An Analysis of Smoke Management in High Rise Buildings

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Abstract: The concept of the fire-resistant building is promptly discussed while designing and incorporation mechanical systems into the building, while smoke management is deeply forgotten in the initial stages and even in later stages of equipment installation. Although, it is a well-established fact that smoke is more dangerous to life and life-taking than a fire during a fire in a building. In this study, active and passive methods like a smoke purge, pressurization control, smoke reservoirs, etc. of creating a building smoke proof are discussed. Also, factors influencing these active and passive measures like buoyancy, stack effect, etc. are discussed, and how to calculate the implication of these factors are assessed. The design guideline from different codes like NFPA 92, NFPA 92A, NZBC C3/AS 1530.4, BS 476 part 24, ISO 5925/1, design of smoke management systems for buildings published by ASHRAE, are reviewed for smoke management, and analysis of most relevant and new research in the field of smoke management systems that demonstrates significant evolution in the field. The idea of the smoke-resistant building can be easily achieved if incorporated in the early stages of design, even if applied with proper technique and equipment can also be achieved in later stages.
***Keywords*:** smoke management, smoke purge, pressurization control, buoyancy, stack effect

1. Introduction

When a substance undergoes combustion or pyrolysis gases emitted, smoke is a collection of flying solid and liquid particles and those gases, as well as the amount of air entrained or otherwise mixed into the mass. Although, smoke management is a term used interchangeably with smoke control to define the use of active or passive means to minimize and control smoke movement within a building in the event of a fire (Kulkarni and Agashe, 2016). Life safety, lower risk evacuation route, lower smoke migration to additional building spaces, property protection, aid in fire department operations, and post-fire clean-ups are all goals of smoke control systems (NFPA ® 92A, n.d.).

2. Smoke management

During developing a smoke management system, the smoke management system can be properly designed only with agreement on the objectives of the system (Klote et al., 2002). The smoke management system must be built as a comprehensive mechanical control system capable of operating successfully in the smoke management mode (Ferreira & Strege, 2005). The smoke management system should be built separately from the HVAC system and then incorporated, when possible, without impacting the smoke control system's functionality. The smoke control system must be efficient, simple, and easy to maintain (XLS1000 Smoke Management Application Manual P/N 74-3118 • Rev 2.0 • 04APR03, 2003). The smoke control system must be built to reduce the chances of failure and must be tested regularly. Sensors that provide operational status and building automation controllers that provide system monitoring and printed records can help with the testing process.

2.1 Importance of smoke ventilation

Smoke ventilation is considered an important part that shall be implemented in the designing phase of the building as this improves the conditions for safe passage and permits the fire to be fought in its early stages. Smoke ventilation creates a smoke-free layer above the floor by removing smoke or by moving smoke towards the ceiling which shall create enough height for safe passage. In high-rise buildings atrium is also considered to be one of the best options for smoke ventilation.

2.2 Factors affecting smoke management

Smoke management is based on two processes production of smoke and movement of smoke if the understanding of factors involved in these processes is created then it will be easier to handle the smoke management of a high-rise building through active and passive measures. Factors involves in the production of smoke are the size of the fire, nature of the material under combustion, smoke temperature, air entrainment, the effective height of the column of hot gases above the fire (Klote et al., 2002) which can be related to the equation:

$$M = 0.096 P P_O y^{\frac{3}{2}} \left[g \frac{To}{T} \right]^{\frac{1}{2}}$$

Where:
P = perimeter of fire (m)
y = Distance between floor & bottom of smoke layer under ceiling (m)
P_O= Density of the ambient air (1.22 kg/cum at 17 degree C)
T_O = Absolute Temperature of ambient air (290 K)
T = Absolute temperature of flames in smoke plume (1100 K)
g = Acceleration due to gravity (9.81m/s^2)
M = Rate of Production of smoke

Smoke Movement on the other hand based on factors like buoyancy (self-mobility), air movement. Buoyancy typically is, if gas or smoke is lighter than the surrounding air, it will rise. As it is obvious that smoke from the fire is hotter and because of that, it is lighter than the surrounding air. Air movement is a fire surrounding is based on certain factors like stack effect, wind effect, expansion, mechanical ventilation.

