fire

Review

A Systematic Review on Cavity Fires in Buildings: Flame Spread Characteristics, Fire Risks, and Safety Measures

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Abstract: Fire spread scenarios associated with concealed cavity spaces have been relatively less discussed. The variation in studies with respect to geometry, influential parameters, and protection strategies has been an obstacle to deriving more generalized solutions in terms of cavity fire in buildings. A systematic literature review was conducted following the PRISMA method to identify the conclusive fire behaviour, safety risks, and protection strategies to enable future researchers to address cavity fire scenarios effectively, avoiding catastrophic disasters. This study identified that relative to open-fire scenarios, cavity fires could result in up to 10 times higher flame spread, up to 14 times higher heat exposure, and temperature conditions 13 times higher. Increased toxicity and smoke velocity are also found with cavity fires. Fire protection strategies and their efficiency were identified for a range of cavity geometries. Altogether, cavity spaces, especially narrow ones, cannot be neglected during fire safety, and proper risk identification is required to ensure the safety of the buildings and the occupants in a fire scenario.

Keywords: fire safety; cavity fire; ventilated façades; modular construction; gap analysis

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1. Introduction

Thousands of human lives and significant economic losses are reported yearly due to building fire accidents, even though the fire safety of buildings has become an integral part of the construction and service stages of buildings. During fire safety designs of buildings, various fire scenarios have been considered. Compartment fire and fire scenarios in façades, atrium spaces, stairwells, and corridors are often considered in fire safety designs. Nevertheless, the fire spread through cavity spaces is relatively unexplored, even though such geometries are frequently found in façade systems, wall and floor systems, and storage geometries.

Various studies identified fire behaviour within cavity geometries [1–6] with their own focus, and thus, could not identify the generalized fire behaviour in cavities. Most often, in these studies, clear indications were not given for the severity of cavity fire scenarios compared with open-fire scenarios to highlight the importance of considering cavity fire in building designs [2–4,7,8]. Several research studies attempted to develop expressions to predict fire behavior within particular cavity types [4,5,9–13]. Nevertheless, their validity must be identified by comparing them with other studies. A range of fire safety issues associated with cavity fire spread have been identified by different studies [3,8,14,15]. However, various parameters govern these fire risks, and studies often consider individual parameters. Identifying the most significant parameters among these parameters is crucial to determine the associated risk due to fire and improve the structure's fire safety by implementing precautions to protect the critical elements or alternative design strategies. Moreover, the same parameter can act differently on the severity of fire risk for different fire scenarios and cavity types [7,16]. The cavity geometries and techniques implemented to control the cavity fire risk [15,17–19] indicate a distinguished difference.

These aspects make it challenging to obtain a conclusive idea of the cavity fire scenarios. On top of this, recently, concerns have arisen regarding fire spread through cavity spaces in modular buildings [20–25], but no in-depth or comparative analysis of research findings or case studies that disseminate the knowledge on fire risks associated with these modular building cavities is available. Therefore, addressing these issues in modular constructions could be unsuccessful without a clear understanding of fire behaviour in cavity fire scenarios. After critically analyzing published sources, this paper systematically highlights fire risks associated with cavity systems, behaviour, and protection strategies. This paper will raise the attention of building developers, fire engineering professionals, and scholars on this crucial risk, its effects, and effective strategies to be developed to overcome or reduce this fire risk.

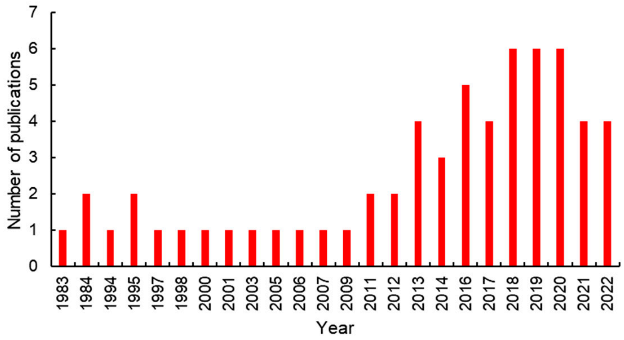
2. Research Methodology

Following the PRISMA method [26], journal articles, proceeding papers, and review articles in the English language were identified through electronic searches in the "Web of Science" and "Scopus" databases. In addition, fire-related newspaper articles, reports, and design standards were also reviewed. The referenced publications found in the selected articles that were not included in the databases yet identified as significant were manually picked up for the study. The process presented in this paragraph is illustrated in the PRISMA diagram given in Figure A1 in Appendix A.

3. Research on Cavity Fires

The yearly propagation of studies considered in this review is presented in Figure 1a. The right-skewed shape of the graph clearly indicates the recent attention given to cavity fire scenarios. Based on the characteristics of various cavity geometries included in these studies, they can be classified into several cavity types. In this classification, the environment or the components where the cavity exists plays a role, along with attributes such as the cavity width, combustibility of the cavity boundaries, cavity orientation, and the possibility of airflow along the cavity. Rainscreen façade cavities, double-skin façade cavities, cavities or flue spaces in rack storages, cavities in wall components, gap spaces between buildings, and cavities between parallel panels are the main cavity types considered in this study. However, the parallel panel cavity type represents the research experiments conducted to identify the cavity fire behaviour that can be generalized to other cavity types. The trend of using these cavity types in research studies is shown in Figure 1b, and the respective geometries are presented in Figure 1c. According to Figure 1b, research has mainly focused on façade cavities, flue spaces in rack storage systems, and cavities between parallel panels. Despite the increasing concerns about fire spread through intermodular cavities in modular buildings [22–24], comprehensive research studies have not been conducted. According to the authors' knowledge, the only study directly connected to cavities in modular buildings was done by Just et al. [25], even though the study was limited to identifying suitable testing conditions for cavity barriers used in combustible intermodular cavities. Perhaps the reason could be its relatively late appearance or unawareness of intermodular cavity fire spread.

The main attributes of the cavity types included in this study are given in Table 1. The studies associated with fire scenarios within these different cavity types have indicated that cavity fire scenarios can have unique characteristics compared with open-fire scenarios. Extension of flame heights, severe heat exposure and temperature environment, rapid fire spread, rapid smoke spread, and smoke toxicity are among the identified fire characteristics. However, certain characteristics are more applicable to specific cavity types. Therefore, the applicable cavity fire characteristics are also mentioned in Table 1 under each cavity type. Researchers have highlighted several protection measures to ensure fire safety from cavity fire scenarios. The applicable fire protection methods are also given for each cavity type in Table 1. A detailed discussion of the identified fire characteristics, associated fire safety risks, and relevant protection strategies are presented in Sections 4–6.



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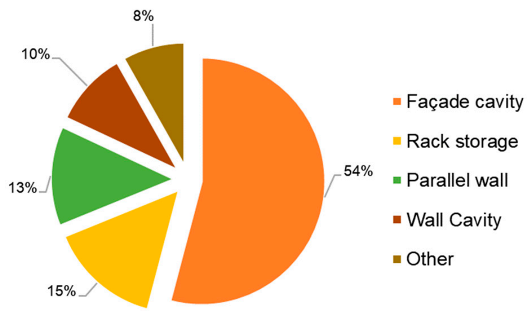

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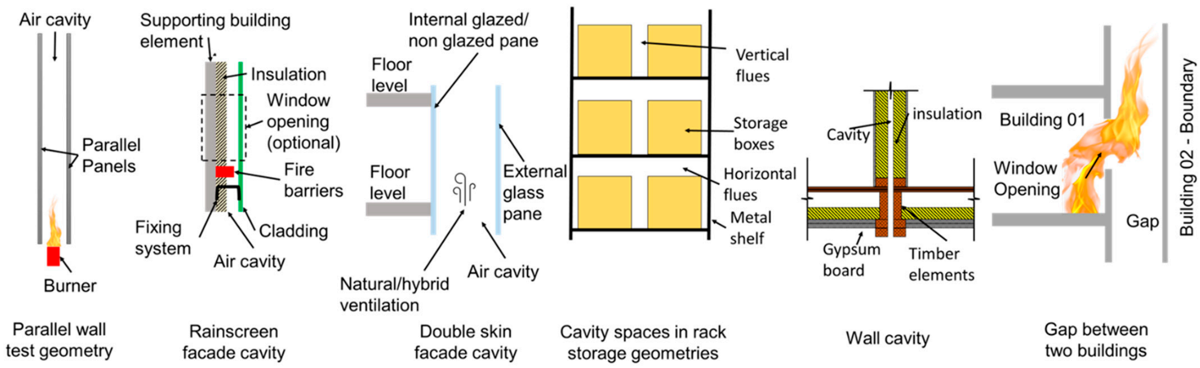

(**c**)

Figure 1. Cavity fire research analysis: (**a**) approximate propagation; (**b**) composition of cavity fire; (**c**) cavity geometries included in the study.

Previous studies suggested several governing parameters for the highlighted cavity fire characteristics in Table 1 and associated fire safety risks presented in Section 5 (Figure 2 and Table A1). Most studies agreed that the cavity width, ventilation, and fire size are the most crucial parameters that decide fire behaviour. However, since most cavity fire studies are done with idealized setups, it is questionable whether the realistic airflow conditions within building cavity geometries are replicated. More studies are needed to identify how airflow within cavity spaces governs fire behaviour. Further, there is a dearth of data for combustible cavity spaces, which is essential in identifying determinant parameters governing fire spread within combustible cavity spaces. However, based on the existing research, the impacts of the identified sensitivity parameters are discussed in detail under Sections 4–6.

Table 1. Classification of cavity types and their characteristics.

Cavity Type	Characteristics	Fire Characteristics	Fire Protection
Rainscreen façade	Vertical cavity space within façades with a narrow cavity width (20–200 mm). Combustible/non-combustible boundaries. Unrestricted airflow under normal conditions.	Flame extension, increased thermal conditions, rapid fire and smoke spread, smoke toxicity	Cavity barriers, non-combustible materials, and tested assemblies
Double-skin façade	Vertical cavity space in façades between two glazed panels. Wide cavity width (0.5–2 m). Non-combustible. Unrestricted airflow.	Increased thermal conditions, rapid smoke spread	Geometrical planning, toughened glass
Rack storage	Vertical and horizontal flue spaces between storage boxes. Narrow cavity width (50–300 mm). Combustible boundaries. Unrestricted airflow.	Flame extension, increased thermal conditions, rapid fire spread, high flow/smoke velocity	Geometrical planning, sprinklers
Wall cavity	Vertical cavity spaces within wall systems. Narrow cavity width (13–300 mm). Combustible/non-combustible boundaries. Restricted airflow under normal conditions.	Flame extension, increased thermal conditions, rapid fire spread	Cavity barriers, non-combustible materials
Gap between two buildings	Narrow-to-wide vertical gap between two buildings. Combustible/non-combustible boundaries. Unrestricted airflow.	Flame extension, increased thermal conditions, rapid fire spread	Non-combustible materials
Parallel panels	Vertical cavity between two combustible or non-combustible boundaries. Narrow to wide cavity width (12.5–600 mm). Unrestricted airflow.	Flame extension, increased thermal conditions, rapid fire spread	-

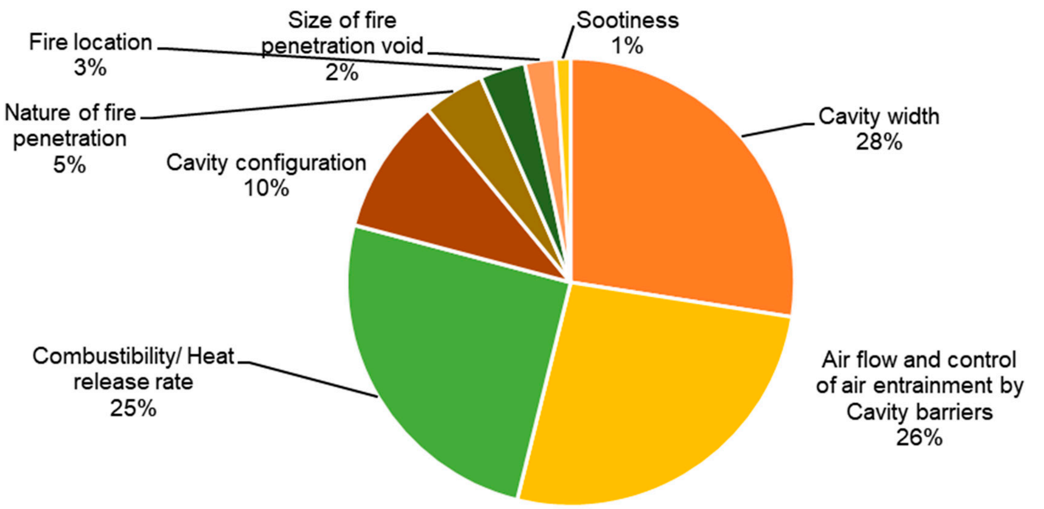

Figure 2. Parameters governing fire/smoke behaviour within cavity systems (Figure 1c) based on the number of references (Table A1).

