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Summary The fire safety codes for buildings in Hong Kong are reviewed in terms of building type, building interior layout, construction materials, occupancy levels, circulation patterns, access and escape routes, fire detection and firefighting systems. The fire safety codes are valid only for traditional buildings in Hong Kong. Following these codes in modern buildings might lead to 'over-design' or to providing safety systems which are not workable in case of fire. The prescriptive approach is found to be insufficient to design fire safety for an atrium. It is timely to review the fire codes, to identify and revise those parts which are not workable. The possibility of implementing engineering performance-based fire codes is discussed. The fire safety requirements in atria are taken as an illustrative example. An engineering approach to designing fire safety is strongly advocated.

Fire safety codes for Hong Kong: Inadequacy for atrium design

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1 Introduction

The construction industry in Hong Kong (now a Special Administrative Region of China) has developed rapidly in the past ten years. Fire safety must be designed to the satisfaction of the local authorities as it is a key area to be considered seriously. A building is designed to protect its occupants, the property it contains, and continuity of operations (e.g. for a railway station or a power station) in case of fire. Local fire safety codes(1–4) have been developed to specify the fire protection provisions in buildings. An acceptable level of safety design for buildings is defined through legislation. Special attention is paid at the early design stage to the means of escape for occupants and to the means of access for firefighting. Both active and passive firefighting measures are designed; these are intended to assist suppression of fire by the firefighters. For buildings which are 'typical' in size, shape and use, such as a normal high-rise building, the available prescriptive codes provide the designers with sufficient guidance in designing fire safety provisions. Compliance with the prescriptive provisions in these codes would be regarded as a reliable way not only to satisfy the local authorities' requirements, but also to give adequate protection, though very little scientific evidence was provided in substantiation.

Two recent serious fires have drawn public attention to the fire safety aspects of buildings(5). The public(6) have started to be aware of the hidden problem of fire safety, and to ask whether they are sufficiently protected while occupying a building. Further, novel design features such as high-rise atria feature in large-scale developments including multi-purpose buildings, modern shopping centres, luxury hotels and prestige office buildings. Whether current safety provisions are adequate and whether they can suppress a fire is questionable.

The main objectives in building fire safety are to minimise the occurence of a fire and to prevent it spreading from its origin to other parts of the building. Fire safety is provided through design, construction and management. Key factors are the building design, the construction materials, building structures, furnishings, combustible contents, ventilation arrangements and firefighting systems.

Hong Kong has many high-rise buildings, atria, buildings enclosing large indoor spaces, and deep basements. The occupancy level and usage of buildings may change. Using the open space in a shopping mall as a food court is a typical example. The prescriptive codes may not be sufficient for fire safety in buildings with special designs. The public authorities have just started to recognise that it may be possible to take an 'engineering approach' to fire safety over and above the prescriptive provisions. This is particularly obvious for buildings with particular hazards, where special considerations and specific international codes and standards have to be used(7,8). But this approach is impossible without a basis of strong scientific fire research. Therefore, studies on the development of engineering performance-based fire codes are being carried out at The Hong Kong Polytechnic University. The objectives are:

(*a*) to study the feasibility of applying engineering performance-based fire codes

(*b*) to study the potential fire risk in buildings in Hong Kong by determining the fire load density and the combustible contents in different buildings

(*c*) to apply mathematical fire models to the fire spread in buildings

(*d*) to evaluate the performance of fire protection systems

(*e*) to develop engineering performance-based fire codes.

This paper reports preliminary findings by discussing the key provisions in the current fire safety codes for Hong Kong buildings(1–4). The main areas of concern are the building type, compartmentation, structural protection, escape routes for occupants, accessibility of the building's interior for firefighting, and fire engineering systems. The atrium(9) is adopted as an example to illustrate where the codes fall short. The necessity for establishing engineering performance-based fire codes is highlighted.

2 Review of local fire safety codes

Wong and Chow(10) have briefly reviewed fire safety codes in Hong Kong. Key areas are discussed in terms of building type, compartmentation, structural protection, escape routes, firefighting accessability and fire engineering systems.

