otherwise be damaged by hot gases.

- Smoke and heat ventilation from each storey separately

  If the height of the atrium is very large, it may be beneficial to prevent smoke from entering the atrium altogether. This can be achieved by the use of strategically placed smoke curtains around the atrium space at each storey, and providing smoke exhaust ventilation from each storey separately.

- Depressurisation

  This approach consists of preventing smoke from travelling through the adjacent spaces by reducing the pressure of the gases in the smoke layer (suction of surrounding air). This technique does not provide protection to the atrium space. This technique is similar to that employed for natural ventilation in atrium buildings [54].

- Pressurization

  This approach is related to the previous one although it consists of raising the air pressure inside spaces that serve as evacuation routes, such as corridors and attached rooms, and vertically connected spaces through which smoke spreads to the other stories, with fresh air during a fire, and prevents smoke from entering into the spaces by positive pressure differences.

  Airflow could be used to prevent smoke flowing from a fire in a communicating space to the atrium and also can be used to prevent smoke flowing from the atrium to the communicating space. In case of airflow, the air needs to be exhausted from the communicating space.

- Hybrid smoke control

  This approach consists of the combination of different strategies from the discussion above. For example, the ‘smoke and heat exhaust ventilation from the atrium’ approach and the ‘smoke and heat exhaust from each storey separately’ [55] approach were compared by Xiong [56]. The results showed the reliable performance and easy control of the former method but its relatively low effectiveness when a fire is located adjacent to the atrium and the fire size is very large. For this last case, the second method was more effective. However, it was not effective in extracting smoke from the atrium. Yin [57] suggested a combination of both methods, that is, a hybrid smoke control system.

Draft or ‘smoke’ curtains can also be used as part of a smoke system design. They are vertical walls that deep in the enclosure certain distance from the ceiling creating smoke reservoirs underneath it that not only limit the spread of smoke but also allow the smoke to build up a buoyancy pressure below the ceiling which will enhance the flow though a vent.

In addition to these smoke control strategies, there are also safety strategies to provide quick detection and also to reduce fire growth, including the installation of automatic sprinklers and limitations on the quantity of combustible materials used in the construction of the building and located on the area of the atrium. For further information on fire safety strategies see [9, 11, 24, 33, 46].

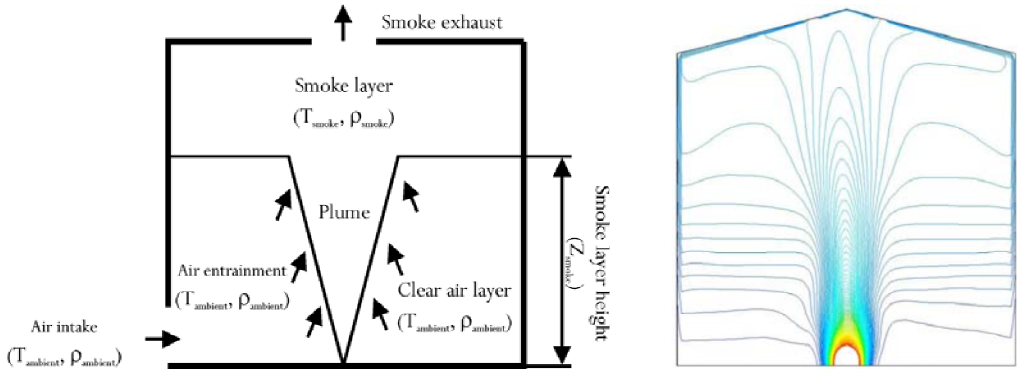
6. Computer Modelling

In terms of smoke control design, nowadays there is a movement towards performance-based design and the extensive use of computer models. Numerical models are important engineering tools [58] and for the study of fires within large enclosures. There are two main different types of numerical models: the zone models [59-62] and the field models [63-66], see Figure 6.

The zone model approach divides the area of interest into a number of uniform zones, that when combined, describe the area of interest as a whole [67]. Normally, there are two distinct zones: the hot upper smoke layer and the lower layer of cooler air. Within each of these zones, the pertinent conservation laws (e.g. mass and energy), in the form of mathematical equations describing the conditions of interest, are solved. However, these models neglect the momentum equation within a zone, because they assume that flow within a layer is quiescent. Additional equations can describe other physical processes, such as fire plumes and radiative, convective, and conductive heat transfer. The plume acts as an enthalpy pump between the lower layer and the hot upper smoke layer. In the field models approach, the fire compartment is divided into a large number of elements or control volumes and the conservation equations are solved inside each control volume. This allows for a more detailed solution compared to zone models.

The zone model approach was the first used [68-70]. A large number of the correlations in codes [51] were based on it. However, in the mid 90's it was not clear whether this kind of studies could be applied for simulating fires in big volume buildings. There were still some problems to be considered. One of these problems was, and is still, whether a steady and uniform smoke layer, separated from the lower clear air layer, is formed in the upper level of the atrium. Another issue was that the hot upper smoke layer had not a uniform temperature but higher temperatures are observed closer to the fire, the plume and at the higher locations. The validity of the entrainment equation for some conditions was also another problem identified. Additionally, the codes developed were usually for buildings with specific sizes and shapes. When the shape or the ratio between the dimensions deviates from the standard size, the equations used in the code may not be suitable [71].

CFD models started to be developed fast in the 90's [72]. Because of the thermal gradient present during fires in large enclosures, a field model can, in principle, be more appropriate for complex geometries where zone models do not accurately describe the fire phenomena. In the beginning, they solved only a natural convection problem good only for predicting the flow field driven by buoyancy for distances away from the fire source [72]. Neither the combustion nor the radiation heat transfer processes were solved, e.g. fire was simulated as a source releasing heat and smoke. Later, sub-models of combustion [73, 74], radiation and turbulence [64, 65, 75] explicitly to model fire, started to be developed. With the inclusion of more accurate models together with the increasing computing power and resources, more accurate results were predicted, making them more reliable.



a) b)

Figure 6. Sketch of the two layers assumed in a zone model, in a; temperature contours calculated by a field model, in b.

Numerical studies comparing the zone models and field models performance [71, 76] have been carried out. In general, it was observed that field models provided a more detailed representation such as transient and special development of the plume and its interaction with the ceiling, ceiling jet and walls. Thus, the field model has been proposed to substitute the zone model to develop fire safety strategies, although zone models are applicable for quick and reasonable estimations of the smoke layer height and temperature, and field models are yet not free from inaccuracies. For further information on CFD simulations see [67].

7. Sprinklers and Smoke Detectors

While the use of smoke detectors and sprinklers is not directly a smoke management method, this forms part of the overall fire safety strategy. For an efficient smoke control strategy, it is very important to identify the smoke and fire source as rapidly as possible. It is also important to control and reduce the fire spread and growth. For this, sprinklers are the most widely used mechanism, and they have been recommended in various parts of the world (e.g. USA, Canada, etc) [21, 77]. By limiting the size of fire or by extinguishing it prior to the fire service intervention, the requirement for smoke management is reduced. Furthermore, it is argued that the operation of sprinklers would reduce the probability of windows breaking.