4. Characteristics of Cavity Fires

4.1. Flame Extention

Flaming demarcates the combustion of fuel species. Once a gas burner is ignited, with the air entrainment from horizontal directions, gaseous fuel undergoes combustion. Therefore, at the tip of the flame, air entrainment satisfies the completion of combustion of the released gaseous fuel. However, air entrainment is obstructed when the burner is between two parallel panels, as in the case of a cavity configuration. In this case, the flaming region stretches up in the vertical direction for the completion of combustion until it receives the required oxygen amount from air entrainment. In addition, once fire enters a cavity, the air temperature rises beyond the outside temperature. This temperature difference creates a pressure drop inside the cavity, resulting in a convection current. This phenomenon is called the chimney or stack effect [16]. The chimney effect [16], the seeking of oxygen for combustion due to low air entrainment [9] and the lack of convective cooling from external air [7], causes flame extension within the cavity spaces compared with an open fire. Table 2 presents analyzed data for flame height increment within cavity spaces compared with open-fire scenarios ($L_f/L_{f,open}$) and compared with flame heights in the case of flame spreading over a single wall ($L_f/L_{f\,one\,wall}$). Several authors cited that cavity fire flames can extend 5–10 times the open-fire flame heights [3,7,27]. However, Table 2 shows that this statement is valid only for combustible cavity systems, such as rainscreen façade cavities and cavities in rack storage geometries. The flame height increase is around twofold for non-combustible cavities compared with open-fire scenarios. Based on this, it can be identified that the combustibility of the cavity plays an influential role in deciding the cavity fires' characteristic flame extension. Once the flame enters a combustible cavity, the heat release rate is higher than for a non-combustible cavity, as the combustible materials also contribute to the cavity fire. It was identified that the cavity fire's flame height is always proportional to the heat release rate [1,4,5]. This can be explained as an effect of higher fuel load. Once a higher fuel load is released along the cavity, with the air entrainment, it takes a higher height to completely combust the fuel amount than for a lower fuel load. Thus, the tip of the flame is higher than for the lower fuel load.

Table 2. Effects of cavity boundaries on flame extension.

Ref.	Cavity Fire Scenario	Combustibility	Cavity Width (mm)	HRR (kW)	$L_f/L_{f\,open}$	$L_f/L_{f\,one\,wall}$
[9]	Rack storage	Non-combustible	50–100	18.8–44.5	1.9–2.9	-
[11]	Building gap	Non-combustible	100–500	8–21	0.9–1.7	-
[1]	Parallel panel	Non-combustible	20–100	6.5–15.8	-	0.9–2.2
[16]	Parallel panel AL 45 + MW	Combustible	50	25	-	3.3
[16]	Parallel panel AL 45 + PIR	Combustible	50	110	-	5.2–9.6
[16]	Parallel panel AL 45 + EPS	Combustible	50	58	-	1.1–3.8
[5]	Parallel panels	Non-combustible	140–600	8.3–25.4	-	1–1.3

AL 45—Aluminium composite cladding; EPS—expanded Polystyrene; PIR—Polyisocyanurate; MW—mineral wool.

Several other studies highlighted the dependency of airflow into the cavity on the flame extension within the cavity. However, when sufficient airflow into the cavity is not available (when airflow is restricted from three boundaries), experiments on combustible cavities [28] showed that rather than flame extension, flaming occurs at the boundary that is open to the air. Further, in his parallel panel test (Figure 1c), Mendez et al. [29] showed that airflow through the bottom boundary of the cavity could result in higher flame heights than when the bottom boundary is closed for airflow. Nevertheless, this is critical for lower cavity widths of 50 mm and relatively high fire sizes used in their tests (16.8 and 24 kW). In the study by Giraldo et al. [3] on the façade cavity, variations in the upwards airflow velocity within the cavity showed a direct impact on flame behaviour. Once the airflow velocity through the bottom of the cavity is increased, it indicates an increase in the flame height. This observation further validates the support from chimney/stack flow on flame stretching within the cavity. Similarly, An et al. [2] also studied the effect of airflow through openings at the side boundaries of a channel-type rainscreen façade cavity on fire spread over combustible insulation within the cavity. Their results suggest that the airflow from side boundaries can directly impact the stack effect and air entrainment into the combustion. Therefore, the flame height within the cavity is vulnerable to the airflow from side boundaries. In real situations, external wind speeds can influence the airflow from the open cavity boundaries (bottom or side) but not for closed cavities. However, comprehensive research has not been done yet. Therefore, while the external wind can have an impact on cavity fires in certain façade systems, such as rainscreen façades with an open cavity, this factor is beyond the scope of this review. However, the rack storage fire studies by Ingason [21,22] and Karlsson [23] that investigated cavity spaces (flues) in vertical and horizontal directions found that a change in horizontal flue spacing does not significantly affect the flame height within vertical flues. This observation suggests that side ventilation into cavity spaces in rack storage may be insignificant to vertical fire behaviour. Perhaps the reason could be the lack of influence from the horizontal cavity spaces in rack storage geometries on improving or diminishing the chimney/stack effect within the vertical cavity space.

Another crucial factor influencing flame extension characteristics is the width of the cavity. For a fire scenario of flame ejecting through a window opening of a rainscreen façade, the flame height within the cavity increases with the cavity width, as cavity width plays a role in the amount of flame or pyrolyzed gas species entering the cavity [3,7]. However, once the flame is within the cavity, the cavity width is inversely proportional to the flame height, irrespective of the combustibility of the material and the type of the cavity [1,4,5,16]. Reducing the cavity width further obstructs air entrainment into the cavity and plays the leading role in incrementing flame height. However, this phenomenon prevails only when the cavity width is below a certain critical width [5]. When the cavity width exceeds this critical cavity width, the parallel panels have a minor or no effect on obstructing the air entrainment, and thus, on flame extension.

Various studies have attempted to produce correlations to predict flame heights for different cavity types. Ingason [4] identified a proper correlation between flame height L_f (m) within vertical flue/cavity spaces in rack storage geometries for a cavity width of w (m) and a total chemical heat release rate of Q (kW). They identified a linear relationship between the L_f/w and $Q^{2/5}/w$ parameters. Considering these two parameters, the existing flame height data for selected cavity types are shown in Figure 3. These data include both combustible and non-combustible cavity geometries, including rack storage geometries [4,9,10,30], fire entering a building gap through a window [14], and parallel panel cavities [1,5,12,29,31]. Since the flame was beyond the top of the cavity, data from Sharma et al. [16] and some cases in Jamison and Boardman [31] were not considered. Figure 3 further highlights that once the cavity width is reduced and fire size increases, the non-dimensional flame height (L_f/w) increases. However, the linear relationship observed by Ingason [4] for rack storage geometries does not seem applicable to all cavity types, especially for parallel panel cavity spaces in ventilated façades. Instead, they showed a nonlinear increasing trend with increasing $Q^{2/5}/w$. This variation could be due to the lower degree of air entrainment in parallel panel cavities as opposed to the much better air entrainment in rack storages due to additional horizontal flue spaces. Moreover, data towards higher $Q^{2/5}/w$ values show a significant scatter. Therefore, further studies are needed to predict flame height within cavity geometries. For this task, the involvement of air entrainment needs to be considered.

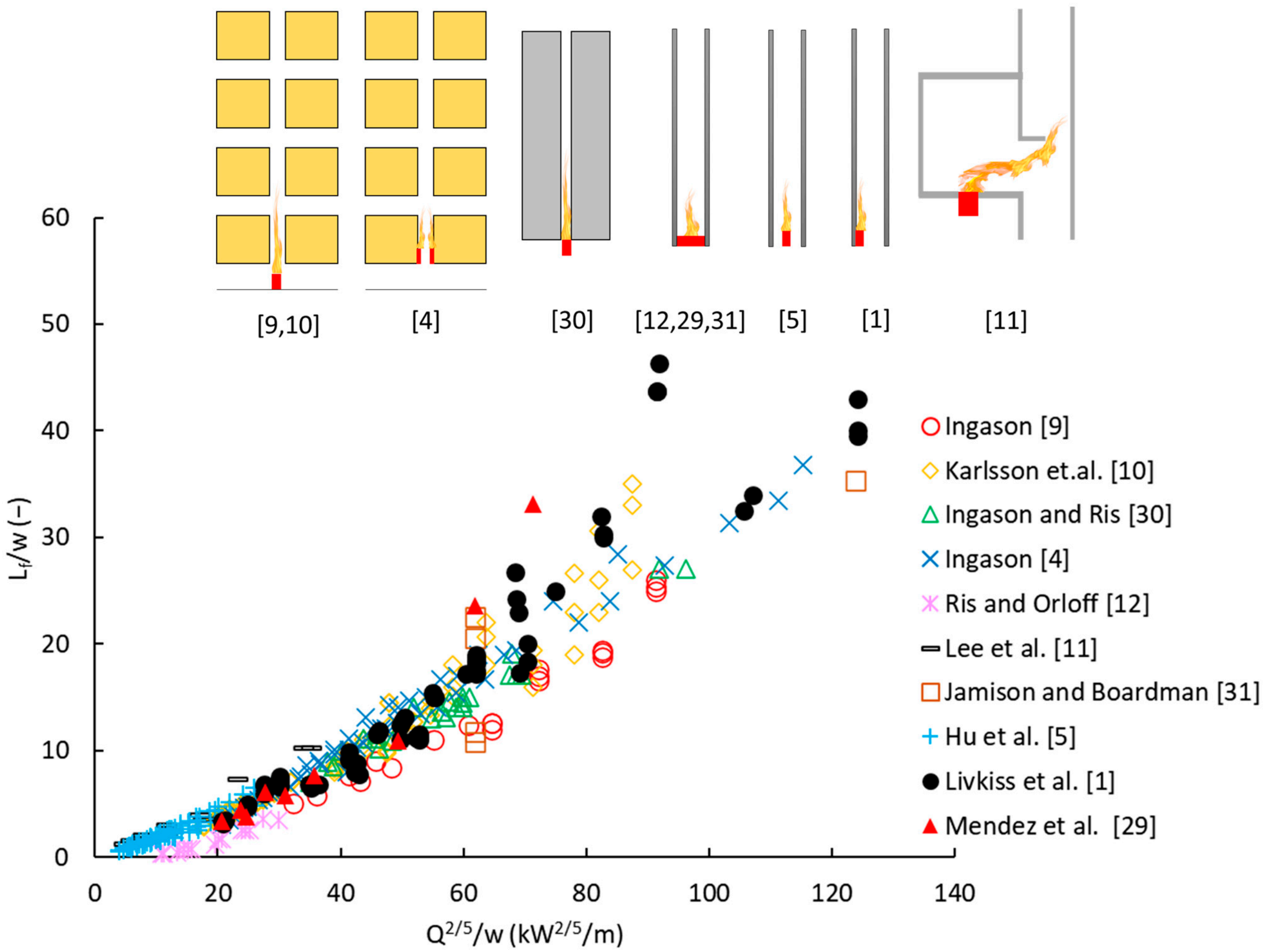

Figure 3. Flame height data of different cavity types [1,4,5,9–12,29–31].

