Chapter 6
Façade Fires in High-Rise Buildings: Challenges and Artificial Intelligence Solutions

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6.1 Introduction

United Nations Member States adopted the 2030 Agenda for sustainable development in 2015, providing a blueprint for peace and prosperity for people and the planet [1]. Global partnerships are called for through its 17 sustainable development goals (SDGs), which are an urgent call for action by developed and developing countries. Goal 11 of these SDGs focuses on making cities and human settlements inclusive, safe, resilient, and sustainable [2]. To achieve this the construction industry is employing new techniques and materials to meet the ever-growing demand for high-rise buildings and make them sustainable. However, these high-rise buildings have associated fire safety risks that usually include [3–6]:

- Rapid external and internal spread of fire and smoke
- Difficult firefighting and rescue
- Difficult safe evacuation of the occupants
- Fire lasting for a longer time
- Stairwell filling with smoke
- Electrical short circuits

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- Cooking and heating equipment failure
- Carelessness and human error in handling and storing combustible materials

Façades are also being increasingly used to protect these buildings from wind, rain, and sunlight, and have become an integral part of the building. Figure 6.1 shows some of the buildings with façades.

The façade of a high-rise building is one of the components most susceptible to damage, especially in the event of a fire [7, 8]. Consideration of fire safety procedures has been hampered by visual appeal, efficiency of energy, materials, and sustainability. The problem has gotten more difficult as the number of high-rise structures has increased, providing a greater fire threat. The construction industry is utilizing various combustible materials in building façades to achieve sustainability and cost-effectiveness, which presents fire safety concerns [7, 9–11]. These are relatively low-frequency events, but they result in immense loss [12]. Many accidents worldwide have already proved the magnitude of fire risk involved in these façades (Fig. 6.2). Considering the severity of these accidents and to meet SDGs (specifically goal 11) of the Paris Agreement [1, 2], there is an urgent need to study façade fires to prevent future occurrence. However, due to their complex construction features and the presence of a variety of flammable items, fire scenarios can be complicated for these buildings. Undoubtedly, such fires cannot be reconstructed physically. Possible alternatives are assessing these complex fires in high-rise buildings using experimental set-ups and/or a modeling-driven approach [7, 11, 13–19] and developing test standards [20]. This chapter presents an overview of characteristics and testing methodology for understanding high-rise building fires with a particular focus on façades.

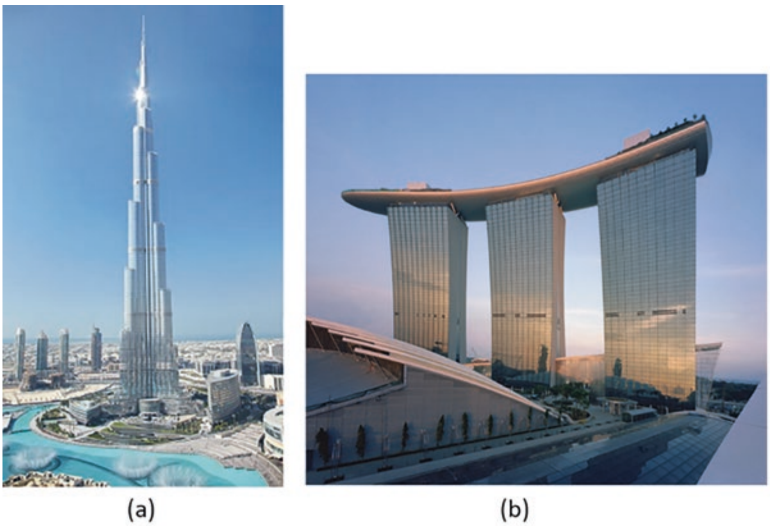

Fig. 6.1 Commonly used façades in high-rise buildings (Source: Google Images)

Fig. 6.2 Grenfell tower fire accident in London UK (2017) [21]

6.2 Fire Growth: From Internal (Enclosure) Fires to External Spread

Fires are one of the most severe load situations for any construction. The capacity of the construction to endure then depends on how effectively it is planned. As previous big fires clearly have demonstrated, façade design may have a significant influence on the course and rate of fire spread. To understand how enclosure fires can spread to external façades, firstly there is a need to understand how fire initiates, grows, and propagates in a compartment and reasons for flashover occurrence. The advancement of fire spread is usually described as a curve dependent on time and energy or heat release rate (HRR) and is commonly known as fire growth curve, illustrated in Fig. 6.3. As can be seen, it consists of four main stages:

- Ignition and growth
- Flashover
- Fully developed fire
- Fire decay

Initially, the fire will start in a compartment if all three components of the fire triangle, i.e., fuel, heat, and oxygen, combine to produce a chain reaction. After the fire has ignited, its further growth is mainly influenced by the chemical and physical properties of fuel (heat of combustion, ignition temperature, chemical composition, density, etc.) and its configuration (shape and size) and hence also known as fuel-controlled fire. It is commonly expressed using the power-law equation as:

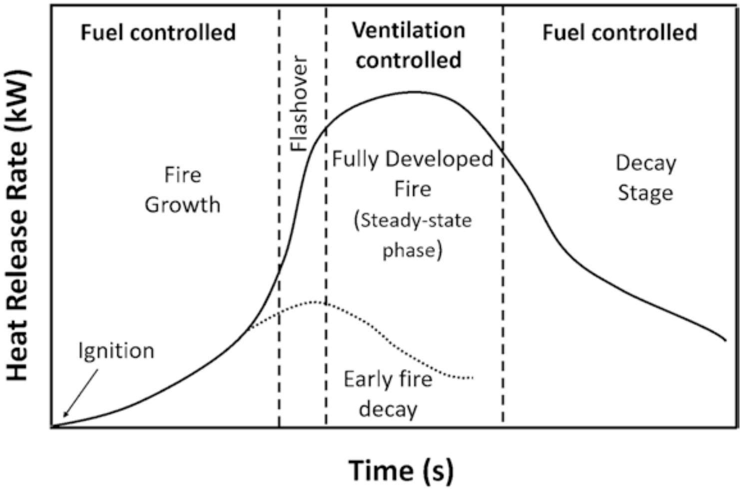

Fig. 6.3 Fire development curve for an enclosure [9, 22]

$$Q = \alpha t^2 \tag{6.1}$$

where Q (kW) is the heat release rate (HRR), t (s) is the time, and α (kW/s^2) is fire growth coefficient. HRR is not a fundamental property of fuel and has to be determined from testing either using oxygen consumption calorimetry (ASTM E1354) [23] or using mass burning rate $\dot{m}$ (kg/s) as:

$$Q = \dot{m}\Delta H_c \tag{6.2}$$

where ΔH_c is the heat of combustion (kJ/kg). HRR can be as low as 5 W for a burning cigarette [23] or can range from 7 kW to 2 MW for a liquid pool (d = 0.1–1 m) [24–26]. HRR growth period may be ultra-fast, fast, medium, or slow depending upon the critical time of 75, 150, 300, and 600 s, respectively, to reach 1055 kW [23]. It is characterized by the appearance of a fire plume that reaches the ceiling, and further spread occurs first as a ceiling jet and then in the form of a smoke layer. The short stage between growth and the fully developed fire is known as flashover when the fire spreads rapidly, and all the combustibles present in the compartment are involved. Flashover occurs when the temperature in the ceiling level has reached 600 °C or radiation to the floor of the compartment is greater than 20 kW/m^2 [23]. After flashover, fire reaches its fully developed state. It also marks a transition of fire from fuel-controlled to ventilation-controlled as at this stage, all the fuel is involved in the fire, so further growth will depend on the amount of air/oxygen available. After all the combustible items have burnt, fire again becomes fuel-controlled and starts decaying due to decreased fuel load and eventually extinguishes when no fuel is left.

It must be noted here that the fire curve depicted in Fig. 6.3 is ideal and need not be necessarily followed by all enclosures. It depends on various parameters, including ventilation conditions and available fuel load, which directly affect fire growth by changing the peak heat release rate and burning duration. If during the growth stage, sufficient ventilation and fuel are not available, fire may not reach flashover or fully developed stage and experience early decay without burning the entire compartment, as displayed in Fig. 6.3.

Enclosure fires often lead to external fires depending upon the energy released during the fully developed stage, which being ventilation-controlled is dependent on the ventilation factor (F_v) [27, 28] an expression derived for the ventilation factor as:

$$F_v = A_0 H_0^{0.5} \tag{6.3}$$

where A_0 (m^2) and H_0 (m) are the area and height of the ventilation opening, respectively. Based on this ventilation factor, maximum heat release rate HRR_{in} (kW) in fully developed stage inside an enclosure can be calculated as:

$$HRR_{\text{in}} = 1500\ A_0 H_0^{0.5} \tag{6.4}$$

Enclosure fires generating HRR higher than HRR_{in} result in flames coming outside the doors and windows with heat release rate HRR_{ext} (kW) as:

$$HRR_{ext} = HRR - HRR_{\text{in}} \tag{6.5}$$

HRR_{ext} impinges directly on the façade, and in the case of high-rise buildings with combustible façades, it will lead to rapid vertical fire spread from one floor to another depending upon the type of façade system installed on the building. Commonly used façade systems are discussed in the next section.