2.2.1 Stack effect

Stack effect is the effect caused by the indoor and outdoor air temperature. Because of this temperature difference, there is a difference in the air density inside and outside of the building (Riebau and Fox, 2001). This difference creates the pressure difference which then causes vertical movement of the air within the building. This process of movement of air because of pressure difference is known as the stack effect. Depending on the temperature of the outside of the building there are two types of stack effects normal stack effect and reverse stack effect.

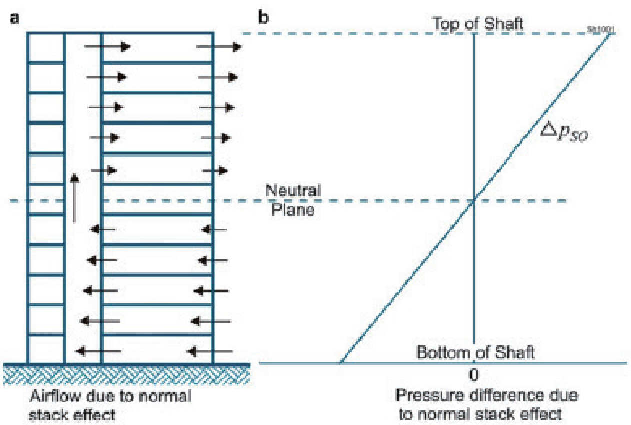

Figure 1. Airflow and pressure differences of normal stack effect.

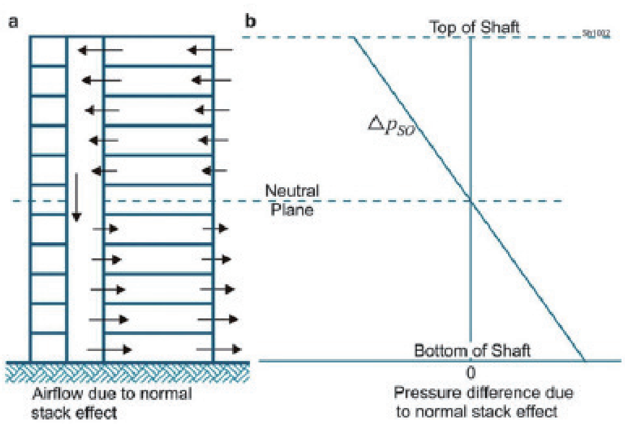

Figure 2. Airflow and pressure differences of reverse stack effect

The pressure difference across the exterior wall caused by temperature difference whether normal or reverse stack effect, according to Design of Smoke Management Systems for building published by ASHRAE is expressed as (William Webb & Member ASHRAE, n.d.):

$$\Delta P = K_S \times \left(\frac{1}{T_O} - \frac{1}{T_i} \right) \times h$$

Where:
ΔP = Pressure difference in W.C
K_s = Coefficient, 7.64
T_O = Absolute temperature of outdoor air, Rankine (R)
T_i = Absolute temperature of the air inside the shaft, Rankine (R)
h = Distance from the neutral plane, ft

2.2.2 Wind effect

Wind effect contributes to the horizontal spread of smoke from the Leeward side to the windward of the building. The outdoor air that causes the infiltration and exfiltration can also cause the movement of smoke to areas other than the fire compartment (Harrison and Spearpoint, 2006). Although, this effect is negligible on a tightly constructed building. However, buildings with open doors or windows or loosely constructed buildings can face significant effects. The pressure caused by wind on a building surface can be calculated with the same pressure difference equation.