Sprinklers are effective in suppressing fires in floor spaces with limited ceiling heights [78] but they may not be effective in suppressing fires in space with ceiling heights greater than 11 or 15 m or in controlling fires in atria exceeding 20 m in height, e.g. because of delayed response. Chow [79] indicated that there were three key issues to be considered when assessing the performance of an atrium sprinkler: the possibility of actuating the sprinkler in a pre-flashover fire, the thermal response of the sprinkler head and the interaction between the water spray and the smoke layer. The last, when the sprinkler head is activated, the smoke is cooled by the discharged water and loses buoyancy. This together with the drag from the water cloud, pulls the smoke layer downward and can result in adverse effects on the occupants that are inside the atrium. If a smoke exhaust system is installed, its effectiveness could be affected. Furthermore, it has been argued that while sprinklers will reduce the temperature of the fire gases, the amount of smoke generated may be more hazardous in respect to the levels of carbon monoxide [80]. Benefits achieved by limiting the fire size, and hence lowering temperatures and expansion and buoyancy forces, may be offset in part at least by higher volumes of cooler smoke, possibly containing greater concentrations of hazardous gases [78, 80]. All this makes critical the decision of installing sprinklers in a high ceiling atrium or not.

The first studies on sprinklers and smoke detectors date back to the 70's. At that time, Degenkolb [81, 82] found the ability of sprinklers to suppress fires in spaces with ceilings higher than 11 to 15 m limited. Since the temperature of smoke decreased as it rose, due to entrainment of colder ambient air, smoke may not be hot enough to activate sprinklers mounted under the ceiling of an atrium. Even if such sprinklers activated, the delay could allow fire growth to an extent beyond the suppression ability of ordinary sprinklers. This study put forward the possibility of the formation of a hot layer of air at the upper parts of the atrium, due to thermal stratification, preventing the smoke of a weak plume from reaching the ceiling. This applies to small fires or very tall atria. This could cause the smoke detectors to fail. The use of beam smoke detectors was suggested instead. The reduction on effective exhaust for relatively thin smoke layer was also noticed. Some other studies concerning predictions of smoke movement and temperature in tall spaces are those by Notarianni and Davis [83] and Walton and Notarianni [84]. In 1994, Chow and Chau [85] and Tamura [86] noticed that automatic sprinklers installed at the atrium ceiling could not be effective in controlling fire in an atrium exceeding 20 m in height.

In 1997, due to the lack of scientific data regarding the behaviour of heat and smoke in ceiling heights over 9.1m [87], Gott et al. [88] carried out experimental full-scale tests to determine the behaviour and response time of fire detectors and sprinkler heads to increasing sizes of fire. Thirty-three full-scale experiments were conducted in two Navy high bay aircraft hangars, of 15 m and 22 m high, using JP-5 and JP-8 as combustion fuels. The heat release rate ranged from 100 kW to 33 MW. The effects of draft curtains, ambient temperature, shape of ceilings and open versus closed hangar doors were also analyzed. Regarding fire detection, they found the spacing between spot-type heat detectors to be up to 12.2 m without reduction in response time. Respect to sprinklers use, only the quick response heads proved to be effective. The use of draft curtains was also advised because they increase the number of sprinklers activated and decrease their response times due to smoke and flow of heat control. The correlations [89] used to predict sprinkler activation proved unsatisfactory due to the thermally stratified hot air upper layer and the ceiling jet. Further researches were found needed to improve these correlations.

Chow [90] indicated that activating the sprinkler head by hot smoke at adjacent high-level shops could draw smoke to the floor level. Lougheed and McCartney [32] conducted a study to address the concerns that smoke cooled by the sprinklers in retail spaces connected to malls could travel downward, where it could endanger people evacuating the building. Full-scale test were carried out in a mechanically ventilated atrium. The results indicated that, during the growth and steady phases, the smoke entering the atrium area was hot enough to rise towards the ceiling. During the steady phase, the visibility in the upper portion of the mall and its carbon monoxide concentration both exceeded tenability limits. Any accumulation of this smoke in exit routes could limit evacuation. Thus, a smoke management system using mechanical exhaust could be used to remove the smoke. During the decay phase of the fire scenario, the visibility for the smoke in the secondary space approached or exceeded tenability limits. However, the extent of the smoke zone was limited and occurred after occupants should have evacuated the fire zone.

Yin and Chow [91] applied the fire modelling technique to investigate the response time of the sprinkler heads installed in a 10 m high atrium ceiling due to a fire in an adjacent shop in a high level. For this study, a two-parameter sprinkler response time model was combined with a fire model. Fires from 0.4 MW to 2MW were studied. Comparisons with experimental data [32] found good agreement. They stated that, if the atrium height was much higher than the normal compartment (e.g. 3 m), the temperature of the smoke generated by the fire on the floor could not be high enough (e.g. higher than 68 ºC) to activate the sprinkler. However, for a fire located near the top of the atrium, the sprinkler could be activated very quickly (e.g. within 200 s) even by a small fire, less than 400 kW.

An important concern is whether sprinklers on atrium ceilings would operate and be effective. As commented before, deciding not to install a sprinkler system is critical as there are few alternative fire protection systems. The Mountain Star Group [92] performed a study in which the no installation of sprinklers in high ceiling facilities was suggested. For this study, fire tests in a 29.6 m high stadium were conducted by means of using a 2 m squared heptane pool-fire. It was indicated that a 15.5 MW fire on the floor failed to activate any ceiling sprinklers. However, in a relatively recent work, Nam [93] studied the actuation of sprinklers in high ceiling clearance facilities. Nam analyzed sets of both growing and steady fires to estimate the maximum ceiling heights from given fire sources that would allow actuation of ceiling sprinklers. For this issue, the data from fire experiments in a 18.3 m high ceiling at the FM Global Test Center [94] were used, with the fire located directly under a sprinkler. Then, the minimum fire power that would activate ceiling sprinklers at a given ceiling clearance was calculated. It was shown that deciding the threshold fire size based on a pool-fire, which was a common practise in [83, 88], was not advisable as it might lead to flawed designs.

Nowadays, some engineering guides assume that, unless there is information to indicate otherwise, the effect of sprinklers on the design fire size can be accounted for by assuming that the fire stops growing when sprinklers are actuated and continues to burn at that size until all the fuel is consumed. This assumption cannot be backed up currently for atria and large facilities.

More research is needed to resolve the four atria issues identified, where current understanding is incomplete, that is, smoke detection, sprinklers activation, sprinklers effectiveness to control a fire at the atrium floor and cooling of smoke during sprinklers actuation. These are important topics related to fire safety in atria. For further information of the topic see [11] and the Chapters “Design of Detection Systems” and “Automatic Sprinkler System Calculation” of [15].

8. THE PROCESS OF SMOKE FILLING

The first scenario considered for fire safety within an atrium studied was a vast simplification of a real fire scenario, only including the built up of the smoke layer and putting aside the other phenomena. This was the smoke filling process and related smoke spreading mechanisms. In the first tests, the fire considered was located at the centre of the facility to avoid interactions with the adjacent structures, and thus, generating an axisymmetric smoke plume. Yamana and Tanaka [95] performed one of the first experimental studies. Smoke filling process and natural and mechanical venting were studied. They conducted full-scale fire experiments in an atrium located at the Building Research Institute, Japan. The atrium was a seven-level atrium of 30 m × 24 m × 26.3 m. The fuel burnt was methanol with a heat release rate of 1.3 MW. They also examined theoretically [68] the smoke filling process, for the unvented and the mechanical vented atrium, developing a method for computing the smoke layer descent based on the concept of virtual point for air plume entrainment. Comparison with experimental data showed fairly good agreement. The data from these studies have been widely used in other works for comparison or development of methods [96], normally based on empirical equations for mass of air entrained by the rising plume of hot gases. Hagglund et al. [97] carried out full-scale experiments on a Cubic Hall of 5.62 m × 5.62 m × 6.15 m in Sweden. In these experiments, the fire sizes were varied from 0.25 m × 0.25 m to 0.75 m × 0.75 m, thermal power 70 to 630kW. They varied the height of the fire above the floor level from 0.2 m to 4.5 m, hence varying the smoke filling time.