4.2. Higher Heat Flux on Boundaries

Several studies indicated that cavity geometries can produce severe heat exposure up to 14 times that of heat exposure from an open fire on a single surface (Table 3). The heat flux data obtained for the respective non-cavity geometry was considered to present the heat flux inside the cavity geometry as a fraction. This heat flux ratio is presented as the heat flux increase compared with a single-wall fire in Table 3, and the nature of the heat flux parameter measured in the studies is also presented. The increased heat flux in cavity geometries can be explained by three factors. Once a second parallel surface is introduced to form a cavity geometry, heat exchange between the two parallel planes can happen. Once one panel is heated, it will radiate heat to the other panel and vice versa. As the flame stretches within a cavity geometry, it allows the flame to radiate heat to higher levels in adjacent cavity boundaries. Moreover, restricted air entrainment within the cavity results in incomplete combustion, leading to sootiness. These hot soot particles also radiate heat to adjacent cavity boundaries. To verify these factors, studies on rack storage geometries [30,32] indicated that heat transfer within cavity geometries predominantly relies on radiative heat transfer (70%), while convective and conductive heat transfers have low participation. Nevertheless, Mendez et al. [29] observed that radiation dominates the heat transfer at the lower region of the cavity. The reason for this is the heat radiation from the flaming.

Table 3. Involvement of cavity geometries in increasing heat flux.

Ref.	Cavity Fire Scenario	Combustibility	Cavity Width (mm)	HRR (kW)	Heat Flux Parameter	Heat Flux Increase Compared with Single-Wall Fire
[13]	Parallel panels (open cavity)	Non-combustible	60–100	12.5	Steady-state total heat flux 3 min average	0.5–2.2
[13]	Parallel panels (closed cavity)	Non-combustible	60–100	12.5	Steady-state total heat flux 3 min average	1.8–5
[11]	Building gap	Non-combustible	100–500	8–21	Steady-state total heat flux average	0.5–4.8
[1]	Parallel panels	Non-combustible	20–100	6.5–15.8	Steady-state incident heat flux	0.9–13.8
[33]	Façade cavity	Combustible	20	3000	Peak total heat flux (one min mean values)	1.3
[34]	Façade cavity	Non-combustible	500–1500	550	Peak incident heat flux	1.3–3.9

Research on the influence of cavity width on the heat flux on boundaries has identified that the heat flux increases with the reduced cavity width [1,13,16] and increased fire size [1,16]. The dependency on the fire size is evident, as the higher the fire load, the greater the heat generation and transfer. The effect of heat transfer by radiation can explain the influence of the cavity width on the cavity fire heat exposure. During the radiation process, the view factor or the configuration factor [29] between the source and the receiver plays a vital role. When the cavity width increases, the view factor diminishes between the adjacent cavity boundary surfaces, and between the cavity boundary surface and the flame. This variation results in lower radiative heat transfer when the cavity width increases and higher radiative heat transfer with the reduced cavity width. However, Guedri et al.'s [32] observation of combustible rack storage found that the heat flux increases with increased vertical flue width. Perhaps this trend could be due to the incomplete combustion caused due to low air entrainment. Therefore, reducing the cavity width beyond a certain cavity width can reduce the heat flux on cavity boundaries. An indication of this hypothesis can be found in the study of Livkiss et al. [1] on non-combustible parallel wall geometry. For a fire size of 15.8 kW, incident heat flux has increased when the cavity width is reduced from 100 mm to 50 mm. However, an increase in incident heat flux for a 40 mm cavity width has not been observed compared with a 50 mm cavity width. In contrast, the combustible parallel panel test by Sharma et al. [16] indicated a continuous heat flux increase when the cavity width is reduced from 100 mm to 13 mm. Nevertheless, unlike Livkiss et al.'s [1] arrangement, the cavity length/the panel's width (the horizontal length along the centers of cavity width) was 300 mm, which is lower than the 800 mm of Livikiss et al. [1], allowing more air entrainment into the middle of the cavity. Moreover, in Sharma et al. [16], air entrainment was possible through one of the boundary panels, which had a 200 mm high opening at the bottom of the cavity. Therefore, more studies are needed to identify the possibility of heat exposure reduction for narrow cavity widths.

Foley and Drysdale [13] and Mendez et al. [29] experimented with burner fires within two parallel panels and indicated that airflow characteristics can influence the heat flux distribution within the cavity by flame impingement and cooling effects. Restricting air from the bottom of a cavity between parallel panels allows the flame to touch both panel boundaries, which causes the heating of both boundaries and radiating heat to the opposite wall. However, Mendez et al. [29] identified it as more significant in 100 and 150 mm cavity widths than 50 mm. Further, Foley and Drysdale [13] and Mendez et al. [29] considered providing equations for the heat flux on boundaries, considering cavity width (m), line burner length (m), and the non-dimensional heat release rate of the burner, burner position, and bottom boundary closure condition.

4.3. High-Temperature Environment

The low level of convective cooling [2], radiative heat feedback [10], and flame stretching [32] were identified to exist in cavity configurations and have already been discussed under Sections 4.1 and 4.2. The same characteristics create distinctions in gas temperatures and internal boundary temperatures of cavity geometries with respect to open-fire scenarios [7,27,33]. Due to obstructed external air inflow, the lack of convective cooling diminishes the heat loss in the gas medium in the cavity. The flame stretching also participates in heating the gas volume in the cavity to higher heights from the fire penetration. Thus, the gas temperature within a cavity space exceeds the gas temperature adjacent to an open-fire scenario of the same heat release rate. Moreover, the internal surface temperature of cavity boundary elements is more severe than in an open-fire scenario with the same fire intensity. That can be explained by increased radiative heat transfer within the cavity. Existing data suggest that the temperature on the internal surface of the cavity can be as high as 13 times greater than the non-cavity counterpart (Table 4). In Table 4, the temperature increase is the temperature for cavity geometry divided by the value at the exact location for non-cavity geometry, where one cavity boundary panel is omitted. However, the data used in Table 4 are relevant to different cavity fire scenarios and locations within the cavity. Chow et al. [34], in their double-skin façade test, collected internal cavity temperature data on the double-skin façade along the center line of the door opening in 0.5 m intervals. Similarly, Chow [35], in his double-skin façade study, measured the internal cavity temperature at 1 m intervals, and Sharma et al. [16] presented the temperature measured at the top of the cavity for his parallel panel test. However, the study by Chow [35] was a numerical study without experimental validation, but the other two were experimental results. Variations between the studies could be due to the variation in geometry, fire intensity, and material usage. Therefore, sources of uncertainties include numerical modeling procedures, errors in thermocouples, and considering only centerline data.

Studies on rack storage geometries indicate that the gas temperature within a cavity system is inversely proportional to the cavity width [9,32]. Therefore, the surface temperature of boundary elements would follow the same behaviour. This dependency of gas temperature on the cavity width can be explained as a result of variations in convective cooling and flame extension. When the cavity width is reduced, the lack of air entrainment results in reduced cooling in the middle of the cavity, and the extended flame height increases the gas temperature even at the higher levels of the cavity. Ingason [4] and You et al. [36] found that an excess centerline temperature within vertical flues of storage geometries correlates with the plume's convective heat release rate and virtual origin. Since the heat release rate within the cavity is proportional to the convective heat release rate, the gas temperature within the cavity increases with the heat release rate, and thus, with the combustible material content within the cavity.

Table 4. Involvement of cavity geometries in increasing cavity surface/gas temperature compared with an open-fire scenario.

Ref.	Cavity Fire Scenario	Combustibility	Cavity Width (mm)	HRR (kW)	Temperature Parameter	Internal Cavity Temperature Increase Compared with Single-Wall Fire
[34]	Façade cavity	Non-combustible	500–1500	550	Max internal surface temperature	0.9–6.7
[35]	Façade cavity	Non-combustible	500–2000	1000–5000	Gas temp. next to internal surfaces at a steady burning state	0.3–11
[16]	Parallel panels (AL 45 + MW)	Combustible	50	25	1 min average temp. just outside the cavity	4–4.4
[16]	Parallel panels (AL 45 + PIR)	Combustible	50	110		6–13
[16]	Parallel panels (AL 45 + EPS)	Combustible	50	58		4

AL 45—Aluminium composite cladding; EPS—expanded Polystyrene; PIR—Polyisocyanurate; MW—mineral wool.

4.4. Fire Spread/Combustion

The above-presented flame extension, increased heat exposure, and temperature profiles create an ideal environment for rapid combustion and fire propagation. In addition, severe fire propagation is inevitable once the fire spreads within and outside the cavity [33]. Few studies compared the effect of fire spread/burning with the absence of cavity geometry (Table 5). In Table 5, the increase refers to the ratio between the heat release values for the cavity and single-wall fires. Rogowski [28] experimented on fire entering a masonry cavity wall with combustible insulation through a gap in the masonry facing, highlighting that ventilation plays a critical role in fire spread through the cavity. However, in this experiment by Rogowski [28], a slight cavity fire spread was observed even though all cavity boundaries except the top were closed for airflow. Therefore, fire spread risk exists even with the slightest chance of reaching the air when the system contains combustible material.

Table 5. Involvement of cavity geometries in increasing fire spread compared with a non-cavity geometry.

Ref.	Cavity Type	Combustible Material	Cavity Width (mm)	Fire Spread Rate (mm/s)	Energy Release	Energy Parameter	Energy Release Increment
[33]	Façade cavity	Plywood cladding	20	-	2140 MJ	The total energy released during the test	1.1
[16]	Parallel panels	AL-45 (PE core ACP) + EPS	50	4.4	58 kW	Peak average mass burning rate conversion to the heat release rate	1.5–9.2
[16]	Parallel panels	AL-45 (PE core ACP) + PIR	50	5.1	110 kW		17–27
[16]	Parallel panels	AL-45 (PE core ACP) + MW	50	2.3	25 kW		4

ACP—Aluminium composite cladding; PE—Polyethylene; EPS—expanded Polystyrene; PIR—Polyisocyanurate; MW—mineral wool.