2.2.3 Expansion

Expansion is the energy released by the fire with the help of which expansion of hot gases takes place which can move smoke. It depends on the number of openings if there are few openings then the pressure difference is large. The volumetric flow of smoke out of a fire zone is greater than the airflow (Król, 2011) is expressed as:

$$\frac{Q_{out}}{Q_{in}} = \frac{T_{out}}{T_{in}}$$

Where:
Q_{out} = Volumetric flow rate of smoke out of the fire compartment, cfm
Q_{in} = Volumetric flow rate of air into the fire compartment, cfm
T_{out} = Absolute temperature of smoke leaving the fire compartment, Rankine (R)
T = Absolute temperature of air into the fire compartment, Rankine (R)

For tightly sealed fire zones, the pressure differences across the barrier caused by expansion can be extremely important. Venting or relieving pressures created by expansion is critical to smoke control. Venting is often accomplished with smoke vents and smoke shafts.

2.2.4 Mechanical ventilation

Smoke conveyance can be done even when the system is turned off, through the means of HVAC (e.g., a bypass damper venting smoke) (Courtier and Wild, 1991). HVAC system when utilized in the smoke control methods will help in providing a cost-effective while also meeting the requirement of zone pressurization. In a residential setup, even an air-handling system can also be used to control smoke (Kamal and Khan, 2021). Such a system, if left running, may help in preventing smoke from entering the common and hence protect the non-fire dwellings (Tamura, 1994). In case of fire, the HVAC system can be set to fire mode, which will help in protecting all non-fire floors by 'under-pressurizing' the fire floor compared to nearby floors. Such systems, known as zone or sandwiches (Klote and Klote, 2012).

3. Active methods of smoke management

Active methods of smoke management involve systems through which smoke is dispersed or diluted with the help of advanced equipment and will help in creating a safe passage for the user. Active methods involve airflow method, dilution/smoke purge, exhaust method pressurization, zone smoke control, stairwell pressurization control, zone pressurization control and dedicated mechanical smoke venting, etc (Chow and Chow, 2005). With the help of these methods, when applied to different areas of the building according to space requirements it will help disperse and dilute smoke.

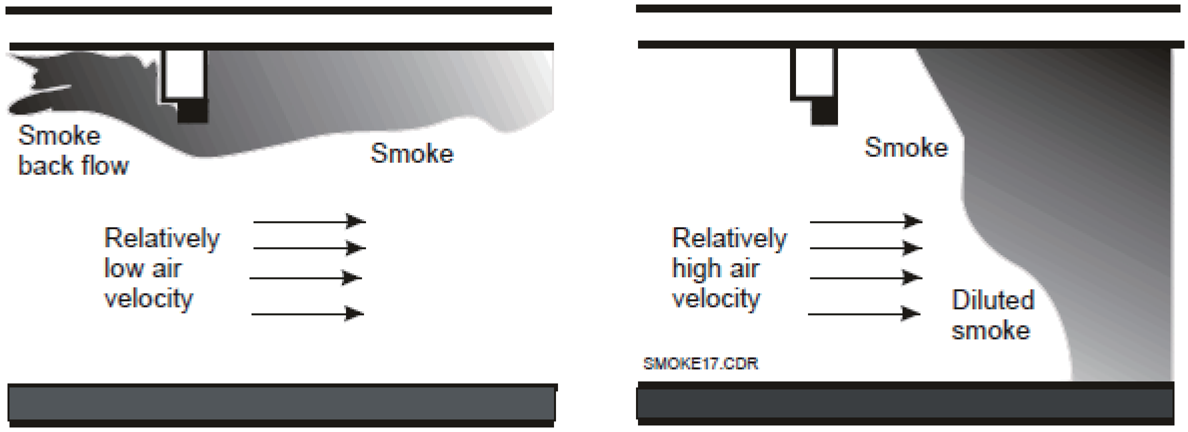

Figure 3. The airflow movement of smoke

3.1 Airflow method

It is the most used method to stop smoke movement through open doorways and corridors. Figure 3 illustrates a system in which a system with relatively high velocity is used to prevent the backflow of smoke through an open doorway. Figure 3 also illustrates a system of relatively low velocity is used to backflow of smoke. The magnitude of the airflow velocity required for the prevention of backflow depends on the energy release rate of the fire. Since the energy release rate can vary, the velocity of the airflow should be regulated to prevent oxygen from being fed to fire. Consideration of the factor that doors maybe sometimes left open during the evacuation of a building, which allows smoke to flow through, should be considered while designing the smoke control system. This can be achieved by designing and testing the system with one or more open doors.