6.3 Façade Systems and Types

Designed by advanced engineering methods and techniques, these external façade systems have become complex and constitute a significant percentage of the building's overall cost. In recent years, the configuration of façade systems has changed from simpler to complex to meet various needs like protection from wind, rain, and sunlight, providing insulation and aesthetic sense to the building. However, this shift to thinner, lighter, and more energy-efficient systems has also led to an increased potential risk of fires. Common types of façade systems demonstrated in Fig. 6.4 are described below [9, 12]:

(a) **Monolithic façades:** This is the simplest form of façade and consists of a single layer of non-combustible material such as concrete, brick, or glazed curtain

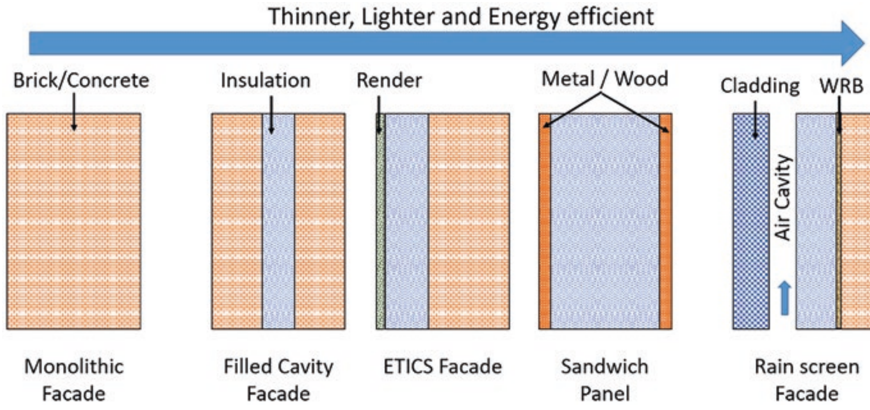

Fig. 6.4 Different types of façade systems [9, 12]

wall. Main fire hazards associated with these façades are shattering and spalling due to heat transfer from fire. However, they pose less risk in terms of flammability due to their non-combustible nature. Despite their lower flammability, they are not commonly used in modern infrastructures as they cannot meet energy efficiency requirements due to the presence of a single material only. Hence more complex systems, as described in the next sections, have been developed.

(b) **Insulated façades:** To fulfil the energy requirement, such façades are equipped with a layer of insulation material assembled between two layers of combustible material. Flammability of such façades depends on the choice of the material used for insulation. They are further divided into the following types depending upon the bonding material used for protecting insulation:

   (i) Filled cavity façades: They consist of insulation material filled between two layers of materials such as concrete or brick wall, which prevent direct impingement of flames on insulation. These are commonly used in low-rise buildings (<15–20 m).
   (ii) ETICS façades: This stands for External Thermal Insulation Composite Systems. They consist of insulation material between a thick layer of brick/concrete wall on the inner side and thin layer (2–12 mm) of render on the outer side for providing insulated and water-resistant finished surface. They provide enhanced thermal insulation and weather protection along with the improved exterior design of the building. However, due to a thin layer of protection, such systems are more prone to fire spread than filled cavity façades.
   (iii) Sandwich panels: In these systems, the insulation material is sandwiched between two thin layers of metals, plywood, or gypsum, for providing inert and aesthetic sense to façades. They are generally used as an external façade in high-rise buildings. Due to their aesthetics and affordability, they

are more commonly preferred by designers and architects. Similar to ETICS, they also pose fire threats if the inner core of insulation material is combustible.

(c) **Rainscreen façades**: In previously described façade systems, there was a common problem of moisture getting deposited over façades. To overcome this problem, rainscreen façades are developed where a small air cavity is kept for ventilation between the external façade and insulation. Generally, they are an assembly of mainly three components: exterior cladding with air cavity behind, continuous insulation (CI), and water/weather-resistive barriers (WRB), as depicted in Fig. 6.4.

(i) Exterior cladding and air cavity: It forms the outermost component of the assembly and is often known as rainscreen cladding as it is mainly designed to protect the buildings against rainwater. The primary types of exterior cladding materials used are aluminum composite panels (ACP), high-pressure laminates (HPL), and fiber-reinforced plastic (FRP). These materials can have a combustible, fire retardant, or mineral fill core, depending on the desired level of fire protection and cost. Various joint systems are used to install them, creating an air cavity of 25–100 mm behind the cladding. This air cavity serves two purposes: draining rainwater and promoting upward airflow within the cavity in hot weather. This ventilation helps to remove moisture from the façade, keeping it dry.