In their combustible open parallel panel tests, Sharma et al. [16] identified that reducing the cavity width (100 mm to 13 mm) increases the mass burning and heat release rate (around 2.6 times) and presented cavity widths between 13 mm and 50 mm as the most critical for fire spread. However, Taylor's study [37], which includes fire spread through closed combustible cavities, indicated a reduction in vertical fire spread by reducing the cavity width. In the validated numerical study by Hassan et al. [38], which simulated the BS 8414.1 façade fire test, using 50 mm and 100 mm cavity widths resulted in earlier failure times than the 25 mm cavity width due to the lack of oxygen in the 25 mm cavity. They believed that having a wide cavity produces less pressure for the fire plume to stretch up, thus resulting in increased fire spread. This idea was further validated with peak heat release rate per unit area values of 9.6 MW/m^2 monitored for the 50 mm cavity and 100 mm cavity and less than 8 MW/m^2 for the 25 mm cavity width. In the study by Ingason [4], the heat release rate for a similar flame height showed a reduction for the smaller cavity widths. For a flame height of 1.42 m, the heat release rate was 37.43 kW, 47.30 kW, and 49.63 kW for the cavity widths of 50, 75, and 100 mm. This trend was also consistent for the flame height of 0.75 m. In Sharma et al. [19], the variation could have been due to considering different flame heights. Once the cavity width reduces, the flame height increases; thus, a higher area is exposed for burning, resulting in an increase in heat release rate. Thus, narrow cavity geometries are critical in spreading fire and combustion only if continuous air entrainment is available and could result in less fire spread/combustion than larger cavity widths. However, more systematic combustible cavity fire tests are needed to verify this conclusion.

4.5. Flow Velocity

None of the studies subjected to this review compared the flow velocities in cavity systems with open-fire scenarios. However, for a rack storage fire [32], smaller flue (vertical) widths show higher velocity than wider flue spaces, indicating cavity geometry could increase the smoke flow velocity compared with open-fire scenarios. Ingason et al. [30] and You et al. [36] identified that the flue velocities within vertical flues of rack storage geometries correlate well with convective heat release rate and virtual origin, which is also applicable to open axisymmetric plumes. Nevertheless, only a slight increment was observed compared with open axisymmetric plumes (1.04 times). Moreover, Livkiss et al. [1] showed that the cavity's flow increases with the fire's heat release rate and has no significant impact on narrow cavities where the cavity width is less than 40 mm. However, no studies considered the flow entering the cavity, which is crucial for the fire development within the parallel panels.

4.6. Air Entrainment and Smoke Toxicity

The physical boundaries that create a cavity space obstruct airflow into the middle of the cavity. For example, Ingason et al. [9] observed 25% less air entrainment in the cavity compared with an open flame in their rack storage study. The lower air entrainment in cavity fires can lead to the incomplete combustion of pyrolyzed gaseous fuel. This incomplete combustion results in toxic compounds. For example, under incomplete combustion, Polyisocyanurate insulation emits hydrogen cyanide and Carbon Monoxide [8]. Indications are available for this characteristic in studies by Peck et al. [8] and Chen et al. [7]. The cavity width, fire size, and type of combustible materials within the cavity can certainly influence the smoke toxicity of cavity fire scenarios. However, no in-depth studies have been done yet on their influence on cavity fire smoke toxicity. Therefore, deep discussion on this smoke toxicity factor is beyond the scope of this review. However, since the cavity boundaries cut off the air entrainment, toxic smoke production within the cavity should be greater than for the counterpart non-cavity fire scenario. In this case, once the fire is within the cavity, lower cavity widths are more likely to produce toxic smoke due to incomplete combustion. However, when the fire enters the cavity from outside, cavity width has a different dependency. In such cases, larger cavity widths allow more flame to enter the cavity. Hence, the large cavity widths are critical for toxic smoke production [7] when the cavity width plays a role in fire entering the cavity. For example, fire extending through a window entering a rainscreen façade cavity can be considered. Moreover, toxic smoke generation increases with the fire size or the amount of combustible materials within the cavity.

5. Fire Safety Risks vs. Cavity Type

The existing studies on cavity fire scenarios indicate various fire safety risks associated with cavity fires' main characteristics presented above. Such risks can vary from one cavity type to another, and even for a particular cavity type, the threat from that fire safety risk depends on the various parameters shown in Figure 2.

Research studies suggested different fire scenarios that affect cavity fire spread (Table A2). Among them, 45% of the studies considering fire scenarios within rooms (Figure 4) highlight the importance of that fire scenario for cavity fire spread. However, in most of the studies, significant idealization of fire scenarios and system configurations was done, and thus, future tests must consider more realistic fire conditions and the actual system configurations as much as possible. A fire within a room is more likely to enter the cavity through the perimeter of a window opening [3,7,39] for rainscreen façades, while the fire enters through inner glass pane cracking for double-skin façades [14,40]. The studies on external fire scenarios consider the combustion of cladding material as the path for the fire to enter the cavity. However, this penetration has been considered a rare scenario [3,41]. Very rarely can the combustible insulation materials within the façade cavity ignite due to heat-involved construction work, such as welding and power tools. For cavity spaces in wall, floor, and roof systems, fire can penetrate through floor/wall joints, sheathing board joints, service penetrations, and cavities connected to façade cavities.

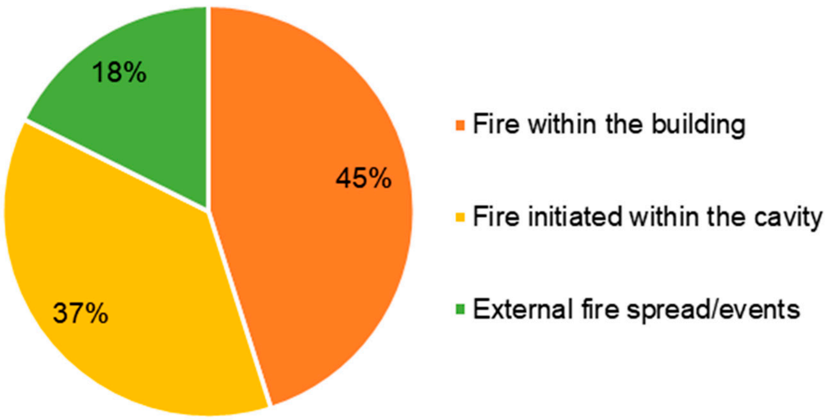

Figure 4. Researchers' attention to fire initiation (Table A2).

5.1. Fire Entering Upper and Adjacent Compartments

The flame extension characteristic of cavity fire invites the risk of fire entering upper levels through window frames exposed to ventilated cavities [3,7]. Giraldo et al.'s [3] numerical simulation verifies that even non-combustible façade cavities allow for a significant risk of fire entering the upper levels. For rainscreen façades, using combustible insulation materials with high thermal resistance (R-value) was beneficial in achieving energy standards while saving costs [16,31]. Nevertheless, this combustible insulation and cladding material in the cavity can further increase the risk [2,3,7,42] because flame extension allows the combustion of combustible materials at higher levels. Therefore, rapid fire spread in a vertical direction risks the lives of those on upper floors [27,43]. Similarly, modern construction methods, especially void spaces in modular constructions, provide a clear path to spreading fire and smoke [44]. Further, if the structural connections within these cavity spaces used to connect building components are unprotected, significant fire penetration can lead to catastrophic structural failures [44].

Contrary to a non-combustible cavity, combustible materials inside the cavity allow for downwards fire spread [2]. If the materials are melting and dripping [2,7,16], they can cause secondary fire sources further downwards from the initial fire location, increasing the fire safety risk. In their parallel panel test, Sharma et al. [16] observed that Polyisocyanurate (PIR) insulation resulted in heavy dripping. However, they did not compare this with the non-cavity situation. However, they believe that dripping caused multiple secondary fires, which resulted in a higher mass burning rate, fire spread, and heat radiation than the non-cavity geometry. Thus, there could be an impact from the cavity geometry to result in severe dripping, as it results in great thermal exposure, but clear indications have not been presented to verify this fact. However, when they were testing the effect of cavity width for the fire spread within a cavity made of Aluminium composite cladding where a Polyethylene core was placed between two Aluminium sheets (AL 43), they observed heavy dripping in the 13 mm cavity width but not with larger cavity widths of 75 mm and 100 mm. Thus, this indicates that dripping could be more critical in a cavity geometry than in an open fire; thus, the fire spreads downwards as well. Even Dr. Lane highlighted the radiation from the fire within the cavity as a reason for the downwards fire spread in the Grenfell Tower [45]. An et al. [2] showed the dripping of molten-extruded polystyrene helping to increase downwards fire spread in their test of where extruded polystyrene insulation was used within a vertical channel. The Grenfell Tower inquiry [45] also highlighted that the dripping of polyethylene in Aluminium composite material (ACM) cladding actively participated in fire spreading, especially in the lateral direction. It has also been noted that dripping polyethylene accumulating on cavity barriers resulted in lateral fire spread [45]. This fire risk is rare for double-skin façade cavity systems unless there are special circumstances, like adding photovoltaic panels in the outer pane [46].

Collier et al. [47] experimentally tested the possibility of fire spread through Polystyrene insulated panels (PIPs) with a core of expanded polystyrene used as both a floor and a wall via fire penetration due to accidental damage to a sheathing board igniting the insulation layer. However, due to limited oxygen availability, a considerable fire spread within cavities was not observed when the panels were intact. However, other combustible sheathing materials, such as oriented strand boards (OSBs), could be more critical, resulting in air gaps or direct insulation exposure to air. Such structural insulated panels (SIPs), which contain combustible insulation material in between timber boards, have been used for the modular units in Moorfield Hotel, which resulted in rapid cavity fire spread [20–22].

For a scenario where fire enters the cavity due to flame ejecting through a window opening of a rainscreen façade cavity arrangement, larger cavity widths and large fire sizes allow more flame to enter the cavity, which increases the risk [3,7,39]. Sultan [15] identified a risk of fire/flame spreading into upper levels through double-stud wall–floor joints for a fire scenario on the floor below the joint and found that when the cavity is narrower than 25 mm in width, it has less chance of fire penetrating the cavity. Based on other existing research on façade cavities, it can be expected that a cavity width of 25 mm [39] reduces the risk of fire entering upper levels, whereas 50, 70, 100, 150, 170, and 200 mm [3,7] cavities show high chances of fire getting into upper levels. However, the experiment [39] that showed a 25 mm cavity width to reduce the risk was a non-combustible cavity. The cavity was 5.2 m in height, suggesting a low chimney flow, and the perimeter of the window opening was protected with perforated steel plates. Therefore, results for the same cavity width of 25 mm could differ with combustible material and high chimney flow.

Moreover, for small cavity widths, even though hot gaseous pyrolyzed products enter the cavity, there is a possibility that flaming may not happen due to a lack of oxygen within the cavity. However, as more hot smoke enters the cavity with the strong buoyancy generated, fresh air will be drawn in, initiating flaming [41]. Further, once the unburnt smoke is mixed with air at the top of the cavity, it can start flaming [28,41], resulting in an upwards draught. Such an upwards draught can increase the flame height both within and outside the cavity [41], rapidly spreading fire in the vertical direction.

Once the upwards airflow within the cavity is high, it gives a higher chance of spreading fire into upper levels [3]. However, An et al. [2] showed that whether the side ventilation into the cavity improves or reduces the stack effect and air entrainment into the combustion within the cavity, flame height and fire spread may be reduced or increased. More research is needed to identify the effect of external wind conditions on fire behaviour within the cavity.