3.2 Dilution/smoke purge

Fire produces large quantities of smoke because that purging cannot ensure breathable air in space while a fire is in progress. But after the fire, purging is necessary for the firefighters to verify that the fire is much extinguished. Traditionally, firefighters used open windows and doors to purge an area. Where open doors and windows are not present or not possible to purge the smoke through them, purge mode HVAC can be designed. In the zones where smoke has entered and is being purged principle of dilution can be applied. Purging dilutes the contaminated air and can continue until the level of cloudiness is reduced and the space becomes reasonably safe to enter. The following equation allows determining a concentration of containment in time:

$$C = C_O \times e^{-at}$$

Where:

C = concentration of a contaminant at the time, t

C_O = initial concentration of contaminant

a = purging rate in the number of air changes per minute

t = time after doors close in minutes

e = constant, approximately 2.718

Factors like buoyancy must be taken into consideration because of the nonuniformity of the smoke.

3.3 Exhaust method pressurization

With the help of the pressurization of non-smoke areas, smoke can be contained. In a smoke control system, a static pressure difference is required across the barrier to perform correctly (Shi-long, 2012). Figure 4 illustrates such an arrangement with a door in a wall. With the help of this static pressure difference, the high-pressure side can act as an escape route and the low-pressure side as a containment area.

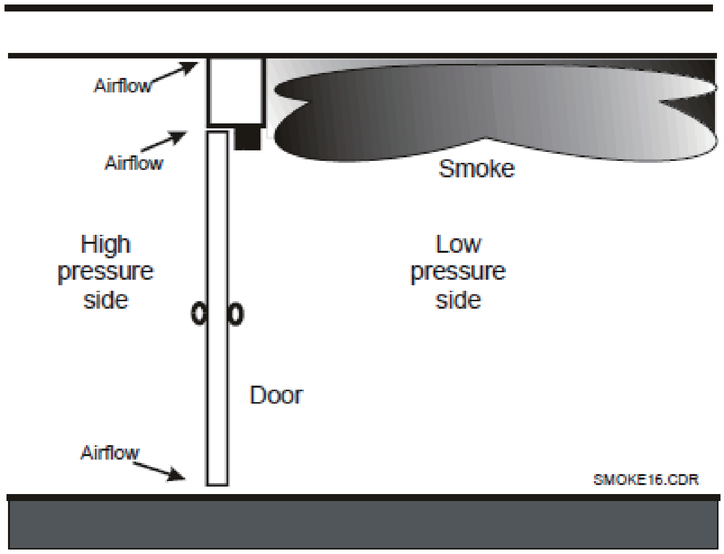

Figure 4. The smoke pressurization

Pressurization values for the smoke control system can be referred to in NFPA 92A, which can be seen in Table 1 (NFPA ® 92 Standard for Smoke Control Systems Handbook 2012, n.d.). The design pressure difference in table 1 is the pressure difference between the smoke zone and adjacent spaces while the affected areas are in the smoke control mode (XLS1000 Smoke Management Application Manual P/N 74-3118 • Rev 2.0 • 04APR03, 2003). The smoke control system should be able to maintain these minimum pressure differences while the building is under the typical condition of stack effect and wind (Hilditch, 2017). This table is for gas temperatures of 1700F adjacent to the barrier. To calculate pressure differences for gas temperatures other than 1700F, refer to data in NFPA 92A (NFPA ® 92 Standard for Smoke Control Systems Handbook 2012, n.d.).