These kind of experimental studies were really scarce in the beginning. Most of the studies were analytical and numerical studies based on the concept of two zones [70, 98]. However, as commented before, there were doubts about their accuracy. After different studies [71, 76, 99] the field model was proposed to substitute the zone model for predicting the smoke layer temperature and clear heights, although, despite the zone models were proved not to be very accurate, they were found applicable for quick estimation of the probable smoke layer height and temperature induced by a fire in an atrium.

The use of numerical models and correlations is important and useful. However, they have limitations and need to be improved. A real fire is the most realistic method of testing a smoke control system. Real fire tests of atria smoke management systems became common in Australia in the 90’s [100]. These tests were carried out using ethyl alcohol pool-fires of 1 to 5 MW. Most of the fire safety design guides for atrium buildings were not well supported or validated by large-scale experimental studies [101, 102]. New experimental studies on smoke filling were to come, like the one that Dillon [103] conducted in a Large Enclosed Stadium by using a propane fire of 5 MW.

In the mid 90’s, the full-scale burning facility PolyU/USTC Atrium [104] was constructed in Hefei, China. This atrium, with inner dimensions of 22.4 m × 11.9 m × 27 m, has been source of numerous full-scale experiments for studying natural smoke filling, natural ventilation, smoke extraction, sprinkler systems in high ceiling spaces and fire detection systems. Different full-scale experiments on natural smoke filling process were carried out. Chow et al. [105] carried out forty hot smoke tests with two different diesel pool-fires of diameters of 0.6 and 1.0 m respectively. The estimated heat release rates were 265 kW, for the 0.6 m pool, and 440 kW, for the 1m pool. Transient mass burning fuel, descending time of smoke and transient vertical temperature distributions near the walls were measured. A smoke filling model describing the descent of the smoke layer was developed, based on the axisymmetric plume equation proposed by Zukoski et al. [106] , and compared with the expressions from NFPA 92B [102]. The agreement between the results with the NFPA 92B equations was not very good due to its limited range of applicability. Since the temperature rise of the previous tests was small, due to the low heat release rates of the fires, later experiments were conducted with higher powers of 654 kW [107] and 1.6 MW [108]. Again the self developed expression for smoke layer descent was compared with the ones from the

NFPA 92B [102] and with the one developed by Tanaka and Yamana [68, 95]. This kind of comparisons revealed the limitations of the then existing analytical proposed expressions for computing different fire hazards. These correlations were not found suitable for the modern atria complex designs.

After the study of smoke filling process, many other researches on different phenomena that appear in case of atrium fire started to be conducted to increase the understanding of the problem. One problem studied has been the smoke exhaust process. The primary goal of a smoke exhaust system is to maintain an environment in which the impact of smoke and heat is low [102]. The performance of the smoke exhaust system can be influenced by various factors like the temperature of the smoke, the formation of a pre-stratification layer in the atrium, the size of natural ventilators or volume of smoke exhausted by mechanical fans, the outer wind or the make-up air among others. All these factors have to be studied and taken into account when designing a smoke exhaust system.

Smoke filling is the most basic phenomenon in atrium fire dynamics and a large amount of studies have been carried out so far on the topic. Thus, there is an extensive and comprehensive accumulated knowledge on the subject. However, further research is needed to study more complex yet realistic situations not fully understood, such as, the presence of obstacles on the plume that deviate the smoke into adjacent spaces and modify the air entrainment, and the smoke filling process in complex designs that can differ from those studied in simpler atria.

9. NATURAL VENTING OF SMOKE

Smoke can be extracted either by natural vents or mechanical ventilation systems. Right after a fire takes place, the hot gases from it rise up to the ceiling due to buoyancy. Upon reaching the roof, a horizontal ceiling jet is formed. Smoke then spreads radially from the fire axis, eventually giving a smoke layer. If a vent is opened on the ceiling or an upper part of the atrium, smoke might flow out of the building through it. Because of the density difference due to the temperature difference between hot smoke and ambient air, a pressure difference across the vent is created. When the pressure inside the atrium is higher than the pressure outside, smoke can be extracted out of the building.

This ventilation method, based on the buoyancy of the hot smoke from a fire, does not require mechanical operation and, thus, is preferred to mechanical exhaust system when it is proved suitable as it saves costs and energy. Natural venting also improves the look of the building as no mechanical equipment (e.g. fans) is installed. However, this approach is much more sensitive to the influence of atmospheric conditions than the mechanical exhaust systems. While a naturally ventilated atrium could be expected to work with sufficiently buoyant smoke, it may be prone to adverse wind and building stack effects if the smoke is not sufficiently buoyant. For example, given the condition of weak plume, for various weather conditions, influencing the building stack pressures in particular, the passage of smoke in smoke atrium with bottom and top openings could be either upwards or downwards.

Many studies, design guides and report guides on studying natural smoke ventilation [54] were performed including vertical vent, the required vent area and the mass flow rates [11, 18, 68, 95, 109-111]. For example, Tanaka and Yamana investigated the natural venting through a vertical vent first, analytically [68] and second, experimentally [95], demonstrating the effectiveness of this venting method. Comparisons of the analytical predictions with measurements showed good agreement. Cooper [110] developed an analytic description for flows through uniform-width vertical vents under conditions of arbitrary cross-vent pressure difference. Li and Delsante [111] studied the natural ventilation induced by combined wind and thermal forces through a vertical vent. They developed analytical solutions for this problem also including the influence of the heat losses. It was noticed that, when the wind force opposed the thermal buoyancy, for a certain range of this last value, there appeared to be three possible flow rates, two downwards and one upwards. The effect of heat loss through the building envelope was found significant.

Other experimental studies on horizontal vent [112-115] were conducted. Jaluria et al. [112] studied the flow of smoke across horizontal vents. For this, a laser sheet was used for visualizing the flow of smoke through the vent. Yamada [113] conducted a series of reduced-scale experiments in a 0.8 m compartment, with fires ranging from 1.1 to 3.5 kW and air supply from 0.2 to 0.3 m^3/s, to study the flow through a circular, horizontal, top-centred of 0.15 m. Cooper [114, 115] developed an analytical model for calculating the buoyancy and pressure-driven flow through a circular, horizontal vent. All these studies indicated that there was a critical value on the pressure difference across the ceiling vent for removing smoke effectively out of the building. If the pressure difference was between zero and this critical value, the buoyant smoke inside the atrium would flow out through the vent and the fresh outside air would flow down into the atrium, that is, the flow across the ceiling vent would be bidirectional. For pressure differences higher than the critical value only the smoke would flow out, being the flow unidirectional upwards.

For buildings with large spaces such as atria, the temperature of smoke could not be very high for relatively small fires. Chow et al. found this for fires up to 1.6 MW [105, 108]. In this case, the pressure difference across a horizontal vent would be small. Thus, there would be a possibility that the heavier cool air above the vent could sink into the building. As a result, smoke could not be extracted so effectively. Li et al. [116] studied the smoke control by natural smoke venting with a horizontal ceiling vent. Two situations were considered, one with no temperature differences between the inside of the atrium and the outside, and another in which the outside temperature was higher than the inside. The critical opening time for the vent to ensure that the smoke layer is thick enough to get sufficient buoyancy for extracting out efficiently during a fire was also studied. It was found that, for the first situation, the critical smoke layer thickness depended mainly on the area of the vent, being the critical operating time short. In the second situation, the critical smoke layer thickness depended on the temperature difference, the heat release rate and the vent area.