2.1 Building type

43 types of building and areas defined in the fire safety codes(4). Occupant conditions and activities in the building are recognised. Minimum fire safety measures are prescribed as the condition for the local authority to approve the building design. Code prescriptions vary according to building classification.

2.2 Compartmentation

Buildings are divided into different areas by structural elements so as to confine fire and smoke(1), to ensure the integrity of the structural elements, and to limit the number of people exposed to a fire. Compartments are classified according to volume(1). The maximum allowed compartment volume is 28 000 m^3 for spaces above ground and 7 000 m^3 for underground spaces. The maximum compartment volume for warehouse is 7 000 m^3 where the less than 30 m of the building height is above ground, otherwise the maximum compartment volume is 3 500 m^3. A larger compartment volume is allowed if equivalent safety can be provided. Building parts with different uses or different occupancies must be separated. The number of compartments into which each storey should be subdivided depends on the number of occupants and on the amount of fuel stored at that level. Escape staircases are considered as separate compartments.

2.3 Structural protection

Structural elements are designed for a specified fire resistance period (FRP)(1). A minimum FRP of one hour is specified for the elements in domestic, hotel bedroom and office buildings; two hours FRP is specified for all industrial buildings and warehouses. The FRP of compartment floors and walls, however, is not less than 4 hours. Basement storeys are considered to pose special risks for escape and extinguishment, so a FRP of 4 hours is specified. Further, the level of fire protection accorded to the structural elements depends on needs for escape and extinguishment.

2.4 Escape route for building occupants

Buildings should be designed so that the occupants can escape when fire breaks out. The time needed to escape must be shorter than the time taken for the fire to spread. This can be achieved by preventing the fire from spread and by ensuring that escape routes are neither too long nor too complex. The likely type, number and behaviour patterns of occupants are important parameters. The movement of people is one of the main concerns of a safety code. The maximum travel distances of people in various building designs are specified and shown in Table 1. Different occupancies(1–4) are classified through the usable floor area per person Aper. This is an important factor used to predict the number of occupants using a storey as intended. Values of Aper vary from 0.5 for assembly halls to 30 for warehouse, 'godown' and storage areas. A code of practice has been developed(2) which emphasises escape route provisions.

'Egress' and 'refuge' are the two strategies adopted in the building design code for fire safety. The codes recommend sufficient provision, design and construction of the following elements of escape routes: staircases, exits (including doors) for all occupant accommodation (e.g. assembly halls, warehouses) and circulation areas (e.g. basements, lift lobbies). These building elements provide a simple and direct escape from the building when the fire alarm is sounded. A refuge floor is the second escape strategy. It is recommended for all high-rise buildings of more than 25 storeys. The refuge floor provides a space of temporary safety within the building during emergency escape(2).

2.5 Firefighting accessibility to building interior

Firefighters' access to the fire area is one of the important considerations in building design, especially for a high-rise building. Requirements for access to the building's interior are described in the local code of practice(3). This includes approach to the building and entry to it. Sufficient numbers of access staircases, fireman's lifts, firefighting and rescue stairways are designed into the building. Location and distribution are determined according to the building classification, height and floor area. The refuge floor acts as a firefighting platform which is open to the air, with provision for water drainage and isolation of staircases.

2.6 Fire engineering systems

Fire engineering systems include fire detection, fire alarm, firefighting and smoke management systems. The minimum requirements for fire services installations and equipment are specified in the fire safety codes of practice(4). The installations and equipment required depend on the building's classification, its height and floor area. An example of the requirements for high-rise commercial buildings is given in Table 2.

A smoke management system is one of the key considerations, as smoke is one of the major causes of death in fire.

Table 1 Direct distance and travel distance for building exit routes(2)

Configuration	Use of premises or part of premises	Type of exit route†	Maximum travel distance (m)	Maximum sum of direct and travel distances (m)
Single-staircase building	Any	A	18	24
		B	12	24
		C	18	18
Buildings with more than one staircase	Offices, schools, and shops	A	36	45
		B	24	36
		C	30	30
	Premises other than offices, schools and shops	A	30	36
		B	24	36
		C	30	30

†Type A exit route is along balcony approach or internal corridor with ventilation; Type B exit route is along internal corridor without ventilation; Type C exit route is within a storey is partitioned into rooms, but not along balcony approach or internal corridor.