Table 1. Suggested minimum design pressure differences across smoke barriers

Building Type	Ceiling Height (ft)	Design Pressure Difference (in. wc)
Sprinklered	Unlimited	0.05
No sprinklered	9	0.10
No sprinklered	15	0.14
No sprinklered	21	0.18

Along with the minimum pressure difference, it is also necessary to understand maximum pressure differences across doors.

Table 2. Maximum pressure difference across doors in wc Source: (NFPA 92)

Door Closer Force (lb-ft)	Door Width (in.)				
	32	36	40	44	48
6	0.45	0.40	0.37	0.34	0.31
8	0.41	0.37	0.34	0.31	0.28
10	0.37	0.34	0.30	0.28	0.26
12	0.34	0.30	0.27	0.25	0.23
14	0.30	0.27	0.24	0.22	0.21

The door widths in Table 2 apply only for doors that are hinged at one side. For other arrangements, ASHRAE design of smoke control systems for buildings can be referred to.

3.4 Zone smoke control & stairwell pressurization control

The main requirement of a zone smoke control system is compartmented volumes. The compartments are formed by a smoke barrier which is defined by NFPA 92A as “a membrane, either vertical or horizontal, such as a wall, or ceiling assembly, that is designed and constructed to restrict the movement of smoke. A smoke barrier may or may not have a fire-resistance rating. Smoke barriers may have openings protected by closing devices or adequate airflows.” Zone smoke control is used in hospitals, high-rise buildings, and similar buildings occupancies where the objective of the system is to prevent smoke spread from one compartmented area to another (Hurley, n.d.).

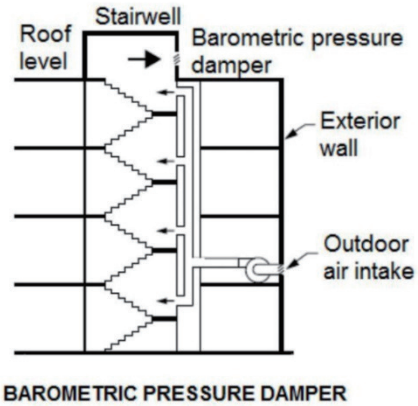

Figure 5. Stairwell pressurization with modulating dampers and multiple injection points to regulate pressure.

The main aim of stairwell pressurization is to provide an acceptable environment within a stairwell. To design a proper stairwell pressurization system, means are necessary to modulate either the exhaust or the supply. Also, multiple supply injections at a minimum of every three floors are needed to be provided for uniform pressurization (Lougheed, 2001). There are two types of systems for stairwell pressurization according to NFPA 92A one is closed-loop and the other is a more complex system that modulates dampers or fans at multiple injection points.

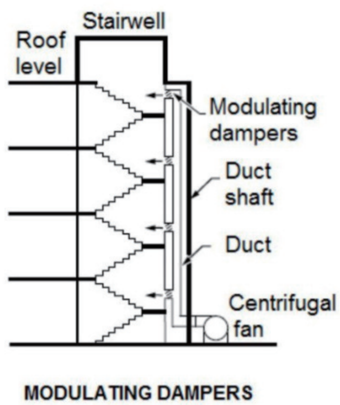

Figure 6. Stairwell pressurization with barometric pressure damper to vent to the outside

3.5 Zone pressurization control and mechanical smoke venting (dedicated)

The basic concept of zone pressurization control is to exhaust smoke, generally, it is done by mechanical means (Poh and Airah, n.d.). By maintaining the floor which caught fire at negative pressure and the other floor at positive pressure, the spread of smoke can be limited to only one floor. Typically, this pressurization difference can be created with the air-handling system, by providing 100 percent fresh air to all floors and extracting air from the floor that caught fire. Rather, the main purpose is to create a pressure differential with the adjacent floors [Klote & Milke, 2002]. It is known also by the term sandwich pressurization (Marchant, 1992), the terminology referencing the fact that the fire floor at negative relative pressure is ‘sandwiched’ between floors at positive pressure above and below (Thomas et al., 2018). The zone pressurization can be achieved by providing supply air to adjacent zones, shutting off all returns or exhausts to floors other than the fire floor, exhausting the smoke zone, shutting off, providing supply air to, or leaving under temperature control all supplies other than those adjacent to the fire floor. A smoke control zone can consist of one or more floors or simply a portion of a floor.