Other studies on natural venting found that the position of the vent was also important. Chow [117] stated that a vent located on the ceiling but not on the vertical line of the fire gave a higher smoke layer height than one that was there. Quin et al. [118] investigated the smoke filling process in a gymnasium and the performance of different smoke exhaust methods. The results showed that natural ventilation was preferred when the smoke exhaust vents were located at the ceiling whereas, when the smoke exhaust vents were on the walls, mechanical smoke exhaust systems were more suitable. The influence of ceiling temperature was also studied indicating that high ceiling temperature slowed down the ceiling jet. Recently, they conducted a similar study in an atrium [119] where results showed that natural exhaust system was more favourable when the smoke exhaust vents were located on the roof of the atrium when the heat release rate of a real fire was not pre-determined. The reader is referred to the Chapters “Vent Flows” and “Smoke and Heat Venting” of [15] and [54] for further information.

The study of natural venting for smoke control in atria is one of the current trends of research within the fire community on atrium fire. Due to the high sensitivity of the ventilation system to external conditions, it is necessary to study the effects on ventilation of the wind, atmospheric temperature and rain, as well as to include them in the numerical models. Also, nowadays, more energetically efficient designs are sought.

10. Mechanical Venting of Smoke

It has been already commented that protecting the occupants of a building from the adverse effects of smoke in the event of a fire is the primary objective of any fire protection system. One of the systems more commonly used for smoke management is the installation of smoke exhaust systems. For the cases in which passive smoke management methods are not capable to provide tenable conditions for sufficient time for evacuation, smoke exhaust systems could be used. In most of these buildings with large interior spaces, smoke is exhausted via the top of the atrium by means of either natural ventilation or extraction fans [50, 120-122]. For this, mechanical or dynamic exhaust systems are commonly installed in big atria for smoke control. It is believed that this system has more reliable performance than others as it does not depend strongly on ambient conditions. This is especially important in large space atria where smoke control designs, such as compartmentation and pressurization, requirements are difficult to meet [46, 102, 123]. In general, mechanical smoke venting can be designed to serve two main purposes. First, it can serve the purpose of creating tenable conditions in the compartment where the fire is and second, to depressurise the space helping protect an adjacent compartment similar to pressure differential schemes [78].

When using a mechanical exhaust system it is necessary to supply make-up air to conserve mass. With all mechanical smoke venting schemes, the provision for make-up fresh air is particularly important [124]. In general, make-up air should be supplied from positions below the smoke layer at lower velocity to give a flow rate less than the exhaust rate [123]. Failure to follow this could lead to pressurize the atrium enclosure respect to adjacent spaces, forcing the smoke into these spaces.

However, there are some situations that can reduce the effectiveness of these systems. For example, the formation of a thermally stratified layer in the atrium [47] could prevent the smoke from reaching the ceiling to be exhausted. Another problem could be obstructions in the path of the smoke plume [46] that could direct the smoke towards adjacent zones or spaces where tenable conditions are necessary for evacuations. When the local exhaust capacity is too strong air from the lower layer can be sucked. As such, less smoke is exhausted increasing the smoke layer depth. This phenomenon is known as plugholing and reduces the effectiveness of the exhaust system [15]. This phenomenon was studied first on natural venting systems [125, 126].

In 1995, a joint research project was initiated by ASHRAE and the National Research Council of Canada to study the effectiveness of mechanical smoke exhaust systems. The objective of the project was to develop methods with which designers could account for the mixing of cold air with the smoke exhaust. The first experiments were carried out by Lougheed and Hadjisophocleous [127] in a compartment of 9 m × 6 m × 5.5 m with two doors, one on the west wall and another on the east. A fan was used to supply fresh air into the compartment through openings in the floor. The openings were designed to maintain an inlet velocity under 1 m/s, value indicated in the NFPA 92B [102], varying the inflow from 2 to 4 m^3/s. Thirty-two exhaust openings were located in the ceiling of the compartment. A square propane sand burner was used generating fires ranging from 15 kW to 1 MW. In addition to the variation of heat release rate, the main parameters varied were the number of exhaust openings, the exhaust height, the exhaust orientation and configuration and the fan speed, varying the nominal exhaust rate from 3 to 4 m^3/s. It was found that when the exhaust systems operated near or just below their design capacity they were effective without exhausting air from the lower layer but only smoke. When the systems operated well above the design flow rates it was noticed that fresh air entered the system although there was no reduction on effectiveness. For relatively thin smoke layers, there was possibility of pulling some air from below the smoke layer into the exhaust, plugholing, reducing the effectiveness of the smoke exhaust system. It was observed that, if the exhaust openings were located above the clear height, they did not impact the effectiveness of the mechanical exhaust system. The location of the smoke interface was dependent on the capacity of the exhaust system and the plume dynamics. If the exhaust openings were located at or below the height for which the mechanical system had sufficient capacity to maintain a clear height, a less than 1 m deep smoke layer formed below the exhaust openings, being limited to 0.25 m in some cases. Later comparisons were performed with CFD simulations and with the correlations from the guide NFPA 92B [102]. The NFPA 92B correlations for designing exhaust systems, based on the work by Heskestad [27], were found to be valid. Later comparisons with zone model were also performed [128] for heat release rates from 15 to 600 kW. For low heat release rates, less than 50 kW, the predicted carbon dioxide concentration of the smoke layer was lower than measurements. Between 150 and 250 kW good agreement was found. For a heat release rate of 600 kW, the predicted concentration was higher than measurements. Temperature was found to be the parameter with best agreement between predictions and measurements.

Later experiments were carried out by Lougheed et al. [129] in a bigger facility. The second facility had dimensions of 13.11 m × 17.22 m × 12.2 m, approximately two times those of the previous one. At these experiments also a square propane sand burner was used, with fires ranging from 250 kW to 5 MW. The maximum volumetric flow rate for the exhaust system was 25 m^3/s approximately. For these tests, the main parameters varied were the heat release rate, the number of exhaust openings, the exhaust height and the volumetric flow rate. It was found to be difficult to develop a test scenario, in this range of parameters, in which the exhaust system would fail. An efficient system was obtained with an increase on heat release rate. A plugholing equation developed by Hinckley [15] was also examined. It was found to be valid to determine if a particular design provided an efficient smoke exhaust system.

These studies were complemented with CFD simulations [130]. Based on these, design criteria were developed to minimize the impact of plugholing using multiple inlets to reduce the mass flow rate. The minimum separation between the exhaust openings to minimize plugholing was calculated. Also, an expression for the maximum mass flow through each exhaust opening was obtained [131, 132]. These criteria was later included in the following version of NFPA 92B [51].

After the studies on the impact of plugholing on the effectiveness of a smoke management system, the impact of the ceiling jet on the smoke venting was also studied [133]. The ceiling jet is the flow of smoke under the ceiling extending radially from the point of fire plume impingement on the ceiling. Some design guides recommended that an atrium smoke exhaust system was designed assuming a minimum smoke layer depth enough to accommodate the ceiling jet [102, 121]. The minimum smoke layer depth to mitigate the impact of the ceiling jet was computed and compared with a previous study [121]. The results were consistent with the assumption of a minimum smoke layer depth of 10 % of the height of the atrium. Algebraic equations [102] and a computational fluid dynamic model [129] were used to estimate smoke properties in the smoke layer and compared with experimental results. The comparisons showed good agreement for smoke layer height except for low heat release rate and high mechanical exhaust rates in which the ceiling jet and plugholing phenomena were not modelled properly. It was also emphasized that the algebraic equations were only applicable for limited range of atria [134]. In summary, it was found that, for atria smoke management designs in which the smoke layer depth below the ceiling was small, the impact of plugholing and the ceiling jet had to be considered to ensure building occupants would not be exposed to smoke. At that time, algebraic equations were included in some guides, e.g. NFPA 92B (2000) [51], for assessing the conditions in the smoke layer.