Table 2 Minimum provision of fire engineering systems, installations, equipment for high- rise commercial buildings[4]

Systems/ Installations/ Equipment	Remarks
Audio/visual advisory systems	For single occupancy part with floor area > 2000 m^2
Automatic actuating devices	To be automatically operated
Automatic fixed installations other than water	For area where the use of water is undesirable
Emergency generators	For fire engineering systems
Emergency lighting	For entire building and exit route leading to ground level
Exit signs	To be sufficient that all exit routes from any floor within the building are clearly indicated
Fire alarm systems	One per hose reel; and to be actuated with fire pump and audio warning device initiation
Fire control centre	Minimum requirement of one; more required for more complex building
Fire detection systems	To be provided in areas not covered by automatic fixed installations
Fire hydrant/ hose reel systems	To be provided so that every part of the building can be reached by a run of not more than 30 m
Fireman's lifts	
Portable hand-operated approved appliances	
Pressurisation of staircases	Required where: (*a*) natural venting of staircase is not provided; and (*b*) the aggregate area of openable windows of the rooms of the building does not exceed 6.25% of the area of those rooms, calculated on a floor-by-floor basis; and (*c*) the cubical extent of the building exceeds 28 000 m^3; and (*d*) the designed fire load of the building is likely to exceed 1135 MJ m^{-2}
Sprinkler systems	Required for all parts of the building including staircases and common corridors
Static or dynamic smoke extraction systems	(*a*) Required for atrium buildings of volume exceeding 28 000 m^3; for basement floors of volume exceeding 7000 m^3; and (*b*) for any fire compartment exceeding 7000 m^3 in that building where (i) the aggregate area of openable windows of the compartment does not exceed 6.25% of the floor area of that compartment; and (ii) the designed fire load is likely to exceed 1135 MJ m^{-2}
Ventilation/air conditioning control systems	Mechanical ventilation systems shall be stopped in the fire compartment.

Smoke control is important both for reducing the danger of death and injury to people and for efficient firefighting. Two approaches, pressurisation and smoke extraction (venting), are adopted to maintain a clear path through the egress system, to inhibit the spread of smoke, to protect human life and to reduce property damage.

3 Engineering performance-based fire codes

Whether existing fire codes will work with novel architectural designs and modern lifestyles living is a large question, as exemplified in the case of atria. Fire safety systems must be designed to cope with major disasters(11). Advances in building design result in buildings becoming larger, more complicated and more sophisticated. Increasingly, hazards in buildings with new design features (e.g. large atria) present new challenges for building designers. For example, what will happen when a fire occurs in the atrium of a large multi-storey shopping mall on a public holiday? According to Chow(12) the installed fire services systems will not be effective in controlling the fire and indicating the escape routes clearly. The main reason is that the local fire codes were developed on the basis of outdated information, perhaps suitable only for older generations of buildings. The design guides do not state clearly the best fire safety design for different types of buildings. For example, the use of space volume to determine whether smoke extraction systems have to be installed is certainly a mistaken concept(9); and installing sprinklers in a tall atrium will produce adverse effects to the occupants, particularly if steam is generated.(12)

Engineering performance-based fire codes are therefore proposed (e.g. References 7 and 13). These are developed based on the basis of research results from fire science and engineering, statistical fire records, firefighting experience and fire investigations. Mathematical fire models supported by full-scale burning tests are the main tool for assessing the fire risk of buildings and evaluating the performance of fire service systems. Appropriate fire codes based on these high-level academic studies should be established and implemented. Fire-engineered methods have been emphasised in developed countries, and the concept appears in standards and design guides (e.g. References 7 and 8). New Zealand is in the forefront of bringing fire engineering into its regulatory framework(14). The concept is being also actively promoted in Australia(15) with strong support from the federal government, the construction industry, steel, timber, concrete, ceramic product and furniture suppliers, academic institutions and research organisations(16). The concept is also supported by Canada; collaborative work with the Australians is under way.