(ii) Continuous insulation (CI): The second element of the construction involves adding a layer of insulation to the exterior of the building structure to enhance the R-value of the outer wall. This improves energy efficiency by providing insulation. Common types of continuous insulation materials are expanded polystyrene (EPS), polyisocyanurate (PIR), phenolic foams, and mineral wool (MW). The thickness of the insulation depends on the climate zone and desired R-value. It is important to note that using combustible insulation in combination with combustible exterior cladding can exacerbate the situation in the event of a fire.

(iii) Weather/water-resistive barrier (WRB): The third element of the assembly is installed over the exterior sheathing and beneath the continuous insulation. This layer helps to prevent moisture damage to the building and regulates the relative humidity to maintain comfort inside the building. Building professionals commonly use either fluid-applied membranes or building wraps as water-resistive barriers (WRBs).

These façades are commonly used in high-rise buildings due to their high thermal efficiency, superior weatherproofing, and aesthetic sense. They also solve the problem of moisture control by having an air cavity. However, in the event of a fire, this internal cavity forms a chimney effect along with combustible façade causing rapid vertical fire propagation to other floors depending upon the fire scenarios as discussed in the next section.

6.4 Design Fire Scenarios for Façades – Internal and External Fires

Multiple fire scenarios can initiate façade fires, which can be divided into the following two main categories (Fig. 6.5):

6.4.1 Internal Fires

Internal fires inside the compartment of a building can occur due to different ignition/heat sources varying in size, intensity, and duration ranging from a tiny spark to flammable liquid fires. In modern infrastructures, there are a variety of factors that have led to frequent internal fires such as complex designs, open spaces (less compartmentation), increasing fuel loads, void spaces, and changing building materials. This has led to shorter time to flashover, faster fire propagation, shorter escape times, and increased exposure. It was also confirmed in an experiment conducted by UL (Underwriters Laboratories) where flashover time of less than 5 mins was observed in modern rooms as compared to 30 mins in legacy (old) rooms. These internal fires (pre-flashover or post-flashover) are among the most common ignition scenarios for façade fires when they come out due to flashover leading to breaking of windows. They can ignite combustible façades by direct impingement on the façade or penetrating the air cavity or void spaces as shown in Fig. 6.6 leading to more extensive flame propagation.

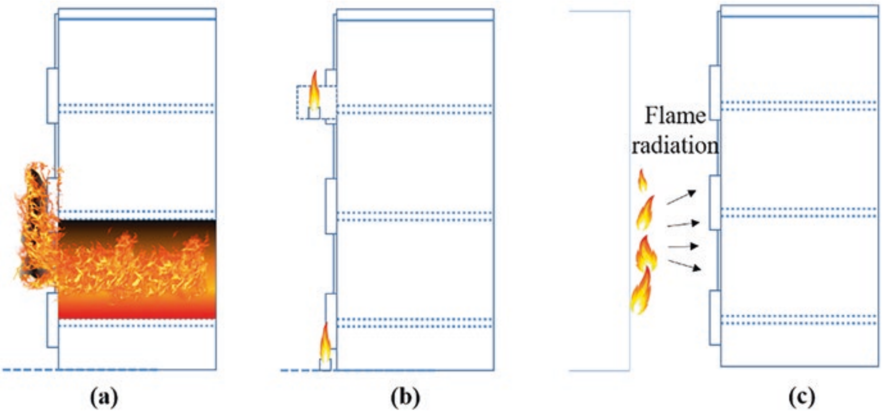

Fig. 6.5 Façade fire scenarios for high-rise building fire accidents [9, 29]

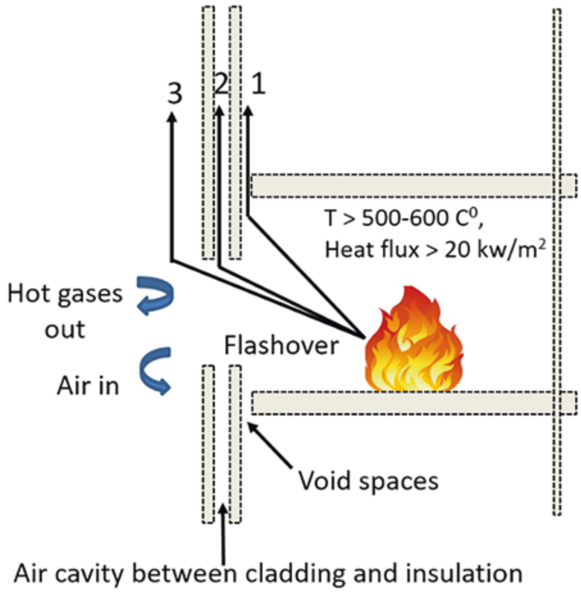

Fig. 6.6 Internal fires spreading via: (1) Void spaces, (2) Air cavity, (3) Direct impingement on exterior façade [9, 30]

6.4.2 External Fires

External fires near windows or balconies can directly impinge on the outer façade without the need for flashover to occur. Nearby burning buildings or combustible items (such as a parked car or trash cans) can also initiate façade fires by heating the façades via radiation.