Chow et al. [135] carried out a total of 19 smoke tests at the PolyU/USTC Atrium varying the fire size, from 1.8 MW to 5 MW, and the smoke exhaust rates, from 3 to 16 air changes per hour (ACH). Two different fuels were burned, methylated spirits and diesel, locating the fire at the centre of the floor. It was found out that increasing the exhaust rate might not move significantly the smoke layer interface height in that facility, e.g. for a 2 MW fire, the smoke layer was less than 4 % higher for 16 ACH than for 10 ACH or for a 3 MW fire, the smoke layer had the same height for 3 ACH and 6 ACH. It was also observed that a clear steady smoke layer was not formed under some conditions, such as under a high exhaust rate and a small fire. This phenomenon was pointed out to be due to the mass flow across the smoke layer interface beyond the plume. In another study from Chow et al. [136] this mass flow was found to be near the 30 % of the exhaust rate. Later comparisons with the correlations from the NFPA 92B [51] were performed without good agreement.

Other experimental works were carried out studying the performance and effect of the mechanical smoke systems in different shapes and sizes facilities. For example, Hostika et al. [137] conducted a series of tests at the 19 m high VTT atrium varying systematically the fire location and the fire size between 1 and 5 MW. Gutiérrez-Montes et al. [138, 139] conducted the Murcia Atrium Fire Tests in a 20 m cubic atrium varying fire size, with heptane pool-fires from 1 to 8 MW, smoke extraction rate and make-up openings size and location. CFD simulations of the tests were made [139] finding good agreement at high locations of the facility and poor at the lower zones, see Figures 7 and 8. All these studies have been later used to modify and improve correlations in the existing codes and regulations [9, 10], to validate numerical models [138-140] or to study and guidance on mechanical smoke systems design [119]. Chow et al. [141] conducted a series of fire tests in an atrium of 35 m × 9 m × 28 m. The atrium had a complex design that made this study and the experimental data really valuable. As fire source, methanol pans were used with a total heat release rate of 2 MW. The smoke was exhausted by a mechanical smoke exhaust system with flow rate of 48 m^3/s. Comparison with a CFD simulation was made. It was found that the CFD model could give accurate predictions, highlighting the importance of choosing the heat release rate and ventilation conditions properly.

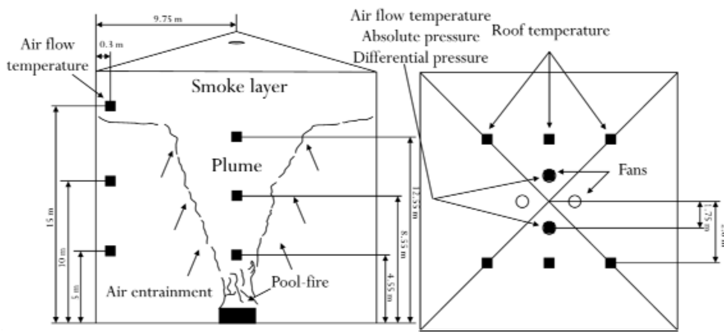
Another important issue is the make-up air. There can be many different combinations with the positions of the smoke exhaust openings and air supply openings which will give different smoke control results. Some studies on fire smoke control in large space atria [116, 122] indicated that these two factors matter much for the smoke control results. For example, if make-up air positions were near the smoke layer interface, the make-up air would increase the amount of mixing of fresh air with smoke to further add to the smoke layer. As a result, the smoke layer would descend to lower levels.

Some authors like Hadjisophocleous and Lougheed [142] performed studies on mechanical exhaust with different make-up air positions. Yi et al. [122, 143, 144] carried out full-scale experiments in the PolyU/USTC Atrium and numerical simulations to study the effects of make-up air. They modelled three scenarios with different relative positions of the air inlet, above, within and below the smoke layer interface. The parameters varied were the fire size, from 1 to 10 MW, the extraction rates, from 0 to 18 air changes per hour, and the make-up air inlets location, at the floor, 9 and 18 m high. Three tests with a 3 MW fire were conducted. Two of them considered mechanical ventilation, one with an inlet soffit at 11.6 m and an inlet sill at 10.5 m high and one with the inlet soffit at 2.5 m and inlet sill at 0 m high. At the third, no mechanical ventilation was considered. They concluded that, ideally, a minimum smoke layer interface height could be maintained for a given fire size and extraction rate. If the minimum smoke layer interface height was above the safe level then air inlets lower than that should be installed. If the air inlet was higher than the smoke layer interface, make-up air would enter the smoke layer accelerating its descending rate. In case the exhaust system were unable to maintain a safe steady height of smoke layer, extraction with higher air inlets could be advisable, as it would reduce the smoke temperature.

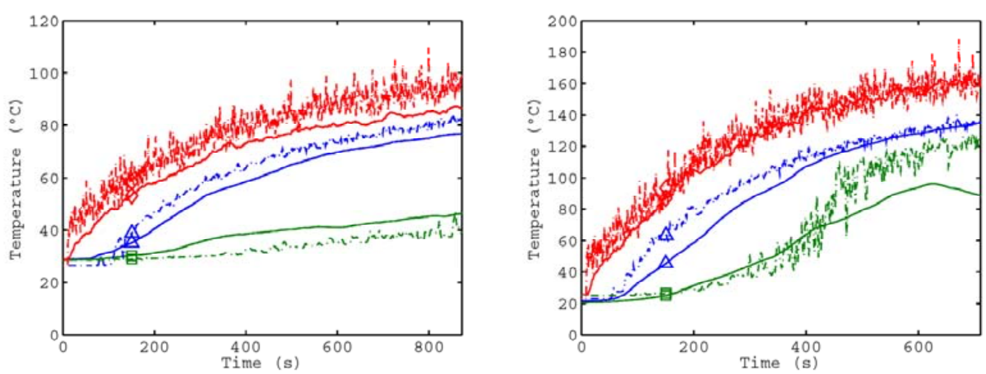
There are other important factors such as the distribution of air inlets, distance of the air inlet from the fire, and air flow velocity through the air inlet, that should also be considered. Due to the great improvement and reliability of some CFD codes [64, 65] many numerical investigations had been performed into this issue. Recently, Kerber and Milke [145] studied numerically the possible effects of various make-up air supply arrangements and velocities in an atrium smoke management system within a 30.5 m high cubical atrium. Up to 10 different numerical tests were performed. The fire source used was a stack of pallets with a peak heat release rate of 5 MW. The make-up air velocities were varied from 0.5 to 3.0 m/s. The arrangement of the inlet air vents consisted of symmetrically located vents placed at floor level, an array of vents distributed from the floor to the ceiling and asymmetrically located vents. The size of the vents was also varied. It was found that even velocities lower than 1 m/s could cause the smoke layer to descend below the design criterion. It was stated the inlet velocities should be diffused so that they were very low when they reached the fire and had no effect on it. It was also found that the best layout of vents was that in which make-up air was supplied to the fire symmetrically to avoid plume perturbations. However, it has to be pointed out that these conclusions were drawn under the assumption that the fire was at the centre of the floor.

a) b) c)

Figure 7. 20-m cube test facility in Murcia for the 2005-08 atrium fire experiments in [138, 139], in a; 1.7 MW pool-fire, in b; 4.2 MW pool-fire, in c.



a)



b) c)

Figure 8. Vertical section, plant and sensor layout of [138, 139] in a; temperature measurements, solid line, and predictions (with FDS and a cell size of 0.11 m), dash-dot line, at exhaust fans, in red, and near the walls at 15 m high, in blue, and 5 m high, in green. 1.7 MW pool-fire, in b; 4.2 MW pool-fire, in c.