4 Fire safety codes applied to an atrium

Many atria have been built in Hong Kong during the past twenty years. Large volumes and high ceilings are common design features(17). Atria are found everywhere in shopping malls, banks, office buildings and railway stations. They are usually crowded with people, especially on Sundays and public holidays.

Atria in buildings are not classified specifically in the local codes. Requirements are prescribed by building type. For example, high-rise commercial building is classified as such whether or not it contains an atrium. The minimum provisions for fire engineering systems, installations and equipment are as shown in Table 2. Geometric factors such as the ratio of the height to floor area of an atrium are not considered in determining the occupant-related fire safety requirements. For example, a fire starting (at, say, 5 MW) in a large space would not transfer heat to the building walls or ceilings. An atrium can be classified as 'high', 'cubic' or 'flat', which would affect its smoke filling time(9). A recent survey(17) showed that the lowest floors of atria are used multi-functionally, for instance as a food court or an exhibition area. Frequent and substantial changes in use and occupant number and consequent fire load may cause significant differences from design values. A single set of escape criteria may be inappropriate for atria. Using the lowest floor as an exhibition area results in frequently changing exit travel distances and access configurations. High numbers of occupants in a large atrium may be significant if fire breaks out. Phased evacuation is obviously not always practical.

In an atrium above ground with a single-compartment volume exceeding 28 000 m^3, a mechanical smoke extraction system must be provided. The configuration and installation of the system are considered for each atrium by the local authority. At least one extraction outlet is installed for every 500 m^2 floor area. The maximum allowed distance between the extraction outlet and the make-up air inlet is 30 m. The extraction flow rate is calculated in terms of the air change rate. At least 8 air changes per hour (ac h^{-1}) over the whole compartment volume of the atrium are required. The minimum make-up air flow rate is 80% of the extraction rate. However, this is unclear that '80% of the extraction rate' may be calculated in terms of 'the mass flow rate' or of 'the volume flow rate'.

Sprinklers are installed in the atrium if the space is in a building classification otherwise requires them, even if the headroom is high. The sprinklers are not only unable to control a fire, but will produce adverse effects for the occupants trapped(12) by the smoke being pulled downward and the production of a large volume of hot steam.

5 Atrium design following the fire codes

An atrium of length 34 m, width 23 m and height 41 m in a Hong Kong commercial building was considered. The space volume is 32 062 m^3. There are eight levels, each of floor area 1600 m^2. Figure 1 is a diagram of the atrium geometry, smoke management system, escape route and sprinkler system.

5.1 Smoke management

Fire shutters are installed at each level of the shopping mall adjacent to the atrium as in Figure 1. Their function is to isolate the atrium space but to leave floor-level entrances open. The shutters may be activated manually, automatically by smoke detectors or by flow switches in the sprinkler system, or on operation of the smoke extraction system. However, there is a distance of 6 m bewteen the balcony and the shutters for extracting smoke and supplying make-up air as in Figure 1. Care must be taken that people are not trapped in this buffer area.

A mechanical smoke extraction system was installed according to the local fire regulations. The system is actuated by smoke detectors installed in the atrium and the shopping arcade at each level. It can also be actuated within one minute by the fire alarm through operating the sprinkler; or by closing the fire shutter so as to isolate the shopping arcade. Separate smoke extraction fans and make-up air fans were installed at each floor. All fans would be operated in case of fire, with a total extraction rate of 8 air changes per hour. The make-up air supply flow rate is 80% of the extraction rate. The system aims at providing a slightly depressurised compartment for the atrium. Smoke extraction grilles were installed at the upper part of each floor and extended along the atrium boundary. Air ducts for the smoke extraction system were shared with the air-conditioning system. The air ducts were common to a mechanical ventilation fan and a smoke extraction fan, with a set of changeover dampers. In case of fire, the ventilation fans would be shut off and isolated but the smoke extraction fan would be connected and actuated. The make-up air is supplied through low-level air grilles in the retail shops furthest from the atrium edge. The ducts for the make-up air were common to the fresh-air supply system with changeover mechanisms.