Two major factors that can lead to the above fire scenarios are the use of combustible materials in the façade system (cladding, insulation, joints, etc.) and the absence of or insufficient vertical cavity barriers and fire stops to avoid fire penetration into the cavity leading to chimney effect as discussed in the next section.

6.5 Vertical Fire Propagation Mechanism over Façades

The flame spread can be defined as the process in which flame moves over a combustible pyrolyzing surface acting as fuel. The moving flame front can be considered as an invisible boundary between the unburnt and burnt part of combustible material. Flame front moves by heating unburnt fuel in the preheating zone from the flame in the pyrolysis zone, where actual burning and thermal degradation of the material occurs. How fast the fire grows will greatly depend on the heat transfer and flame spread rate. Hence, it is crucial to study the mechanism of flame spread and various factors affecting its rate. The rate of vertical fire spread has been noted to increase exponentially over time due to a doubling effect [31, 32].

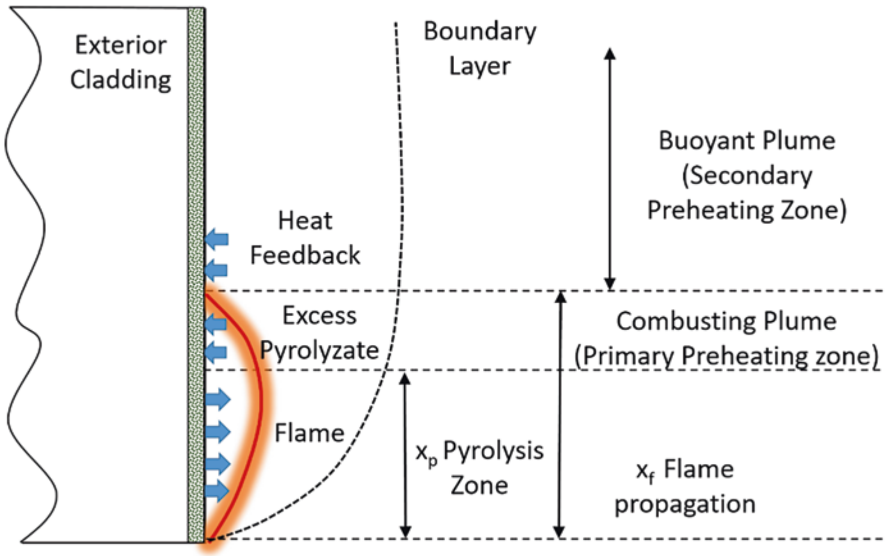

Fig. 6.7 Vertical upward fire spread mechanism over a façade [9, 33]

As shown in Fig. 6.7, three primary regions are observed in upward flame spread over façades. The first zone is the pyrolysis zone where the actual burning of material produces combustible volatiles that burn to produce a visible flame. The next region between x_p (pyrolysis zone) and x_f (flame propagation length) is known as a combusting plume where unburnt volatiles move upward due to buoyancy, burn, and also causes preheating of the unburnt solid fuel above the pyrolysis zone. The third, uppermost zone above x_f consisting of hot combustion products is known as a buoyant plume, where the physical flame is not present. Rate of flame spread over façades is mainly dependent on the heat flux incident on the unburnt material in the combusting zone due to flame from the pyrolysis zone. For small and laminar flames, spread rate follows $x_p, x_f \propto t^2$ while for turbulent and large flames spread rate is much higher and grows exponentially with time.

6.6 Dynamics of Cavity Fires

As discussed earlier, the air cavity is designed to facilitate proper ventilation and air circulation within the façade, as illustrated in Figs. 6.8 and 6.9. Nevertheless, in case of a fire, this space can act as a chimney and facilitate the upward spread of fire through a phenomenon known as the "chimney effect" [4, 19]. In many cases, direct exposure can also cause fire spread inside the cavity. Enclosure fires are often fuel