Mechanical smoke exhaust is the most reliable ventilation methodology, but there are still some gaps of knowledge to fill such as methods to decrease the size of make-up air vents without perturbing the smoke plume. Minimizing the size of the mechanical venting components allows to maximize window areas or eliminate ducting or fans that compromise the architects' vision of space. At this point, make-up air vents are the most significant concern as they are at lower levels and are more visible. Due to the relative maturity of CFD, these models could be used for the design of mechanical smoke systems. However, there is a need to validate the range of applicability of CFD models to predict accurately fire environments under special circumstances such as very large fires that provoke large pressures drops across the fans. The reader is referred to the Chapters "Vent Flows", "Smoke and Heat Venting" and "Smoke Management in Covered Malls and Atria" of [15] and [9-11] for further information.

11. Spill Plume Dynamics

Atrium buildings are commonly designed such that the atrium space is connected to adjacent floors, rooms or spaces, see Figure 1. Smoke flowing from a communicating space can move unimpeded into an atrium space, affecting other areas of the building.

In case of a fire in a communicating space near an atrium, a horizontally moving buoyant layer of smoke will form. This layer will spread and flow toward the opening to the atrium space. If there are no smoke control measures to confine the smoke layer, this horizontal layer will flow out of the opening. If a balcony exists beyond the compartment opening, smoke will flow beneath the balcony. The smoke flow will then turn around the edge of the balcony. The smoke will then rise vertically as a plume into the atrium space and entrain air.

This kind of plume is known as spill plume. Spill plumes can be categorised into two main groups. The first type is the adhered spill plume, when the plume adheres to a vertical surface above the opening as it rises. Thus, entrainment of air will occur only into one side of the plume as it rises vertically, see Figure 9 a. The second type is the free spill plume, when the smoke layer rotates at the spill edge of a horizontal projection, e.g. a balcony, and rises vertically as a plume. Thus, entrainment of air will occur into both sides of the plume as it rises vertically, see Figure 9 b.

Spill plumes entrain large amounts of air, which determine the quantity of gases entering the smoke layer in the atrium. This flow is a key variable to designers to determine the vent area or fan exhaust rate of the smoke exhaust system to install. A fire in a communicating space on the lowest level of the building will entrain the largest amount of air into a rising spill plume and thus, will result in the greatest quantity of gases entering the layer above. In general, a spill plume provides the worst case condition for this scenario [11].

The main factors affecting the amount of air entrainment into a spill plume were reviewed by Morgan and Marshall [31]. These were the mass flow rate or temperature of the gases at the edge of the rotation point into the atrium, the convective heat flux, the lateral extent of the spill plume entering the atrium and the height over which the plume must rise.

There have been many experimental studies on balcony spill plumes. Morgan and Marshall [31] started to study this phenomenon in 1975. A series of reduced-scale ($1/10^{th}$) experiments were carried out simulating the smoke flow from a single shop with a width of 0.7 m and a double shop of 1.4 m. Both compartments were 0.5 m deep and 0.5 m high. A removable downstand of 0.16 m was also used. A 0.4 m balcony extended across the full width of the compartment. Morgan and Marshall [146] continued with another series of reduced-scale ($1/10^{th}$) experiments of a smoke flow from a 0.7 m wide shop into a two storey mall. The hot gases were produced from a convector heater with heat release rates between 1 to 4 kW. The smoke was mechanically extracted from the top of the box. Temperature at different locations and the thickness of the smoke layer were measured. The data from these two sets of experiments were used to develop the Building Research Establishment (BRE) spill plume calculation method. This approach provided methods for estimating the smoke flow approaching the end of the balcony, the air entrainment as the plume rotated around the spill edge and the smoke production in the ascending plume. The results of this study gave rise to the development of the effective layer depth correction to allow for the temperature variation beneath the smoke layer. It was also found that the channelling by draft curtains was effective in reducing the amount of smoke produced. Modifications were later made to extend the method to apply to adhered plumes and to update aspects of the horizontal flow from a compartment opening [147, 148].

The BRE spill plume method involved a complex series of calculations. Law [149] developed a simplified balcony spill plume equation by correlating the maximum temperatures from both previous studies [31, 146]. Law stated that the correlation proposed in her work could be reasonably used for design purposes [150]. Morgan [151] proposed a modified form of the Law correlation. This kind of methods were based on the assumption that the spill plume was generated from a virtual line source below the spill edge that depended on the fire size, the heat output per unit area of the fire and the compartment geometry. These methods made easier the design process of smoke management systems, although it has to be noticed that they had limitations depending on the correlation. Thomas [152] also used the experimental data from Morgan and Marshall [31, 146] to develop an alternative simplified spill plume formula to the one from Law.

Hansel et al. [153] conducted a series of reduced-scale ($1/10^{th}$) experiments with a model atrium. The model had a plan area of 3.3 m^2 and was 3.06 m high. The hot gases were produced from an electrical heater and were exhausted mechanically from the top of the atrium. They measured temperature and mass flow rate of the gases at different locations. This work was carried out to address various uncertainties regarding the horizontal flow of gases toward an opening, air entrainment into free and adhered plumes, and the effect of the balcony breadth. It was confirmed the discharge coefficient of a horizontal flow approaching a flush ceiling free edge assumed by Morgan [148]. It was found that balconies broader than 2 m would allow the plume to rise through the atrium space as a free plume. Balconies narrower than 2 m would provoke smoke logging between the plume and the wall behind. Law [154] later used these data to perform slight modifications on the relationship for the mass flow rate in balcony spill plume rate, which was later included within guidance from Chartered Institution of Building Service Engineers (CIBSE) [12]. The current guidance in the USA [9] was also derived from the work of Law [154] although the NFPA 92B equation was given in terms of the total heat release rate.

Marshall and Harrison [155] conducted five series of experiments on spill plumes using as well reduced-scale modelling. These experiments examined various uncertainties in spill plume calculations including the geometry of the smoke reservoir, the combustion air flow through the compartment opening and plume end effects on air entrainment into the plume. The results from these experiments were used by Poreh et al. [156] in the development of a simplified spill plume expression. They deduced a relationship between the mass flow rate for a line plume and the convective heat output of the gases using dimensional analysis.

Also, Thomas et al. [157] used dimensional analysis in the development of a simplified spill plume. They used the data by Marshall and Harrison [155] and Poreh et al. [156] in the development of the calculation method. This last method was given within guidance on spill plume in the UK [158].

Morgan et al. [11] summarized these four different methods for calculating smoke production rates: the BRE spill plume method, the method by Thomas [152], the method by Poreh et al. [156], and method by Thomas et al. [157]. Morgan et al. compared these calculation methods. Good agreement between all of them was found for a height of rise of plume up to 5 m above the spill edge. The methods diverged for greater heights of rise. Morgan et al. made the following recommendations for an appropriate choice of a spill plume formula: first, the use of the method by Thomas et al. [157] was suggested for free plumes rising less than 3 m above the spill edge, into a large reservoir; second, for free plumes rising more than 3 m above the spill edge it was suggested to use the BRE spill plume method, for large or small area reservoirs, or the method by Thomas [152], for large reservoirs only; and third, the BRE spill plume method was suggested for all other spill plume scenarios.

Computer modelling studies were also carried out to deal with the spill plume phenomenon. For example, Miles et al. [159] used CFD to study the entrainment of air into a spill plume. The numerical results were compared with those from Marshall and Harrison [155] showing good agreement for low heights of the plume but not so good at greater heights. However, the simulations agreed well with the correlations from Poreh et al. [156] and Thomas et al. [157].