The smoke filling process was not considered while designing the smoke management system. However, the smoke filling

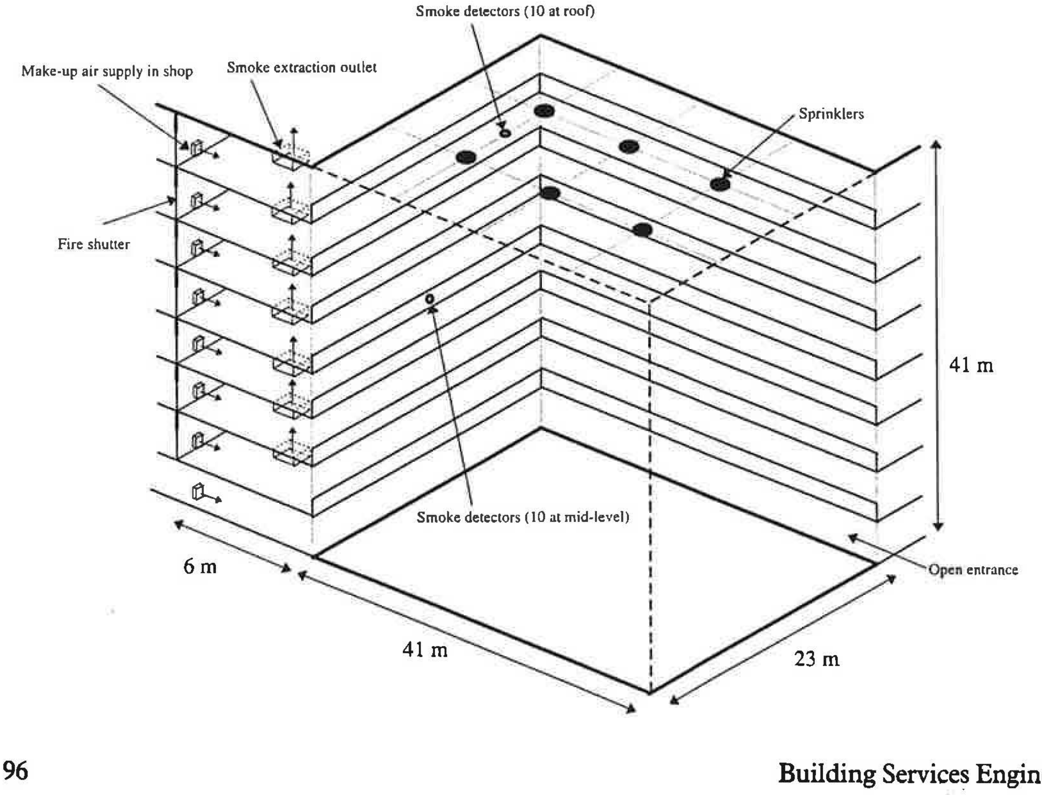

Figure 1 Model atrium

time in an atrium has been shown to depend on configurationt(9). The fire shutter might fail to prevent smoke penetration into the adjacent area. Smoke would spread to upper levels within one minute. The regulations did not specify clearly whether the requirement that 'the make-up air flow rate to be 80% of the smoke extraction rate' is calculated by the mass flow rate or the volume flow rate. For this atrium, the make-up air flow rate was specified at 80% of the smoke extraction volume flow rate at the ambient temperature. This approach is commonly employed for satisfying the local statutory requirements without considering the thermal expansion effect of the make-up air. It is difficult to obtain 'slightly depressurised compartments', and smoke would penetrate into adjacent areas. Moreover, the make-up air flow rate was calculated from the compartment volume, including the volumes of the atrium and adjacent shops. Also, introducing make-up air at the low level of the shops (i.e. the mid level of the atrium) would draw excessive cool air into the smoke layer. This cooling effect would cause 'smoke logging'.