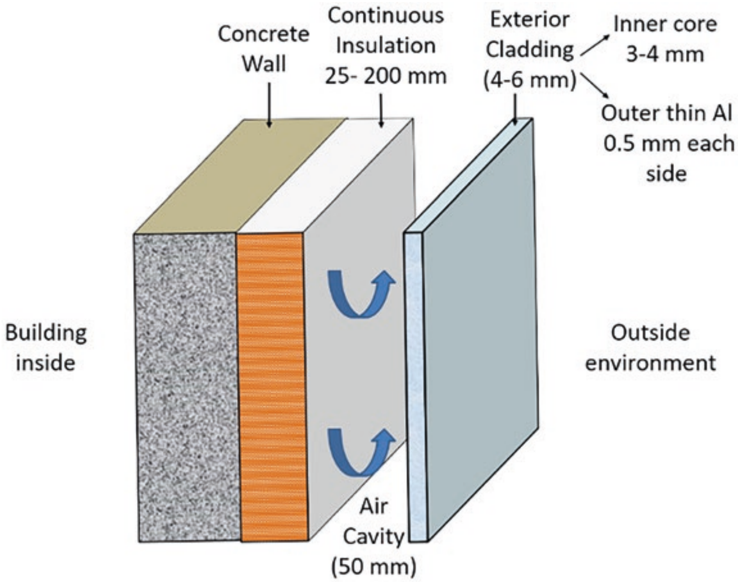

Fig. 6.8 Components of façade assembly [12, 30]

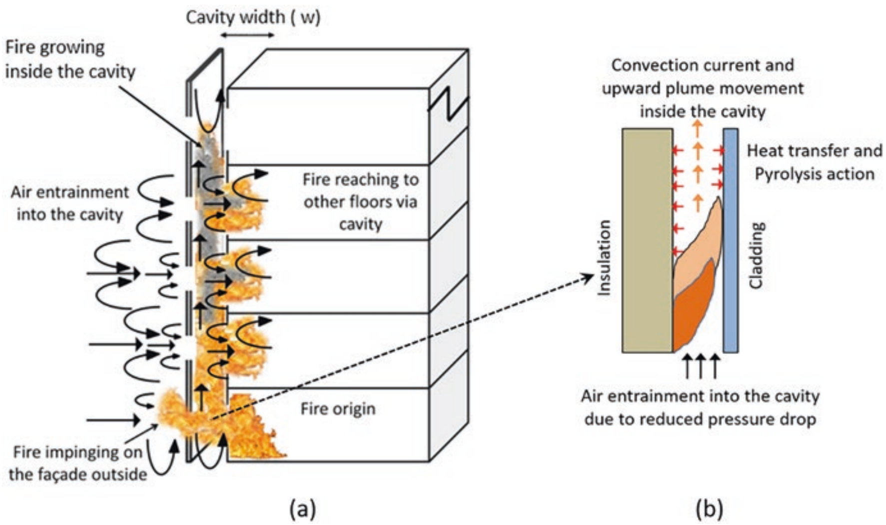

Fig. 6.9 (**a**) Chimney effect in façade fires, (**b**) Zoomed in view of processes taking place inside cavity [9, 30]

and ventilation-limited, but this is not the case for cavity fires, as ample ventilation is available through the chimney effect from the surroundings, making them challenging to contain. Therefore, it is important to investigate the chimney effect and corresponding fire risks in the façade system [5, 23].

Figure 6.8 illustrates a common assembly for the exterior wall or façade system of a high-rise building. After the concrete wall, insulation is added to enhance the R-value and improve energy efficiency, with a thickness ranging from 25 to 200 mm. Following the insulation layer is an air cavity with a thickness of 50 mm, and then aluminum composite panel (ACP) cladding with a thickness of 4–6 mm is attached. If either the insulation or the cladding, or both, are combustible, this can create conditions that encourage the "chimney effect".

In Fig. 6.9, fire spread via the chimney effect is demonstrated for a typical façade system where the buoyant pull on the flame along the cavity can be observed. Internal fire can come out of the compartment openings impinging on the exterior wall assembly. Flames may also enter the cavity region, heating the enclosed air far beyond the ambient temperature resulting in a reduction of air density. This causes initiation of upward buoyant movement or chimney effect leading to vacuum-like conditions inside the cavity of width w. Fresh air is drawn into the air gap created in between due to chimney effect and corresponding fire spread rate as:

$$Y = f\left(\Delta T, h, w, U\right)$$

This indicates that for a fixed sidewall height, the temperature difference can create the required pressure drop and flow rate through the cavity. To explore fires in building facades, it is crucial to examine the collective impact of factors such as the materials used, the construction design (including the dimensions of the chimney), and the intensity of the initial fire source in an experimental arrangement [9, 30].

6.7 Façade Materials – Fire Safety and Toxicity

The fire performance of façade materials is defined by their combustibility and toxicity. If façade material is combustible, it will contribute to the spread of fire to other parts of the building, leading to the complete engulfing of the whole building [34]. Secondly, façade materials may also produce toxic smoke, which causes more deaths than the fire itself as it spreads quickly, worsening the situation even more.