5.2. Smoke Spread into Upper Floors

For double-skin façade systems, the most critical cavity fire-related risk is that smoke spreads to living areas on upper floors due to the inner glass pane failure triggered by heat flow within the cavity [6,14,40,42]. Smoke spreading into the upper levels eventually increases the toxicity levels in upper areas [48]. The risk level is high when the inner pane breaks before the outer pane. The unequal pressure difference adjacent to the smoke plumes caused by the difference in air entrainment affects the plume's impingement on glass panes [6,35], which causes the first glass pane (inner or outer) to break. However, different behaviours can be involved in this process depending on the cavity width [6,14,34,35,49,50] and the heat release rate (HRR) [6,35,40] of the room fire. For a high heat release rate (5 MW), the exterior glass pane heats first due to direct fire plume impingement [35,40], whereas for a small fire (heat release rate = 1 MW), due to the low outflow speed of the plume, the plume impingement on the exterior pane would not be critical compared with a large fire case [6,35]. With smaller cavity widths (1.0 and 0.5 m), smoke plumes attach to the outer pane at first [14,34]. Therefore, the exterior pane may break first [35,49]. For large cavities close to 2 m, due to the intense air entrainment from the bottom, the plume detaches from the exterior pane and impinges on the interior pane [35], resulting in the inner pane breakage. However, if sufficient chimney flow exists, large cavities can have reduced risks because ambient air cools down the cavity space. This circumstances leave the cavity depths of around 1 m as the most dangerous [34,49]. Peng et al. [51] conducted numerical simulations for an experiment on a smoke plume entering a double-skin façade. The plume behaviour for a narrow cavity depth (0.8 m) is consistent with the above-discussed patterns. However, for a wide cavity (2 m), the smoke plume does not impinge on the internal skin as expected. Due to the cavity's low height (6.6 m), the low chimney effect cannot push the plume towards the internal skin. Therefore, the plume behaviour for the cavity can be changed with the floor level of the fire, which determines the chimney flow. Due to high chimney flow, fire in upper levels could produce a plume attachment with the inner pane, resulting in higher risk [52]. Likewise, the plume attachment behaviour is complex, and attempts have been made to develop a graphical criterion to identify the plume impingement on the glass panes for double-skin façade (DSF) window-ejecting plumes [6]. It considers the heat release rate, opening geometry, and cavity width as the main parameters but does not consider the level of the fire room, and thus, the chimney flow. To evaluate the temperature distribution of such glass double-skin façade (DSF) systems, empirical equations were derived [53] using data generated from numerical modeling. However, these equations are limited to the exact conditions or numerical model validations.

In the case of rainscreen façades, toxic smoke can enter tenable areas through openings [7] and vent systems [8]. Since rainscreen façades contain combustible insulation materials and claddings that could emit toxic gases, like Hydrogen cyanide (HCN) and Carbon Monoxide (CO) [7,8], the toxicity levels in the upper floors could be more critical for a rainscreen façade compared with a double-skin façade. Only Peck et al.'s [8] study experimentally quantified the smoke toxicity associated with cavity geometries (ventilated façade). The test included a kitchen vent of 100 mm diameter, which penetrates the façade and opens to the cavity while facing a steel grill on the exterior surface of the façade. Smoke was monitored at the end of this vent pipe to consider an event of smoke entering the building via a kitchen or bathroom vent, broken window, or a void in the building's construction during a façade fire. For burning combustible insulation (Polyisocyanurate (PIR)) within a

50 mm cavity width rainscreen façade, a sudden increase in toxicity (Hydrogen cyanide and Carbon Monoxide concentration) was revealed once the fire entered and ignited the combustible insulation. For example, incapacitation due to smoke coming through the vent, which resulted from smoke in the cavity, was 40 times greater than the smoke outside the cavity and five times higher in lethality. For a scenario of fire entering a rainscreen façade cavity under a fire ejecting from a window, the release of Carbon Monoxide was identified to increase with the cavity width due to an increase in flame entering, increased area for the fire development, and supply of sufficient oxygen (yet below the total requirement) [7]. However, Peck et al.'s study [8] verified that even a 50 mm cavity width can produce severe toxicity once the fire enters the cavity.

5.3. Falling Cladding/Debris

The severe burning of combustible material and high-temperature environment within the façade cavity systems can have secondary risks of supporting elements, especially aluminium frames [35,40] and timber frames undergoing strength reduction, resulting in localized system collapse [3]. The exterior glass panels in double-skin façade systems [40] and cladding panels in rainscreen façades [54] could fall onto pedestrians and damage the lower floors and adjacent buildings [7]. However, experimental evidence investigating the structural deformations and mechanisms caused under such circumstances has not been found, which needs attention. Existing research has not studied the impact of façade cavities on falling cladding/debris during a fire compared with a non-cavity façade. However, in the parallel panel tests by Sharma et al. [16], it was identified that unlike 75 mm and 100 mm cavity widths, due to the severe burning in 25 mm and 50 mm cavity widths, the façade panel tested in parallel panel test arrangement fell off, indicating structural failure. This observation verified that there could be a more significant threat of falling cladding/debris in cavity façades than for non-cavity façades and can be explained by severe heat exposure within the cavity.

5.4. Difficulties in Firefighting and Rescuing

The main challenge that firefighters face is that once the fire spreads through concealed cavity spaces, they are not observable from the outside, and that makes it hard to find the origin of the fire [3,7,27,40]. Thus, it compromises the valuable time available for rescuing people [40]. This challenge could be more applicable to rainscreen façade systems and wall cavities. However, when double-skin façades contain high-strength glass panes to avoid glass breakage during the fire, it can challenge the firefighters' chances to rescue people by entering through glass panes [40]. Further, when firefighters open cavities, a sudden airflow into the cavity can result in a sudden flashover when unburnt smoke enclosed within the cavity space meets oxygen in the air [7,41].

When it comes to extinguishing fires in buildings (especially timber buildings) where fire penetrates and is sustained within the floor and wall cavities, it would be challenging to locate and estimate the fire size to make quick decisions to extinguish [31,40,55]. Thus, significant fire damage can occur with extensive smoke damage [31]. Further, firefighters may enter rooms containing hidden fire propagation through wall and floor cavities. On such occasions, firefighters are in danger of structural system collapse due to the degradation of structural strength.

6. Fire Protection Strategies

Researchers highlighted several protection measures to ensure fire safety from cavity fire spread.

6.1. Geometrical Planning

Researchers' observations and suggestions indicated that cavity fire-related risks in façade systems can be prevented or reduced through geometrical planning by identifying the façade geometries' dependency on the fire safety risks discussed above. Even though this was mainly identified for double-skin façade systems, some indications also appeared for rainscreen façades. For rainscreen façades, the risk of fire and smoke spreading to upper levels from a fire extending from a window is likely to be reduced for narrow cavity widths, especially below 50 mm [3,7,39]. However, if fire enters a narrow cavity, it could also worsen the fire scenario, as discussed in the previous sections. An et al.'s [2] results on the dependence on side ventilation on fire spread on the insulation inside a cavity indicate that when using side vents, a dimensionless side opening area (ratio of sidewall opening area to sidewall area) of 0.13 can reduce the flame spread, flame height, and wall temperature, which needs attention. Therefore, this side vent adjustment approach can lower the fire spread risk and the local collapse of cladding due to structural strength reduction.

Multiple options/suggestions are found for double-skin façades to decrease the fire safety risk of smoke entering upper levels through internal panel failure. Ji et al.'s [52] study highlights that an outwards-tilted outer panel can prevent hot smoke from flowing out of the fire room and decrease the cavity's temperature. Abdoh et al.'s [53] study highlights that when Venetian blinds are incorporated into the façade cavity with high tilt angles (90°), the temperature increases for the upper parts of the panes and decreases for the exterior pane's lower parts, risking the upper levels. Using wider aprons of 1 m above the interior openings was identified as helpful in protecting the interior glass panes of upper levels, as it guides the hot plume towards the exterior skin [17]. Thomas et al.'s [56] suggestions involved closing the internal vents and using a larger external vent area compared with the internal vent area.

Moreover, research on the dependency of cavity width on inner pane breaking risk can be used to obtain suggestions for choosing cavity widths. Thus, cavity widths around 1 m could be dangerous under low stack flow (lower floors) [17,37,52], and much larger cavity widths of 2 m [35] can be critical under high stack flow (higher floor levels). However, this simple guide is incomplete since the plume behaviour within the cavity is complex. The graphical criterion to identify the plume attachment on the interior or exterior skin of a double-skin façade from a window ejecting plumes by Miao et al. [6] can be more helpful in understanding the selected double-skin façade geometry's risk.

Most fire accidents in storage geometries were reported to result from deliberate acts where a conscious effort was made to locate the fire so that it would propagate quickly [13]. Thus, such fire scenarios are hard to prevent with fire protection but can be avoided by understanding the physics to avoid hazardous geometries and causes [13]. Vertical flue (cavity) width and the heat release rate of the fire, and thus, the material combustibility affect the flame height [9,10], which controls the vertical fire spread. However, no significant influence was found from the height of the horizontal cavities [9,10,57]. However, no studies identified the dependency of flue depth on fire propagation through horizontal flues. Studies on a variety of rack storage geometries (2d and 3d), heights, scales, and materials showed that flame height increases with reducing cavity width and increasing flame heights [4,9,10]. These findings suggest that combustible storage geometries with vertical flue spaces of 50 mm width present severe threats. Due to buoyancy and the difficulty of flame turning to the horizontal direction, the vertical fire spread is much faster than the horizontal [18]. Since horizontal fire spread forces fire to move further away from the ignition point, it is also critical for the total fire risk.

6.2. Usage of Non-Combustible Cavity Barriers/Fire Stops

Using non-combustible cavity barriers/fire stops in horizontal and vertical directions to prevent the fire/flame spread and reduce the fire input inside the cavity was identified as a fire protection strategy against cavity fire spread in rainscreen façades and wall cavities [15,44,58]. The usage of cavity barriers showed the ability to prevent rapid vertical fire spread [59]. However, Giraldo et al. [3] identified that using fire barriers only at floor levels of a rainscreen façade cavity is insufficient and should also be added around window perimeters. Grenfell Tower was found to be absent fire barriers around the windows, where the fire entered the cavity by bypassing its frame [45]; this fire accident validates the observations of Giraldo et al. [3]. Since ventilated façades need to allow airflow during normal conditions, cavity barriers with intumescent materials or perforated plates are popular in providing unobstructed airflow under normal conditions [19,42]. The number of horizontal cavity barriers [19] and the width [60] of the cavity barriers are essential parameters in controlling fire spread and are directly proportional to the safety provided. Further, the performance of the cavity barrier is dependent on the usage of insulation materials and cladding materials [22], where it is recommended to use non-combustible materials [27].