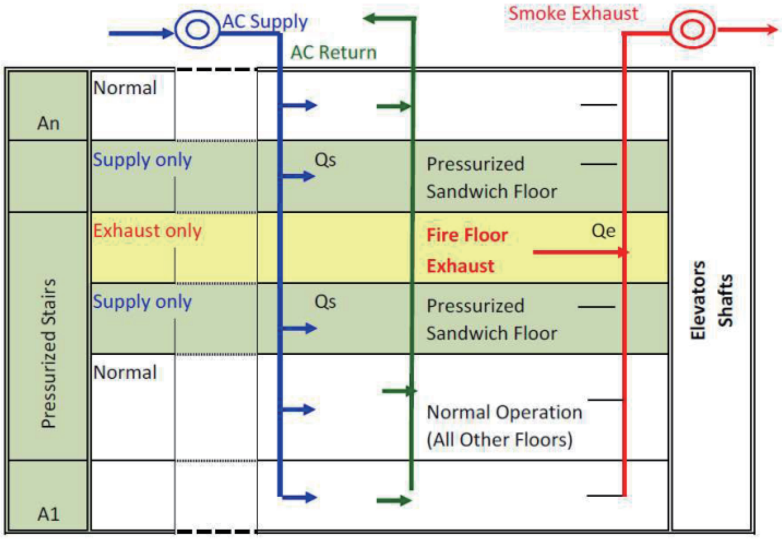

Figure 7. The pressure sandwich

Mechanical smoke venting refers to the provision of dedicated smoke exhaust by mechanical means other than zone smoke control or mechanical dilution scheme. The mechanical smoke can be designed for two possible purposes, one is to create tenable conditions inside the fire compartment and the second is to depressurize the space in question (Li et al., 2018). The design of mechanical smoke shafts venting directly from the compartment(s) of fire origin was studied in some depth in the early years of smoke control analysis (Tamura and Shaw, 1973) are probably most appropriate for office spaces where in Canada design guidance is provided (National Research Council Canada, 1995).