The materials most used in façade assembly are low-density polyethylene (LDPE) for exterior cladding and EPS, PIR, MW, etc., for continuous insulation. The problem with LDPE is that heat of formation of PE is very high while the heat of formation of CO_2 and H_2O is very low, so burning PE is a highly exothermic reaction (43.3 MJ/kg). Moreover, as mentioned in Table 6.1, it is noticeable that combustible insulation materials possess high R-values, which is why they are more

Table 6.1 Different continuous insulations used in façade assembly [30]

Continuous insulation	R-value (h.ft^2.^{0}F/BTU) per inch	Combustibility	Water permeability
Mineral wool	4.0	Low	High
PIR foam	6.5	Medium	Low
Phenolic foam	5.0–8.0	Medium	Low
EPS	5.0	High	Low

frequently utilized as continuous insulation in tall buildings. They can meet climate action SDGs of the Paris Agreement by making the building energy efficient [1]. Nevertheless, past incidents have demonstrated that such materials accelerate the spread of fire on building facades and generate poisonous fumes, as exemplified by the Grenfell Tower tragedy in 2017 [7, 35]. It greatly impacts the goal 11 of SDGs that focuses on making building safer [2].

6.8 Artificial Intelligence/Deep Learning Framework for Early Warning and Fire Risk Assessment

As described, façade fire behaviors are complex and could be affected by many factors, e.g., façade materials, ambient wind, façade type, and so on. Great efforts have been made to build mathematical and physical models for façade fire characteristics with these factors and deepen the understanding of the façade fire phenomenon. Nevertheless, in a real fire accident, many input parameters are unknown or unmeasurable to support the calculation of empirical equations. Also, the estimation depends highly on the user's knowledge and experience. A rapidly developed building fire proposes the requirement of a fire prediction tool which can achieve super-fast response (at second level) with high accuracy based on limited data. Therefore, the artificial intelligence (AI)/deep learning (DL) tools are introduced in firefighting research to accomplish the task to identify and predict the building fire.

Figure 6.10 presents the framework to identify a compartment fire scenario and predict flashover occurrence with IoT sensors and a pre-trained DL model. The aim of detecting fires can be accomplished by using heat detectors, which gather temperature data via an IoT sensor network. The collected data is then transmitted to a cloud server [26, 27], where it can be managed, stored, and accessed by an AI engine that employs a Convolutional-LSTM network to identify the fire state and issue real-time alerts to occupants and firefighters regarding potential fire risks. Finally, a user interface (UI) is created to display the fire information, including measured data and AI outputs, to facilitate cyber-physical interaction.

Validated by a set of multi-scale fire tests, including a large-scale fire test in a 7.5 (L) × 3.4 (W) × 5.4 (H) m^3 chamber and a roughly 1/5 reduced-scaled model chamber, the proposed smart fire prediction system can identify the fire scenario

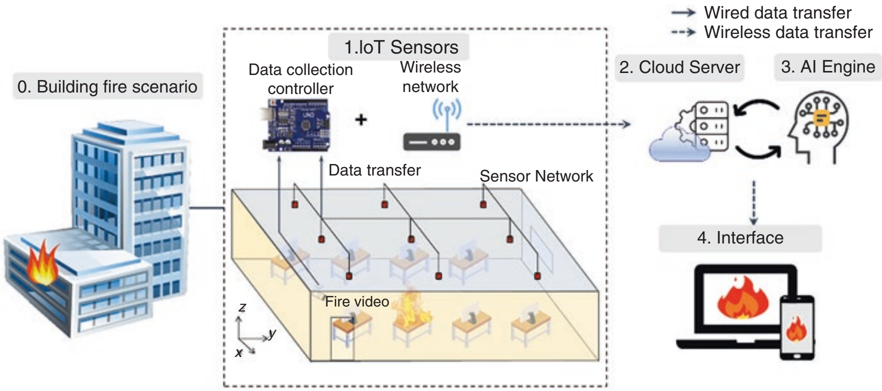

Fig. 6.10 Framework for IoT and DL model-based building fire identification and prediction [36]

(including the fire location and fire heat release rate) with an overall accuracy over 85% [36], and predict the onset of flashover with a lead time of 20 s [37]. This can provide important information to make firefighting decisions in the pre-flashover stage, and hence prevent the occurrence of façade fire.

For the post-flashover stage, the external fire (both the spilled flame and façade flame) is dominant. It is worth noting that the flame parameter(s) are difficult to measure by temperature or gas sensors while the fire images are commonly available. Thus, computer vision methods can be applied to analyze the façade fire features, as displayed in Fig. 6.11. A big database of 112 fire tests from the NIST Fire Calorimetry Database [38] is formed and 69,662 fire scene images labeled by their transient heat release rate (measured by the oxygen calorimetry) are adopted to train a CNN-based (Convolutional Neural Network) DL model.