However, there have been several concerns regarding the intended performance of cavity barriers. Guillaume et al. [59,61] and Drean et al. [62] showed that the cavity barriers become inefficient with combustible Aluminium composite material (ACM) cladding. Due to the expansion of the substructure, the delamination and deflection of façade panels can create gaps that enable fire to pass through cavity barriers [7,41]. However, no thorough research has been reported on identifying their mechanisms. The Grenfell Tower tragedy strengthens this observation. In the Grenfell Tower Inquiry, it was highlighted that distortion of the cladding panels due to heat or the failure of cladding supporting systems, the gap between the cladding and the cavity barrier increased, leading to cavity barriers becoming ineffective at stopping fire spread [45]. Thus, even though cavity barriers can prevent cavity fire spread in non-combustible cavity spaces, they are incapable of preventing fire spread when the system is a combustible cavity space. Poor workmanship and weak designs could also compromise the performance of cavity barriers [58]. Among various defects in cavity barrier application, missing cavity barriers are the riskiest [63]. In contrast, gaps between cavity barriers and joints without adequate taping are the most probable defects [63]. Other common defects include inadequate installation of fixing brackets, cavity barrier sagging in the cavity, vertical cavity barrier placed horizontally, a horizontal barrier placed vertically, the wrong orientation of horizontal vented cavity barrier, gaps between cavity barriers, cavity barrier in front of the insulation, incorrect dimensional gap, and cavity barrier material substitution [63]. The cavity barriers were bypassed in the Grenfell Tower façade due to poor detailing of cladding rails, providing a path for vertical fire spread [45].

Recent concerns have arisen regarding flame spread through intumescent fire barriers during the open state [27,41,63] due to sudden flame attacks, and the development of new test standards has been given attention [41]. Further, it is crucial to distinguish the correct cavity barrier type for the correct fire exposure. Without a proper test standard to distinguish the suitable type of fire barrier for a given fire exposure, Strom [42] summarized cavity barriers and preferable fire exposures that could be effective. The cavity barriers with intumescent stripes were recommended for fire exposures with a slow time gradient where direct flame exposure is absent. Perforated type or sheet labyrinth type suits exposures of embers and flame. The intumescent mesh type is recommended for ember attack and sudden direct flame exposure. The most frequent solid-type cavity barriers (wood/mineral wool/calcium silicate/gypsum/steel) were identified to suit room fires and façade fire exposures.

6.3. Usage of Non-Combustible Materials

In research done by Bonner et al. [43], a database of 252 commercial façade tests revealed that rainscreen cavity façades have a poor fire performance compared with the other types. However, it was suggested that this behaviour is due to the associated combustible materials within these façades. Therefore, non-combustible insulation and cladding materials are helpful for protection from cavity fire spread. In circumstances where combustible materials are unavoidable, the addition of fire retardants can be considered [64]. Therefore, for systems with combustible insulation materials to reduce fire spread risks, using combustible insulation with a proportion of fire retardants or intumescent substances can be considered a new research direction. Moreover, the fire safety risk of toxic smoke generation during partial combustion of insulation materials, like Polyisocyanurate foam, can be prevented by using non-combustible products like mineral wool. Apart from this, organoclay and ceramic-based particles can be used to control overall smoke production in combustible façade materials [65,66].

6.4. Using Sprinkler Systems

Sprinklers within the fire room [56] and the cavity [67] can limit smoke generation and smoke entering double-skin façade cavities. A relatively unconventional method of adding a water spray system in the cavity helps [67] to prevent smoke from spreading beyond room height, resulting in low temperature in the cavity but high temperature within the room space.

Generally, fire protection against fire spread through the cavity (flue) spaces in storage geometries is achieved by sprinklers placed inside or above the rack storage [4,9,57]. The efficiency depends on the geometrical arrangement, flammability of the commodity, and sprinkler properties [57]. The flow conditions provide valuable information for understanding the sprinkler operation time. Therefore, early predictions of flow velocities within flue spaces and gas temperature in plume flow through flues are essential in planning sprinkler systems. Obstructing the bottom of the storage boxes from flame impingement using pallets showed the potential to reduce lateral fire spread [18]. Thus, further research can reduce the fire spread risk by using a variety of pallet materials and geometries.

6.5. Using Toughened Glass

As a protective measure against glass cracking in double-skin façade (DSF) cavities, using toughened glass (tempered glass) for glass panes was suggested [14,40,49]. Ni et al. [40] showed that 6 mm toughened glass double-glazed with a 9 mm gap can resist a temperature of 600 °C to 800 °C, preventing smoke from entering the upper levels through glass breakage. Based on these suggestions, high-strength glass for the inner and low-strength for the outer skins could be advantageous in diverting the smoke entering the DSF cavity to the outer environment through outer pane cracking. In addition, dividing the glass panel area into several small glass panel segments could also be helpful. This is because, for small segments, the temperature difference between the edge of the panel further away from the fire and the center closer to the fire will be lower than for a much larger panel. This lower temperature difference results in lower stresses in the glass panel, lowering the chances of cracking [14].

6.6. Performance Assurance through Tests

Even though the purpose of façade tests is to identify whether it can contribute to a critical fire scenario that is not expected, conducting a façade test utilizing exact details under a standard method can indirectly show the level of fire safety for cavity fire spread. Even though the façade comprises non-combustible elements, these should be tested if they contain cavities, as a cavity can play a critical role in spreading fire to upper levels [68]. Schulz et al. [68] reviewed several standard tests for façades, and the criteria concerned with cavity fire spread in these façade tests are given in Table 6. However, these performance criteria are inconsistent, and the same façade system can pass one test standard and fail another. Moreover, these tests are not specifically undertaken to assess fire safety against cavity fire spread and sufficient assessments are not done for smoke spread. Attention should be paid to measuring toxicity levels to confirm that the designs are safe from increasing toxicity at upper levels. Therefore, attention is needed towards adopting modified or separate tests to ensure the performance of cavity spaces, and the parallel panel test suggested by Jamison and Boardman has great potential in this case [31].

Table 6. Cavity-fire-spread-related performance criteria in façade test standards.

Test Standard	Country Used	Cavity Fire Spread-Related Performance Criteria
ISO 13785-2002	International	No specific criteria
BS 8414	UK	Cavity temperature increase at 5 m above the opening should not exceed 600 °C for a period greater than 30 s during the first 15 min of the test
DIN 4102-20	Germany	The cavity temperature at 3.5 m above the opening should be less than 500 °C with no burn damage
NFPA 285	USA	The cavity temperature should not exceed 538 °C at 3 m above the opening
SP FIRE 105	Sweden	No fire spread beyond 4.2 m above the opening

Similarly, tests are available to assess the performance of cavity barriers. The proposed prEN 1364-6 is for closed and open/ventilating cavity barriers [41]. ASTM E2912-13 tests fire spread under sudden direct flame impingement [41]. However, all these tests are small-scale tests that do not represent the actual application of façades, for example, their surrounding materials, cavity geometry, and fire scenarios. Moreover, concerns have been raised about whether the fire exposures used to test cavity barriers can replicate the realistic conditions during a cavity fire spread. Therefore, Just et al. [25] investigated this concern and concluded that the existing cavity barrier testing methods do not consider the possibility of heating the air between two cavity barriers, which can cause smoldering combustion of materials within the cavity. Therefore, Just et al. [25] suggested using two-cavity barriers with combustible cavity boundaries (if applicable) to assess the performance of cavity barriers.

Further, some cavity fire incidents have caused the reignition of fire within cavity spaces, even after the extinguishment of visible fire [25]. Therefore, Just et al. [25] suggested a potential fire curve to test cavity barriers that consider the possibility of reignition. Moreover, Jensen [69] has cited that fire exposure could reach the hydrocarbon standard fire curve during cavity fire spread. Therefore, these concerns need to be further researched when testing the suitability of cavity barriers.

Smoke leakage through cavity spaces due to poor fire stopping within concealed spaces in building wall and floor systems breaches the compartmentation by spreading smoke to other areas [58]. Therefore, robust attachment methods should ensure that cavity-incorporated elements and fire stops remain in place even under building deformations with time, especially during earthquakes. Thus, methods are needed to identify construction defects causing fire and smoke to spread through cavities, apply remedies, and avoid such defects by design. An excellent initiative for such research was proposed by Littlewood et al. [58], who highlighted the importance of a non-destructive building performance test to correctly identify smoke leakage paths using smoke generation to simulate buoyancy conditions. Further, if there are uncertainties in sealing the cavity spaces, new fire tests [44] or design guidance to restrict or resist cavity fire spread is needed.

7. Future Research and Recommendations

Identification of future research needs and recommendations can overall be made based on available literature. They are essential to improve the fire safety of structures with cavities. This study identified the following areas to be further researched to fill the gaps in knowledge on cavity fire scenarios:

- To predict fire behaviour (especially flame height, gas temperature, heat flux, and smoke velocity) within cavity systems, existing correlations should be further improved with experiments on different cavity fire scenarios.
- The increased smoke toxicity associated with cavity fire spread has not been given significant attention, which needs further research to highlight the risk.

- Future experimental tests must consider more realistic fire conditions and system configurations to capture the realistic fire penetration and spreading scenarios through cavity spaces.
- The effect of wind conditions within and outside the cavities must be further investigated, considering different wind speeds and directions.
- The effect of cavity fire spread in buildings on the structural performance needs further experimentation to identify failure mechanisms to avoid sequential failure, and thus, allow occupants to evacuate safely.
- Detection and extinguishment of hidden cavity fires need affordable and effective methods to make firefighting more effective.
- Robust measures to avoid performance compromisation due to cavity barrier defects and cavity barriers' performance under combustible substrates and building movements must be identified, and full-scale fire tests must be conducted with proper instrumentation. Non-destructive in situ tests can be implemented to check whether the cavity barriers and fire stops are performing correctly.
- Attention needs to be raised to develop standard fire tests to assess the performance of cavity spaces under cavity fire spread and smoke spread.
- Knowledge of general cavity fire spread should be applied to novel modular construction methods to identify the risks of fire spread through intermodular cavity systems as a first step in improving modular buildings' fire safety.

8. Conclusions

Cavity fire scenarios have not received much attention compared with other fire scenarios. Individual studies on cavity fire spread are insufficient to provide a conclusive idea of cavity fire scenarios and their threats. Hence, a systematic literature review following the PRISMA method was conducted to identify the possible fire safety risks associated with cavity fire spread and protection strategies, and the following conclusions were made:

- Even though cavity fire scenarios are less explored, attention to cavity fire scenarios has increased throughout the years due to the adoption of cavity spaces in building geometries. Cavity fire scenarios in façades have received greater attention as being critical, while fire spread through intermodular cavities in novel modular constructions has not yet received much attention.
- Fire behaviour within cavity spaces has significant variations compared with open-fire scenarios. Due to the low air entrainment and chimney flow, flame heights can be as high as two times the counterpart open-fire scenarios for non-combustible cavity systems and up to 10 times for combustible systems. Re-radiation from cavity boundaries and lack of convective cooling can increase heat exposure on cavity boundaries up to 14 times compared with non-cavity systems. The gas/surface temperature can be as high as 13 times that found in open-fire scenarios. It is possible to exceed the standard fire curve to reach hydrocarbon fire at the beginning of the fire. All these characteristics lead to severe fire spread through cavity geometries. Increased toxicity with increased smoke velocity can produce severe smoke spread compared with open-fire scenarios. Therefore, cavity fire scenarios can not simply be ignored in building fire safety.
- Cavity width, ventilation, and fire size have greater control over the cavity fire scenarios, which can control the level of fire risks. Narrow cavities bounded with combustible materials can be disastrous in fire spread under the continuous airflow into the system. Wide cavities with combustible materials are crucial when there are obstructions to continuous airflow into the cavity space.
- Various fire safety risks associated with the characteristics of cavity fires are discussed, and the safety strategies presented in other research studies are discussed and reviewed.
- Among the various protection strategies applied to cavities, cavity barriers were identified as the leading fire protection strategy for narrow cavities in building geometries. However, it was concluded that it may not be applicable when the substrates are com-

bustible. Various other challenges exist in achieving fire safety using cavity barriers that need attention are also highlighted.