Chow [160] also studied numerically the entrainment of air into a spill plume with a different CFD model. Comparisons were again made with the data from Marshall and Harrison [155]. Simulations were conducted varying the fire size and the smoke exhaust rate from the atrium and a linear correlation was derived. The numerical model was found suitable for simulating the atrium smoke filling from a spill plume. Later, again Chow [161] used a different numerical model to simulate the fire scenario from Marshal and Harrison [155]. At this study, the parameter varied was the exhaust rate from the smoke reservoir, examining the location of the neutral plane in the smoke reservoir. There have been many other numerical studies that have helped to improve the state of the art of this problem.

Later, Yii [162] continued with reduced-scale ($1/20^{th}$) experiments carrying out a study of the spill plume using salt water. Harrison [13] conducted reduced-scale ($1/10^{th}$) experiments in a 1 m × 1 m × 0.5 m with a 0.3 m balcony facility. The parameters studied at this series of tests were the heat release rate, the compartment opening width and the depth of the downstand at the spill edge. A computational fluid dynamics model was also used in the analysis. It was found that the presence of a downstand at the spill edge of a compartment opening appeared to have little effect on the entrainment of air into the subsequent spill plume. A simplified spill plume formula was developed to predict the mass loss rate of gases produced by a free spill plume, which included entrainment of air into the ends of the plume. An empirical correlation to predict the entrainment of air from a compartment opening to a higher projecting balcony was also developed. Fang et al. [163] studied experimentally and numerically the different types of thermal plumes such as axisymmetric plume, wall plume, corner plume and balcony spill plume. They also studied the smoke movement in atrium with sloping floor. Three axisymmetric plume equations and two balcony spill plume models were assessed. It was also found that, on the same air supply and smoke exhaust condition, the smoke layer height was lower while the angle of the sloping floor was larger. The smoke layer height was lower while there was a heat source on the sloping floor. All these studies were summarized by Harrison [13] and Fang et al. [163].

Recently, the American Society of Heating, Refrigerating and Air-Conditioning Engineers initiated a project to study the balcony spill processes and to evaluate the balcony spill plume equation of North American codes and standards [9, 21]. This project was motivated by two main reasons: the first one was that smoke management requirements for atria in US buildings specified that the design of atrium smoke management systems had to include fire scenarios in the atrium and adjacent spaces [10, 164]; and the second one was the lack of verification by full-scale experiments of the balcony spill plume equations provided in some codes and standards. This project included full-scale experiments and CFD modelling. The full-scale experiments were carried out to investigate smoke flow in balcony spill plumes and the resulting mechanical exhaust requirements for an atrium. The CFD modelling simulations were used to study the smoke entrainment in the balcony area and smoke entrainment in high atria.

For the experimental part, eighty-five experiments were conducted. The atrium used was a section of the NRC Burn Hall facility with dimensions of 16.8 m × 30.5 m x 12.2 m. The smoke was extracted from the ceiling with a variable capacity smoke exhaust system. A 13.8 m wide by 5 m deep by 5 m high fire compartment with attached balcony was located near one end of the atrium. The fire source was a propane burner of 3 m × 3 m. The parameters varied and investigated were the fire size, from 0.5 to 5 MW, the compartment opening width, from 5 to 12 m, and the downstand depth of the compartment opening, from 0 to 1.6 m.

The experimental results and their analysis were presented as a first part of the study [165, 166]. It was observed that wider openings resulted in a lower temperature smoke layer and higher interface height. For tests without a downstand, the measured temperature profile increased linearly with height. The addition of the downstand resulted in a deepening of the smoke layer and an increase in the smoke layer temperature. The discharge coefficient for the smoke flow through the compartment opening was also estimated for the compartment fire scenario with and without a downstand.

The mass flow through the opening was also estimated and compared with estimates determined using two algebraic equations published by CIBSE [12] and BRE. It was found that both relationships provided conservative estimates for the mass flow rate through the opening, in general. However, the CIBSE correlation was found to underestimate the mass flow rate for the scenario with a downstand and a wide opening whereas the BRE relationship did the same for the scenario with a downstand using the small compartment entrainment coefficient. The results also indicated that the air entrainment estimated using the design equations provided reasonable estimates for the region near the balcony in most scenarios. However, two exceptions were noticed. It was found that for the scenarios with draft curtains and a narrow opening the air entrainment was over-estimated. Also, for scenarios in which the smoke layer was immediately above the balcony, calculations resulted in underestimation of air entrainment. Finally, the experimental results for air entrainment into the spill plume for scenarios without draft curtains were found consistent with the results using the algebraic equations being tested.

For the modelling part, McCartney et al. [167] conducted a series of simulations to investigate smoke entrainment below the balcony, at the balcony edge and into a balcony spill plume for high atria. These numerical simulations were performed as an alternative to investigate the effect of the many parameters on air entrainment in the balcony area which could not be studied using full-scale testing and the limited distance between the balcony and the ceiling at their experiments. The compartment model atrium was a 50 m cubic one. It was noticed that the CFD simulations did not provide accurate estimates for the initial mass flow at the balcony edge. However, an analysis indicated that the total mass flow in the far field was not sensitive to the initial mass flow rate at the balcony edge. The results also indicated that a virtual origin at floor height or up to 3 times the height of the balcony below the balcony edge could be used to provide conservative estimates for the mass flow rate in the far field. Finally, a new correlation for the variation in mass flow rate with elevation for a balcony spill plume was developed, extending the then current ones to high elevations.

Despite the large amount of studies on spill plumes, only few full-scale experiments on shop fires within an atrium have been carried out [168]. For a plume spilling out of a small shop with finite width, there are some differences with the plume discharging out of a wide horizontal balcony. Thus, the balcony spill plume expressions from the literature might not be applicable for a shop fire with finite width. Huo et al. [169] studied experimentally the smoke filling process due to smoke spilling out of a shop fire. Six full-scale experiments were conducted at the PolyU/USTC Atrium. A chamber of 4 m × 3 m × 3 m was placed inside the atrium. Three different sizes diesel pool-fires were used. Two models based on different plume expressions [102] and [106] for simulating smoke spilling out of a shop were proposed and assessed. Shi et al. [170] investigated as well the full-scale growth and smoke movement due to a retail shop at the same facility. The fire power ranged between 400 and 600 kW. A spill model for this fire case was proposed as well as a zone model. Later simulations were performed to compare the new zone model with experiments and FDS observing that, for this configuration, both models agreed and also with experiments. The inclusion of a mechanical exhaust system was also studied.

In a later work, Shi et al. [171] continued studying the case of shop fire within an atrium at the PolyU/USTC Atrium. They conducted full-scale experiments for different air changes per hour. Normally, the smoke is allowed to enter the large space building and is extracted effectively by an exhaust system installed in the atrium. However, they pointed that there could be enclosures with large fire loads in which the smoke exhaust system of the atrium might not be effective on preventing the smoke to spread. A set of supplementary distributed mechanical exhaust system at these enclosures was suggested to reduce the smoke and heat spilling out. A two-zone model for mechanical exhaust rate was also used to show the effectiveness of this approach to control the smoke.

Other investigations on different phenomena affecting the smoke movement from a spill plume have been carried out. For example, Li and Chow [172] studied numerically the upward motion of a balcony spill plume in an atrium with a thermal stratified layer. The smoke filling in an atrium of 20 m × 10 m × 30 m due to a balcony spill plume resulted from a 2 MW fire within an adjacent compartment was simulated. It was observed that, in case of a highly thermal stratified layer, smoke failed to rise and might spread to other areas adjacent to the atrium. Furthermore, if smoke detectors were installed at the ceiling they could not be activated and the hot air be extracted efficiently. Other alternatives, such as beam smoke detectors [47, 121] or video smoke detection system were suggested.