The AI-image fire calorimetry approach is then employed to estimate the transient fire heat release rates (HRRs) for tests conducted in both the same and new laboratory environments, as well as real-world fire incidents. The outcomes demonstrate that the AI-image fire calorimetry technique can accurately predict the fire HRRs based on flame images, with a high degree of accuracy (coefficient of determination >0.8), irrespective of image background, camera settings, or viewing angles. This vision-based model exclusively uses fire images as inputs, offering an alternative means of determining the fire HRR through fire scene images when conventional calorimetric methods are impractical. For the post-flashover fire stage, the proposed model can be installed in a smartphone or carried by a UAV (Unmanned Aerial Vehicle) to get the façade fire picture and predict the fire heat release rate for fire risk assessment.

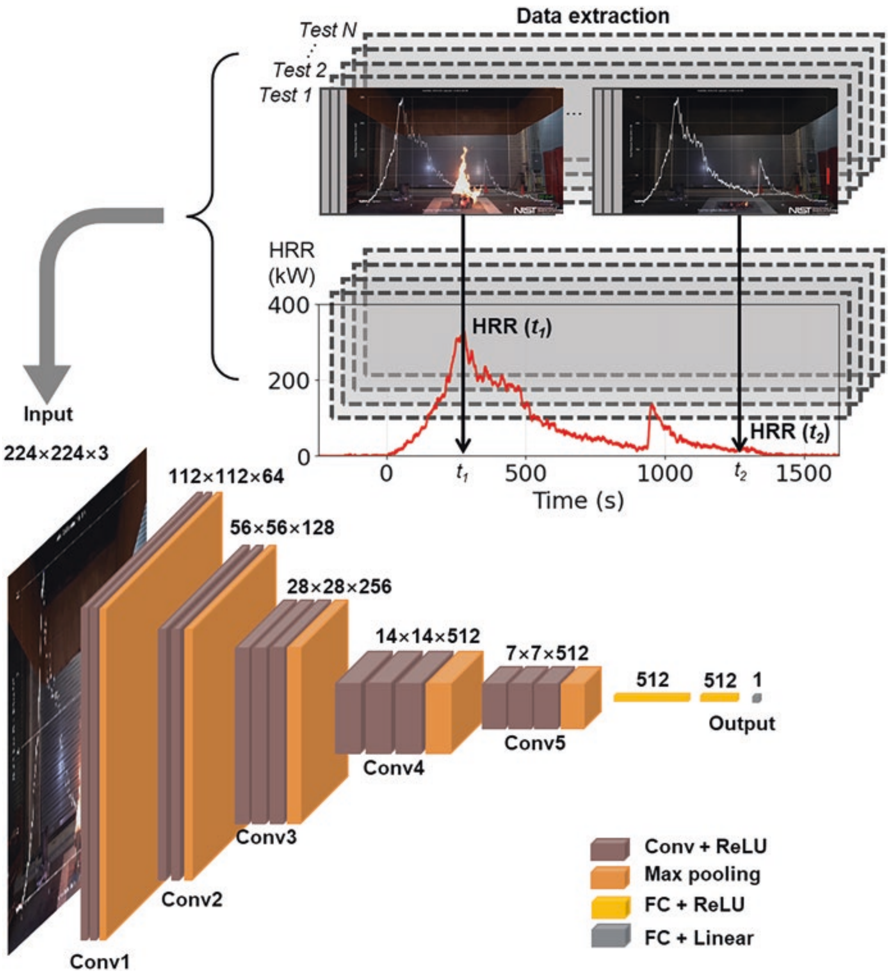

Fig. 6.11 Computer vision methods to analyze façade fire features [39]

6.9 Concluding Remarks

In light of the recent incidents involving façade fires and the importance of achieving the SDGs outlined in the Paris Agreement, it is imperative that we prioritize the study of various mechanisms that contribute to these types of fires. This will require diligent research and analysis to identify potential areas of improvement, as well as the development and implementation of robust safety standards and regulations to mitigate the risks associated with façade fires. This research can include studying the materials used in building façades, examining the design and construction of buildings, and investigating the causes of past façade fires. It is also important to engage with architects, building owners, and other stakeholders to ensure that they are aware of the dangers posed by façade fires and are taking appropriate measures to address them.

In addition to these measures, we can explore innovative technologies and materials that can help mitigate the risk of façade fires. For example, AI solution can help detect and respond to these fires more quickly and effectively. By analyzing data from sensors and cameras, an AI system can quickly identify the location and severity of a fire and help firefighters take appropriate action. Ultimately, by taking a proactive and multifaceted approach to façade fire safety, we can help protect the lives and property of individuals and communities, promote sustainable development, and build a safer, more resilient world.

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