- More research is needed to ensure the fire safety of cavity-involved building components. Suggestions for future research are highlighted to contribute knowledge on cavity fires towards strengthening awareness and safer building designs.

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Appendix A

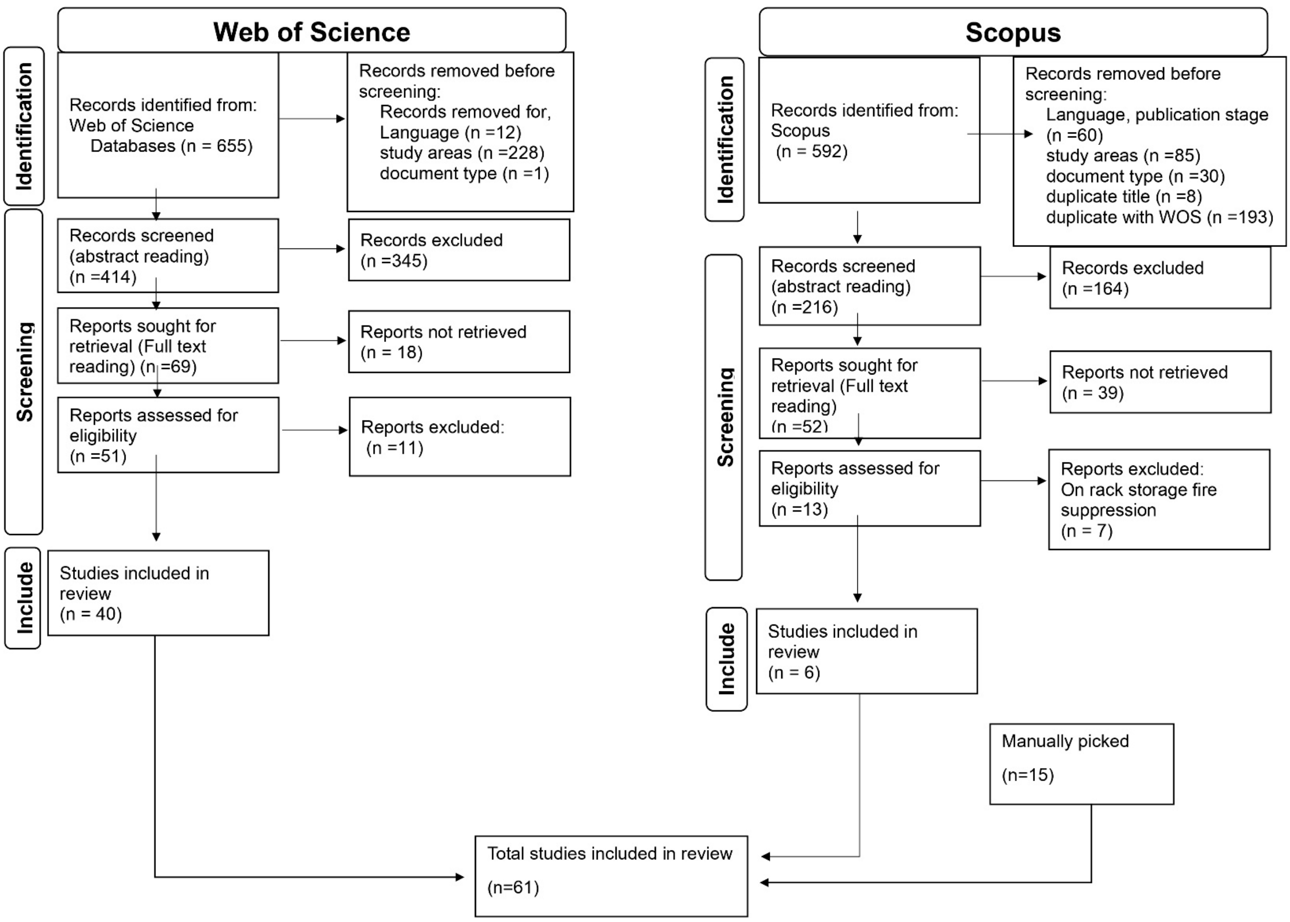

Figure A1. PRISMA flow chart for article selection.

Table A1. Influential parameters for fire behaviour within cavity spaces indicated in the reviewed articles. A—cavity width, B—airflow/cavity barriers, C—combustibility/heat release rate, D—cavity configuration, E—nature of fire penetration, F—fire location, G—size of fire penetration void, H—sootiness, F1—rainscreen façade, F2—double-skin façade, R—rack storage, W—wall cavity, P—parallel panel cavity.

Ref.	Cavity Type	Parameter							
		A	B	C	D	E	F	G	H
[39]	F1					✓			
[2,19,27,45,62]	F1		✓	✓					
[33,43]	F1			✓					
[3,70]	F1	✓	✓	✓		✓			
[41,59,60,63]	F1		✓						
[68]	F1	✓	✓						
[38]	F1	✓							
[42]	F1,2	✓	✓		✓				
[6]	F2	✓		✓				✓	
[14,34,35,49,50]	F2	✓							
[46]	F2			✓					
[52]	F2				✓		✓		
[51]	F2	✓	✓						
[40]	F2			✓			✓		
[17,53,58,67]	F2				✓				
[32]	R	✓							
[18,36]	R			✓					
[4,9]	R	✓		✓	✓				
[30]	R								✓
[10]	R	✓			✓				
[11]	W	✓		✓				✓	
[15]	W	✓	✓						
[44]	W			✓					
[25,28,47]	W		✓						
[1]	P	✓		✓					
[13]	P	✓	✓	✓		✓			
[16,37]	P	✓	✓						
[5,29,31]	P	✓	✓	✓					
[12]	P						✓		

Table A2. Location of fire initiation.

Fire Scenario	Ref.
Fire within the building	[3,6–8,11,14,15,17,19,25,33,35,39–41,46,48,51,56,60,62,67,70]
Fire initiated within the cavity	[1,2,4,5,9,10,12,13,16,18,28–32,36,37,57,71]
External fire spread/events	[16,28,37,38,41,43,47,59,62]

References

1. Livkiss, K.; Svensson, S.; Husted, B.; van Hees, P. Flame Heights and Heat Transfer in Façade System Ventilation Cavities. *Fire Technol.* **2018**, *54*, 689–713. [CrossRef]
2. An, W.; Yin, X.; Chen, S.; Zhang, G. Study on downward flame spread over extruded polystyrene foam in a vertical channel: Influence of opening area. *Fire Mater.* **2018**, *43*, 153–161. [CrossRef]
3. Giraldo, M.P.; Lacasta, A.; Avellaneda, J.; Burgos, C. Computer-simulation study on fire behaviour in the ventilated cavity of ventilated façade systems. In *MATEC Web of Conferences*; EDP Sciences: Les Ulis, France, 2013; Volume 9, p. 03002. [CrossRef]
4. Ingason, H. Plume flow in high rack storages. *Fire Saf. J.* **2001**, *36*, 437–457. [CrossRef]
5. Hu, L.; Liu, S.; Zhang, X. Flame heights of line-source buoyant turbulent non-premixed jets with air entrainment constraint by two parallel side walls. *Fuel* **2017**, *200*, 583–589. [CrossRef]
6. Miao, L.; Chow, C.L. A study on window plume from a room fire to the cavity of a double-skin façade. *Appl. Therm. Eng.* **2018**, *129*, 230–241. [CrossRef]
7. Chen, T.B.Y.; Yuen, A.C.Y.; Yeoh, G.H.; Yang, W.; Chan, Q.N. Fire Risk Assessment of Combustible Exterior Cladding Using a Collective Numerical Database. *Fire* **2019**, *2*, 11. [CrossRef]
8. Peck, G.; Jones, N.; McKenna, S.T.; Glockling, J.L.; Harbottle, J.; Stec, A.A.; Hull, T.R. Smoke toxicity of rainscreen façades. *J. Hazard. Mater.* **2020**, *403*, 123694. [CrossRef] [PubMed]
9. Ingason, H. Two Dimensional Rack Storage Fires. *Fire Saf. Sci.* **1994**, *4*, 1209–1220. [CrossRef]
10. Karlsson, B.; Thomas, P.H.; Holmstedt, G. Flame Sizes in a Small Scale Stack: Pilot Experiments. 1995. Available online: https://www.lunduniversity.lu.se/lup/publication/6d4662b5-2ec2-4eab-95eb-72a773e6bc9e (accessed on 28 December 2021).
11. Lee, Y.P.; Delichatsios, M.; Ohmiya, Y.; Wakatsuki, K.; Yanagisawa, A.; Goto, D. Heat fluxes on opposite building wall by flames emerging from an enclosure. *Proc. Combust. Inst.* **2009**, *32*, 2551–2558. [CrossRef]
12. de Ris, J.L.; Orloff, L. Flame Heat Transfer between Parallel Panels. *Fire Saf. Sci.* **2005**, *8*, 999–1010. [CrossRef]
13. Foley, M.; Drysdale, D. Heat transfer from flames between vertical parallel walls. *Fire Saf. J.* **1995**, *24*, 53–73. [CrossRef]
14. Chow, W.; Hung, W. Effect of cavity depth on smoke spreading of double-skin façade. *Build. Environ.* **2006**, *41*, 970–979. [CrossRef]
15. Sultan, M.A. Fire Spread via Wall/ Floor Joints in Multi-family Dwellings. *Fire Mater.* **2000**, *24*, 1–8. [CrossRef]
16. Sharma, A.; Mishra, K.B. Experimental investigations on the influence of 'chimney-effect' on fire response of rainscreen façades in high-rise buildings. *J. Build. Eng.* **2021**, *44*, 103257. [CrossRef]
17. Chow, N.C.L.; Li, S.S.; Huang, D.X. Apron design for protecting double-skin façade fires. *Fire Mater.* **2014**, *39*, 189–206. [CrossRef]
18. Ren, N.; de Vries, J.; Zhou, X.; Chaos, M.; Meredith, K.V.; Wang, Y. Large-scale fire suppression modeling of corrugated cardboard boxes on wood pallets in rack-storage configurations. *Fire Saf. J.* **2017**, *91*, 695–704. [CrossRef]
19. Čolić, A.; Pečur, I.B. Influence of Horizontal and Vertical Barriers on Fire Development for Ventilated Façades. *Fire Technol.* **2020**, *56*, 1725–1754. [CrossRef]
20. Apps, P. Are Two Fires on the Shetland Islands a Canary in the Coal Mine for Modular Construction? Inside Housing. Available online: https://www.insidehousing.co.uk/news/news/hotel-destroyed-in-fire-was-constructed-offsite-using-insulated-panels-documents-show-67428 (accessed on 4 September 2021).
21. Cope, C.; Marter, H. Investigation Underway after Huge Fire Destroys. Shetland News. Available online: https://www.shetnews.co.uk/2020/07/27/investigation-underway-after-huge-fire-destroys-moorfield-hotel/ (accessed on 4 September 2021).
22. BBC News. Shetland Fires 'Should Act as Warning to Modular Building Industry'. Available online: https://www.bbc.com/news/uk-scotland-north-east-orkney-shetland-57942459 (accessed on 4 September 2021).
23. Gallagher, K. The Dangers of Modular Construction. Fire Eng. Available online: https://www.fireengineering.com/firefighting/the-dangers-of-modular-construction/#gref (accessed on 5 September 2021).
24. Gallagher, K. Modular Construction: Hidden Hazards within. Fire Eng. Available online: https://www.fireengineering.com/fire-prevention-protection/modular-construction-hidden-hazards-within/#gref (accessed on 5 September 2021).
25. Just, A.; Brandon, D. *Fire Stops in Buildings*; SP Report 2017:10; SP Technical Research Institute of Sweden: Borås, Sweden, 2017.
26. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ* **2021**, *372*, n71. [CrossRef]
27. Hossain, D.; Hassan, K.; Yuen, A.C.Y.; He, Y.; Saha, S.; Hittini, W. Flame behaviour, fire hazard and fire testing approach for lightweight composite claddings–A review. *J. Struct. Fire Eng.* **2021**, *12*, 257–292. [CrossRef]
28. Rogowski, B. Fire performance of combustible insulation in masonry cavity walls. *Fire Saf. J.* **1985**, *8*, 119–134. [CrossRef]
29. Mendez, J.E.; Lange, D.; Hidalgo, J.P.; McLaggan, M.S. Effect of cavity parameters on the fire dynamics of ventilated façades. *Fire Saf. J.* **2022**, *133*, 103671. [CrossRef]
30. Ingason, H.; de Ris, J. Flame heat transfer in storage geometries. *Fire Saf. J.* **1998**, *31*, 39–60. [CrossRef]
31. Jamison, K.L.; Boardman, D.A. A new fire performance test for cavity wall insulation. In *MATEC Web of Conferences*; EDP Sciences: Les Ulis, France, 2016; Volume 46, p. 02004. [CrossRef]
32. Guedri, K.; Borjini, M.N.; Jeguirim, M.; Brilhac, J.-F.; Saïd, R. Numerical study of radiative heat transfer effects on a complex configuration of rack storage fire. *Energy* **2011**, *36*, 2984–2996. [CrossRef]
33. Boström, L.; Skarin, C.; Duny, M.; McNamee, R. *Fire Test of Ventilated and Unventilated Wooden Façades*; SP Report 2016:16; SP Technical Research Institute of Sweden: Borås, Sweden, 2016.