5.2 *Escape route*

The maximum escape travel distance and the maximum sum of the direct distance and travel distance are 30 m for this atrium shopping centre. Spaces at each storey are partitioned into rooms, so the exit routes could not be assigned along the balcony, nor along the internal corridor. The maximum distances were determined on the assumption that the atrium floor was not occupied by furniture. But what happens when the atrium floor is used for a temporary exhibition? Exhibitions of motor cars, art, estate agency etc. would last from a few days to a few weeks. Large exhibition boards and exhibits would block both sight of the escape signs and the escape routes. Longer travel distances and a longer escape time would result, bearing in mind that many people would be attracted to the atrium floor by the exhibition.

5.3 *Fire engineering systems*

Fire engineering systems including sprinklers, hydrants, hosereels, emergency lighting and fireman's lifts were installed to satisfy the local regulations. The fire services systems required for an atrium high-rise commercial building in Hong Kong are shown in Table 2.

Ten smoke detectors are installed at the atrium roof, with another ten at the mid-level of the atrium walls. The smoke extraction system is turned on only when two smoke detectors are activated.

The atrium is protected by sprinkler heads installed at the ceiling at height 41 m. It is difficult to actuate sprinklers installed at this level because the smoke layer temperature is not high enough(12). Even though the sprinklers are actuated, the water density at floor level is much smaller. Whether a fire in the atrium can be suppressed by a sprinkler water spray discharged under the same operating pressure and flow rate as for ordinary buildings is still open to question. If a large water flow rate is applied, steam would be generated when the water droplets reach the fire. The occupants trapped in the atrium would be seriously injured by the steam. The downward drag of the sprinkler water droplets on the smoke layer would exceed its buoyancy for large water flow rates. Smoke logging will result.

6 Application of engineering approach

It has been demonstrated above that the existing fire safety codes are inadequate for the atrium. The 'engineering approach', that is, application of engineering performance-based fire codes would be a solution. The potential fire hazard in the atrium must be assessed.

The space volume for the atrium is 32 062 m^3, which is larger than the Fire Services Department (FSD) volume limit of 28 000 m^3 for special fire safety measures such as a smoke extraction system. The atrium is located in the lower part of the building which is used as a shopping mall, with the upper part used as offices. The atrium is of open design and connected directly to the adjacent area. Potential fire hazards should be identified so that adequate fire protection systems can be installed. Heat and smoke are the two key elements to be addressed for fire safety.

Smoke movement and smoke management systems have been studied extensively(18–22). The National Fire Protection Association of the USA has been developing a code which sets out a fire engineering approach to the design of smoke control for atria(18–20). These atria systems do not rely on pressurisation, but on the buoyancy due to hot smoke. Relatively 'smoke free' conditions will be maintained below a smoke layer. Further, smoke entry to the atrium from adjacent spaces is assumed. The theory to estimate the amount of air entrained into free thermal spill plumes was developed at the Fire Research Station of the UK Building Research Establishment(21). Recent work on thermally buoyant horizontal flow and gathered plumes is also addressed in the spill plume calculations. The calculations can be done manually but this may be time-consuming. Design features have been included in the recent *CIBSE Guide*(22). Design requirements for fire precautions in the design, construction and use of shopping complexes are given in Reference 7, where the such smoke control provisions as the smoke control zone, smoke reservoirs, ventilation systems, and inlet air supply are included.

The two-layer zone model CFAST(23) developed at the Building and Fire Research Laboratory, National Institution of Standards and Technology, USA may be used as a tool for assisting fire assessment.

6.1 *Thermal and smoke aspects*

The atrium floor is used as a circulation space, and so the fire load density is not expected to be higher than the FSD limit of 1135 MJ m^{-2}(4). The dead fire load can be controlled to ensure that the FSD limit is not exceeded. Good staff training in fire safety management will enable the live fire load to be minimised. Therefore the thermal aspect should not be unduly significant and sprinklers are not required.