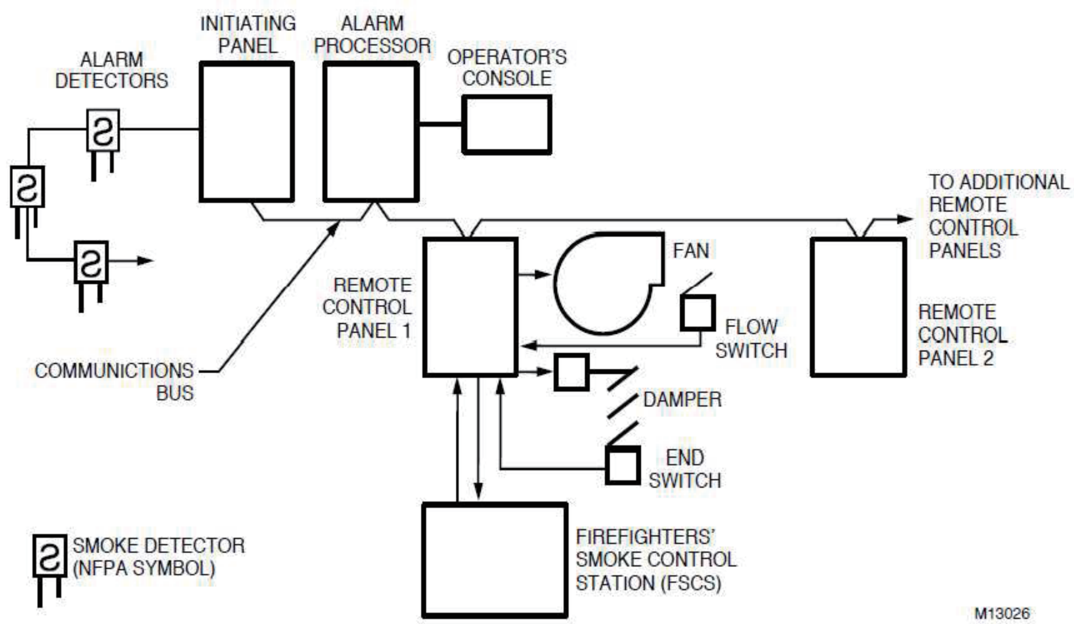

Figure 8. Typical smoke system meeting the requirements of UL Standard 864 and NFPA 92A

4. Passive methods of smoke management

The passive method utilizes different areas of a building by walls that extend from the floor to the bottom of the roof deck. These "compartments" may use self-closure devices (fire dampers, doors) to trap smoke and create a smoke reservoir. Passive smoke control systems involve smoke barriers, natural ventilation, and smoke reservoirs from built-in features of the building that are always functional (Rabia, n.d.). They serve one or both two purposes, one is to restrict the spread of smoke and fire by restricting ventilation or creating barriers and the other is to restrict the passage of smoke to areas that are away from escape routes of the occupants. Effective performance of passive smoke control systems is founded on their ability to maintain integrity for the required duration and intensity of the fire. Real fire temperatures may vary greatly from the standard time-temperature curves (ISO 834, 1975) used in testing the fire-resisting performance of construction elements (Australian/New Zealand Standard, n.d.).

4.1 Smoke barriers and smoke reservoirs

The smoke barrier is the resistance and containment of smoke through a proper barrier that can be incorporated in the design or later stage in the building. Ceilings, walls, and imperforate floors form adequate smoke barriers. The problem of smoke leakage arises where there are perforations or construction joints present in these elements. On the other hand, a smoke reservoir restricts any horizontal spread of smoke. Smoke reservoirs are structured underneath the roof or ceiling to form a pool that stores rising smoke from the spaces within the fire compartments, from where smoke can be extracted easily (Huang et al., 2020). In a high-rise building, where there are large connecting spaces between floors, smoke reservoirs are needed to be provided directly above such spaces to prevent the staggering of smoke into upper floors (FRN-1001, n.d.).