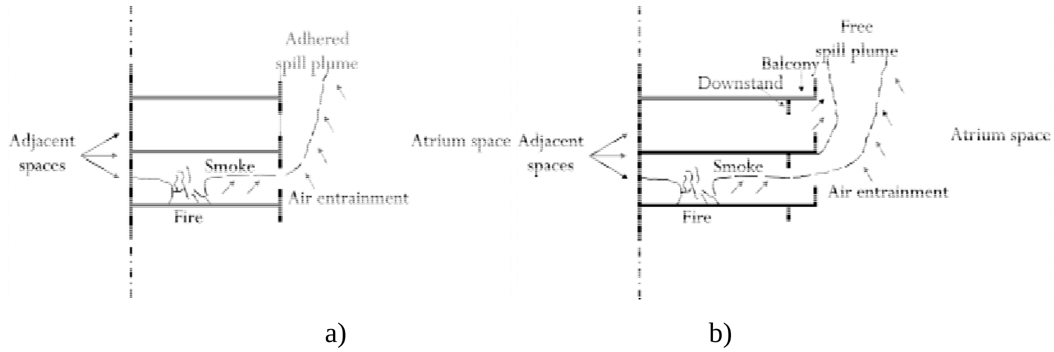


Figure 9. Adhered spill plume, in a; free spill plume, in b.

This fire scenario has been widely studied. Due to this, there is an extensive knowledge on the matter, being the possible smoke behaviour and smoke flow rates well bounded. There are accurate correlations and also some CFD codes have been found to be appropriate to predict the spill plume process. Thus, both tools could be reliably applied together to both design and research. However, there are still some issues to study deeper such as the influence of different parameters, e.g. thermal stratification, the influence of non common architectonical obstructions (different from studied downstands or balconies) or the spill plume development in complex design atria. There is also a need to carry out full-scale experiments and modelling in larger facilities than the ones used to verify the existing correlations for high atria and to extend their range of applicability, e.g. to spill plumes in wide balconies without downstand.

Other smoke control strategies, e.g. depressurization and pressurization, have been studied. Hansell and Morgan performed an analytical study on smoke control in atria using depressurisation [173, 174]. They showed how depressurisation could be combined in a hybrid system to achieve a determined clear height or a temperature controlled ventilation. The limitations of this approach were also discussed, such as a extremely large atrium height. Hirota et al. [175] showed the performance test of a pressurization smoke control system in a large-scale shopping centre. They first calculated the amount of air supply from the system. The effectiveness of the approach was showed. However, the high dependence on the mechanical devices used as well as the difficulty of implementing this approach by means of achieving enough airtight was also highlighted.

The outer wind is one of the parameters that influence the performance of a smoke exhaust system. Under some circumstances, the movement and concentration of the smoke can be affected by ambient winds that generate a non-uniform pressure distribution on the outer envelope of the building. Various wind effects were studied in atria by Hansell and Morgan [176], in shopping centres by Morgan and Marchant [177], even in high-rise buildings by Kandola [178] and Tamura [86]. Poreh and Trebukov [179] used dimensional analysis to study the wind effect on a natural vented atrium. The threshold wind speed at which wind effects became significant was calculated. When the wind velocity was larger than two times this threshold, buoyancy effects were relatively small and the smoke was driven mainly by wind generated pressure. The cases more sensitive to outer winds were those with small buoyancy smoke plumes, shallow elevated layers and large area vents. They also highlighted that wind effects were likely to occur often and should not be ignored.

The smoke movement in open vertical enclosures has been also studied. Marshall [180, 181] studied stairwells and elevator shafts experimentally with a 1/5th scale model of a relatively short enclosure. Mercier and Jaluria [182] studied experimentally, with a 1/3rd scale model and aspect ratio (height/width) of 3, the flow due to a fire in multi-level buildings with vertical open shafts or atria under natural ventilation. Smoke and hot gases were injected into the enclosure at a lower opening studying operating conditions ranging from high buoyancy levels, for which the flow stayed close to the vertical wall of the enclosure, to much lower levels, at which the flow entered the enclosure with a significant flow velocity and spread outward very quickly. It was found that the flow and temperature were not uniform across a horizontal plane in the enclosure. It was observed how a wall plume was generated which conveyed the hot fluid rapidly along the enclosure wall from the inlet to the outlet. A recirculating flow arose away from the wall affecting the heat transfer and flow in the wall plume. It was stated that horizontally uniform conditions could not be assumed.

12. Current Design Trends in Fire Safety

In terms of fire protection, floors, ceilings and partitions are traditionally used to provide compartmentation to limit the spread of fire and smoke within a building. However, atrium buildings violate this approach in terms of horizontal compartmentation and vertical separation. In the event of a fire, the lack of physical separations can allow extensive smoke spread to occur throughout the entire space to areas remote from the fire source. Furthermore, atrium buildings can contain large quantities of combustible load and hold significant numbers of occupants who could be exposed to smoke.

The current international trend in fire protection engineering practice and building regulations is towards performance-based design and risk-informed analysis in [14, 16, 183-187]. In some codes [186], the fire safety clauses are being re-examined and changes are being proposed that require performance-based fire engineering design to be assessed against a set of specified fire scenarios. Performance-based design is especially important for prestigious and iconic building types, for which building industry is constantly seeking more robust and more reliable methodologies to establish stronger links between the design and the actual performance of the building. Also, fire engineers can give the architects and building designers greater scope for achieving their architectural vision in an atrium. This assessment of performance is reaching great importance to insurers, clients, regulators and the general public.

For complex structures like atria, a proper understanding of fire dynamics and smoke movement for each particular building is important for providing the scientific understanding required for the design of fire-safe structures [188]. Modern high-rise buildings include complex and non conventional architectonical elements and designs that can lead to fire environments diverging significantly from those assumed in the development of current codes and standards and many engineering calculation methods. These distinctive characteristics of high-rises and other modern buildings influence the fire environment that is not fully understood under the current state-of-the-art of fire dynamics. Significant differences in the geometry lead to potentially significant differences in the fire behaviour. With such remarkable architectural features, the fire dynamics in one building does not necessarily correspond to the fire dynamics resulting in another building.

Testing in full-scale enclosures is too complex, expensive and labour intensive, resulting in a small number of tests that can be reasonably carried out. Reduced-scale testing [13, 163] is also a potential method to study flow in large facilities although it has to be taken into account its limitations as, in case of fire, it is not easy to preserve the fluid, thermal and radiant similarities at the same time [189].

Successful design of a smoke management system depends on the correct specification of a design fire and on the calculation of the entrainment of air into the gases as they rise toward the buoyant layer beneath the atrium ceiling. The development and improvements of computer models indicate that this technique is becoming more and more reliable for research or designing purposes [119, 167]. These models offer practical tools for investigating particular features or changes to design, without the need to perform full-scale experiments.

Because the shift towards performance-based codes and the difficulty of testing in full-scale atria, fire models are increasingly being used for developing fire safety engineering solutions in modern buildings. As commented before, these models allow to study unconventional and innovative features in new designs or non-trivial changes to existing designs. For this end, it is essential to generate more reliable and comprehensive experiments for numerical model validations. It is necessary to perform fire tests in new, complex and larger-scale facilities [141] to develop better models and to enlarge their range of applicability as they will play an important role in the future. It is also important the development, improvement and inclusion of more accurate models and numerical techniques that allow to simulate more realistic phenomena.

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