Smoke is identified as a key consideration, as there are shops adjacent to the atrium. A large volume of smoke will be generated and will spread to the atrium space if a shoe shop is on fire. Therefore, smoke management systems(18–20) must be installed so that smoke is retained at the fire origin without spreading out (the smoke control concept); and smoke extracted from relevant areas (smoke removal).

6.2 *Fire shutters*

Because of the 'open' design for this atrium, a fire occurring at the atrium floor will affect and be affected by the adjacent area. It is obviously likely that smoke generated from the fire will spread into the adjacent upper levels. It is also possible that the plume induced by a fire might not be able to ascend because smoke might lose its buoyancy, fall and move sideways. Vertical pressure differentials due to operating the air-conditioning systems at the shopping mall balcony will promote this sideways movement. A fire occurring in a shop spread smoke into the atrium. It is also possible for smoke to pass from one level to another through the atrium. Again, the pressure differences at various levels will facilitate this spread. Fire shutters are installed at each level so as to isolate the atrium from the adjacent shops. Shutters should be kept as close to the atrium space as possible.

6.3 *Fire simulations*

Suppose that a 5 MW fire of size 3 × 3 m of duration 1 800 s is located at the atrium floor. Fire shutters are operated to enclose the atrium space, leaving the four entrances at the floor of height 5 m. The problem was simulated using the two-layer zone model CFAST(24).

The time required to fill up 80% of the atrium with smoke (with the smoke layer interface at height 32.8 m) is less than 15 s, when the smoke temperature is very low at 32 °C. The maximum smoke temperature will be 92 °C, occurring at 1800 s, and the corresponding smoke layer interface height at this time is 4.7 m. The minimum smoke layer interface height is 4.5 m at 270 s when the corresponding temperature is 58 °C. The simulation results thus show that the thermal aspect is not too important.

Smoke will flow out from the atrium to outside when the smoke layer falls to the top of the entrance, i.e. the smoke layer interface height is 5 m. This occurs at 180 s, and the maximum flow rate of 8.87 kg s^{-1} per entrance door is found at 180 s.

The simulation was repeated with the same conditions but with the thermal power of the fire increased to 10 MW. The time required to fill up 80% of the atrium with smoke is less than 10 s, slightly faster than with a 5 MW fire. The smoke temperature at this time is only 33 °C. The maximum smoke temperature predicted is 130 °C at 1650 s; and the corresponding smoke layer interface height at this time is 4.6 m. The minimum smoke layer interface height is 4.3 m at 180 s when the corresponding temperature is 67 °C. The maximum flow rate of smoke per entrance opening is 15 kg s^{-1} at 180 s.

Simulation at double the thermal power confirms that the thermal aspect is not important as the maximum temperature is 130 °C. A 10 MW fire is unlikely in an atrium used as circulation area, but smoke will nevertheless fill 80% of the atrium space within 15 s.

6.4 *Atrium sprinkler*

Although the space is located in a commerical building with a shopping mall, sprinkler installation at the atrium ceiling is not recommended. The reasons have already been clearly set out(12) and the main points of concern are:

- thermal activation of the sprinkler head high in the atrium.
- no burning objects to be cooled on the atrium floor
- 'smoke logging' due to smoke cooling and the drag effect of the water spray
- Production of steam while cooling the hot smoke layer, hot wall surfaces or burning objects (if any).

6.5 *Recommendations*

The following recommendations are made on the basis of preliminary assessment of fire safety design for the model atrium:

- Install a smoke curtain and smoke extraction system in the atrium space.
- Train the mall security personnel well in fire safety management; in particular in keeping combustible contents to the minimum, directing the occupants to escape by the correct route in case of fire, and in routine checking of all fire protections.
- Spriklers are not recommended, even though the space is classified for commercial use.

7 Conclusions

A brief review of the existing fire safety codes in Hong Kong is presented in this paper. They are demonstrated to be inadequate for atria. It is timely to review current fire safety codes critically and to ascertain whether they can cope with new fire safety problems. Research and development are necessary for support the formulation of new codes. Performance-based fire codes are strongly recommended for buildings requiring special design. The application of an engineering approach to fire safety design for atria is demonstrated.

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