34. Chow, W.; Hung, W.; Gao, Y.; Zou, G.; Dong, H. Experimental study on smoke movement leading to glass damages in double-skinned façade. *Constr. Build. Mater.* **2007**, *21*, 556–566. [CrossRef]
35. Chow, C.L. Numerical studies on smoke spread in the cavity of a double-skin façade / skaitinis dūmų sklidimo dvigubo fasado Ertmėje tyrimas. *J. Civ. Eng. Manag.* **2011**, *17*, 371–392. [CrossRef]
36. You, H.; Kung, H. Strong buoyant plumes of growing rack storage fires. In *Twentieth Symposium (International) on Combustion*; The Combustion Institute: Pittsburgh, PA, USA, 1984; pp. 1547–1554.
37. Taylor, W. Fire spread in concealed foamed plastic insulation. *Fire Technol.* **1983**, *19*, 192–203. [CrossRef]
38. Hassan, K.; Hossain, D.; Gilvonio, M.; Rahnamayiezekavat, P.; Douglas, G.; Pathirana, S.; Saha, S. Numerical Investigations on the Influencing Factors of Rapid Fire Spread of Flammable Cladding in a High-Rise Building. *Fire* **2022**, *5*, 149. [CrossRef]
39. Asimakopoulou, E.K.; Kolaitis, D.I.; Founti, M.A. Performance of a ventilated-façade system under fire conditions: An experimental investigation. *Fire Mater.* **2020**, *44*, 776–792. [CrossRef]
40. Ni, Z.; Lu, S.; Peng, L. Experimental study on fire performance of double-skin glass facades. *J. Fire Sci.* **2012**, *30*, 457–472. [CrossRef]
41. Strøm, R.A. Recent progress on test evidence, standardization and design of protection for exterior openings. In *MATEC Web of Conferences*; EDP Sciences: Les Ulis, France, 2016; Volume 46, p. 01004. [CrossRef]
42. Nguyen, K.T.; Weerasinghe, P.; Mendis, P.; Ngo, T. Performance of modern building façades in fire: A comprehensive review. *Electron. J. Struct. Eng.* **2016**, *16*, 69–87. [CrossRef]
43. Bonner, M.; Wegrzynski, W.; Papis, B.K.; Rein, G. KRESNIK: A top-down, statistical approach to understand the fire performance of building facades using standard test data. *Build. Environ.* **2020**, *169*, 106540. [CrossRef]
44. Meacham, B.J. Fire performance and regulatory considerations with modern methods of construction. *Build. Cities* **2022**, *3*, 464–487. [CrossRef]
45. Grenfell Tower Inquiry: Phase 1 Report—Vol. 4. 2019. Available online: www.gov.uk/official-documents (accessed on 18 July 2023).
46. Miao, L.; Chow, C.L. Investigation of burning photovoltaic panels on a double-skin facade with ejecting flame from an adjacent room fire. *Indoor Built Environ.* **2018**, *28*, 938–949. [CrossRef]
47. Collier, P.C.R.; Baker, G.B. The Influence of Construction Detailing on the Fire Performance of Polystyrene Insulated Panels. *Fire Technol.* **2011**, *49*, 195–211. [CrossRef]
48. Wang, R.Q.; He, S.-J.; Yue, H.-R. Numerical Study of Smoke Spread upon Shaft-box Type Double Skin Facades. *Procedia Eng.* **2018**, *211*, 755–761. [CrossRef]
49. Li, J.; Xing, X.; Hu, C.; Li, Y.; Yin, C.; Liu, S. Numerical Studies on Effects of Cavity Width on Smoke Spread in Double-skin Facade. *Procedia Eng.* **2012**, *45*, 695–699. [CrossRef]
50. Chow, C. A qualitative investigation on double-skin façade fires. In *MATEC Web of Conferences*; EDP Sciences: Les Ulis, France, 2013; Volume 9, p. 03007. [CrossRef]
51. Peng, L.; Ni, Z.; Huang, X. Experimental and numerical study of fire spread upon double-skin glass facades. In *MATEC Web of Conferences*; EDP Sciences: Les Ulis, France, 2013; Volume 9, p. 03009. [CrossRef]
52. Ji, J.; Li, Y.F.; Shi, W.X.; Sun, J.H. Numerical studies on smoke spread in the cavity of a double-skin façade. *J. Civ. Eng. Manag.* **2015**, *22*, 470–479. [CrossRef]
53. Abdoh, D.; Kodur, V.; Liew, K. Smoothed particle hydrodynamics modeling of the thermal behavior of double skin facades in fires considering the effects of venetian blinds. *Appl. Math. Model.* **2020**, *84*, 357–376. [CrossRef]
54. Schabowicz, K.; Sulik, P.; Zawiślak, Ł. Identification of the Destruction Model of Ventilated Facade under the Influence of Fire. *Materials* **2020**, *13*, 2387. [CrossRef]
55. Kristoffersen, M.; Log, T. Experience gained from 15 years of fire protection plans for Nordic wooden towns in Norway. *Saf. Sci.* **2021**, *146*, 105535. [CrossRef]
56. Thomas, G.; Al-Janabi, M.; Donn, M. Designing double skin facade venting regimes for smoke management. In *Fire and Materials*; John Wiley and Sons Ltd.: Hoboken, NJ, USA, 2018; pp. 549–560. [CrossRef]
57. Ingason, H. Modelling of a two-dimensional rack storage fire. *Fire Saf. J.* **1998**, *30*, 47–69. [CrossRef]
58. Littlewood, J.; Alam, M.; Goodhew, S. A New Methodology for the Selective Measurement of building Performance and Safety. *Energy Procedia* **2017**, *111*, 338–346. [CrossRef]
59. Guillaume, E.; Dréan, V.; Girardin, B.; Benameur, F.; Koohkan, M.; Fateh, T. Reconstruction of Grenfell Tower fire. Part 3—Numerical simulation of the Grenfell Tower disaster: Contribution to the understanding of the fire propagation and behaviour during the vertical fire spread. *Fire Mater.* **2019**, *44*, 35–57. [CrossRef]
60. Zhang, M.; Song, W.H.; Ni, Z.P.; Huang, X. Study on the External Insulation System with Curtain Wall for Fire Prevention Based on Numerical Simulation. *Appl. Mech. Mater.* **2013**, *444–445*, 1592–1599. [CrossRef]
61. Guillaume, E.; Fateh, T.; Schillinger, R.; Chiva, R.; Ukleja, S. Study of fire behaviour of facade mock-ups equipped with aluminium composite material-based claddings, using intermediate-scale test method. *Fire Mater.* **2018**, *42*, 561–577. [CrossRef]
62. Dréan, V.; Girardin, B.; Guillaume, E.; Fateh, T. Numerical simulation of the fire behaviour of facade equipped with aluminium composite material-based claddings-Model validation at large scale. *Fire Mater.* **2019**, *43*, 981–1002. [CrossRef]

63. Comiskey, D.; Wilson, K. A Performance Barrier? Cavity Barrier Installation in Wall Envelope Makeups. In Proceedings of the 36th Annual ARCOM Conference, Online, UK, 7–8 September 2020; Scott, L., Neilson, C.J., Eds.; Association of Researchers in Construction Management: Cambridge, UK, 2020; pp. 205–214.
64. Nguyen, Q.T.; Tran, P.; Ngo, T.D.; Tran, P.A.; Mendis, P. Experimental and computational investigations on fire resistance of GFRP composite for building façade. *Compos. Part B Eng.* **2014**, *62*, 218–229. [CrossRef]
65. Nguyen, K.; Kim, N.K.; Bhattacharyya, D.; Mouritz, A. Assessing the combustibility of claddings: A comparative study of the modified cone calorimeter method and cylindrical furnace test. *Fire Mater.* **2021**, *46*, 450–462. [CrossRef]
66. Nguyen, Q.T.; Ngo, T.D.; Bai, Y.; Tran, P. Experimental and numerical investigations on the thermal response of multilayer glass fibre/unsaturated polyester/organoclay composite. *Fire Mater.* **2016**, *40*, 1047–1069. [CrossRef]
67. Sungkono, W.D.; Thabari, J.A.; Brajamagenta, K.; Nugroho, Y.S. Modeling of fire spread control in double skin facade by using water spray systems. In *AIP Conference Proceedings*; AIP Publishing: New York, NY, USA, 2021.
68. Schulz, J.; Kent, D.; Crimi, T.; Glockling, J.L.D.; Hull, T.R. A Critical Appraisal of the UK's Regulatory Regime for Combustible Façades. *Fire Technol.* **2020**, *57*, 261–290. [CrossRef]
69. Jensen, G. Fire spread modes and performance of fire stops in vented façade constructions—Overview and standardization of test methods. In *MATEC Web of Conferences*; EDP Sciences: Les Ulis, France, 2013; Volume 9, p. 02002. [CrossRef]
70. Chow, L.C. Spread of smoke and heat along narrow air cavity in double-skin façade fires. *Therm. Sci.* **2014**, *18*, 405–416. [CrossRef]
71. Ingason, H. Effects Of Flue Spaces On The Initial In-rack Plume Flow. *Fire Saf. Sci.* **2003**, *7*, 235–246. [CrossRef]