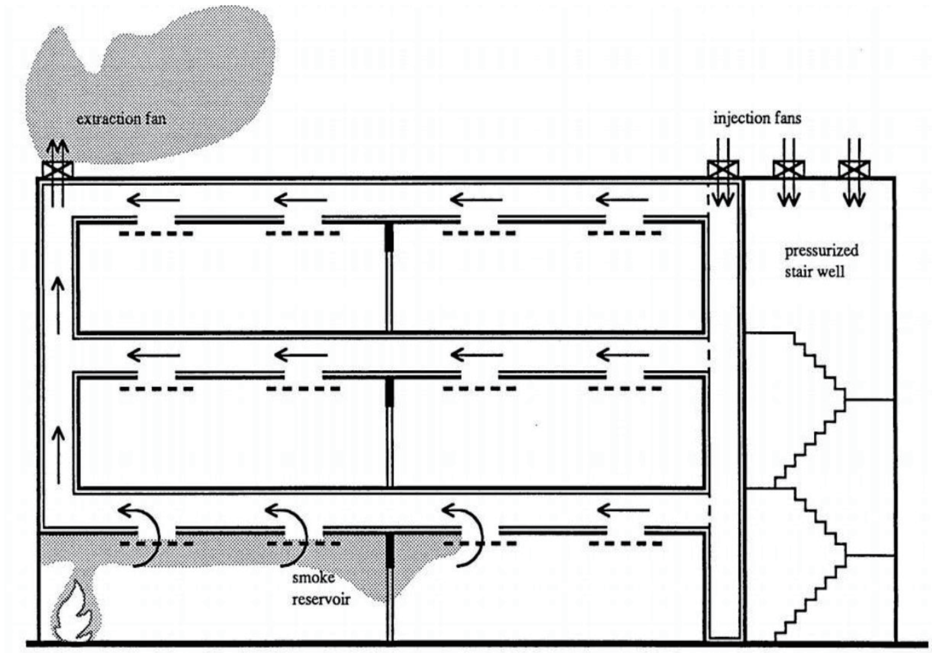

Figure 9. Smoke reservoir in comparted buildings

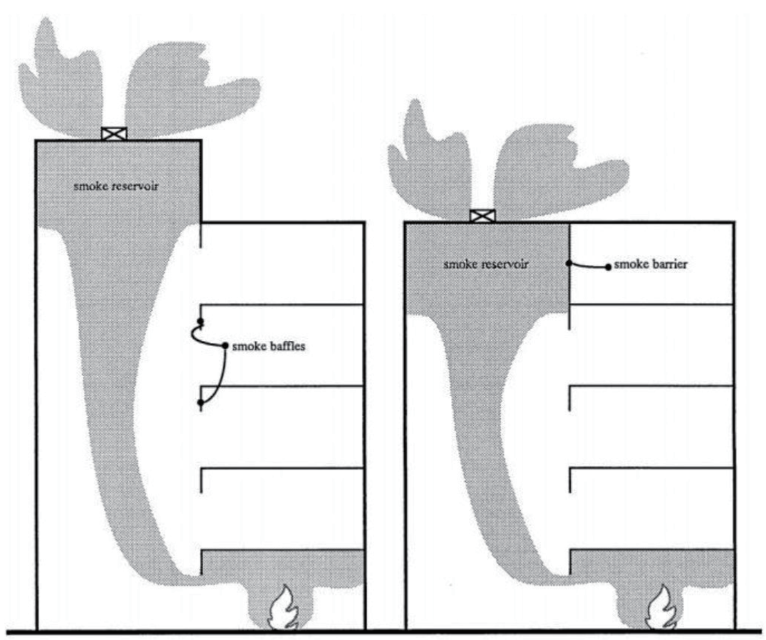

Figure 10. Smoke reservoir in buildings with connecting space

5. Analysis and discussion

In this study, various active and passive measures from various codes and recent research papers, and research advancement in the field of smoke management are analyzed. And based on the analysis, it is evident if the smoke factor is considered at the stage of design then passive measures like smoke barriers and smokes exhaust can be incorporated at the design stage, then the building can be made smoke efficient without even implementing active measures. Even if the passive measures are neglected at the early stage or if there is an existing building that needs to incorporate a smoke management feature or the building is tightly packed and there is a significant risk of smoke. Then, there are many active measures like pressurization control of stairs and lift, smoke dilution, providing dedicated mechanical venting, or creating a compartment around the space which is at the high rise of fire and creating a pressure difference between spaces. Also, there is much automatic equipment like smoke detectors and automatic smoke vents which require minimum human intervention and create a safe environment. These methods will help in creating safe escape routes for the occupants of the building and overall help in saving the life and minimizing the damage to the building.

6. Conclusion

There are many active and passive measures through which smoke management can be easily achieved in any building. In the case of a building that is at high risk of smoke staggering there is a need to provide dedicated smoke vents which can work along in the same vents as the HVAC vents, but these smoke vents are needed to be attached with the smoke detecting system that only operates when detectors detect smoke. Further study on smoke vents efficiency like probable positioning of smoke, probable air flow rate of the vents according to space, the number of vents among all that provide and exhaust the air from the space according to space size is needed to be carried out. For any building that happens to have basic active measures like stairwell pressurization, lift well pressurization, the distance between stairs seems to mostly fail in case of smoke and fire as the basic aim of the designer is only to comply with code but not to save a life if the real situation happens. There is a need to create awareness about the damage that smoke can cause to the life of the occupant and the building. Although the currently active system when combined with the passive measures is proved to be sufficient for any high-rise building, it is necessary for every building to consider the factor of smoke along with the factor of fire-resistant.

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