A Survey of Trends of Building Fire Simulation in the Architecture, Engineering, and Construction (AEC) Domains

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ABSTRACT

Fire has been one of the main disasters of human society for centuries. Although professional practitioners and scholars have conducted a lot of research and experimental work on building fire simulation and related development, the trends for fire-related deaths and economic loss in the United States have increased in the past decade. On the other hand, the emergence of new building forms and the needs of special building functions expose building fire simulation to new challenges and problems. This paper provides a survey of the state-of-the-art works on building fire simulations by investigating the research that has been conducted in this field from 2015 to 2020. This review reveals that the fire simulation of high-rise and public buildings (e.g., subway stations and museums) has received more attention from researchers than others. This paper also summarizes the latest technological advances in this field. The results of this paper will help professional practitioners and scholars to identify challenges and problems to inform future studies.

INTRODUCTION

Among the many casualties caused by natural disasters in the United States in 2015, the deaths caused by fires were an order of magnitude higher than other disasters (Mirahadi et al. 2019), indicating that fires are currently a main natural disaster causing casualties in the United States. From 2008 to 2017, there were an average of 1.3 million fires in the United States each year, resulting in the deaths of 3,190 citizens, injuries to 16,225 citizens, and in the direct economic losses of 14.7 billion annually. Worse still, the trend of deaths and property losses caused by fires each year is growing (Federal Emergency Management Agency (FEMA) 2019). This problem has led researchers worldwide to investigate fire prevention and simulation (Elhami Khorasani et al. 2016; Hosser and Hohm 2013).

Compared to other types of fires, building fires accounted for the main part of fires that caused deaths and injuries. For example, it accounted for 78% of reported deaths and 76% of reported injuries in 2017 (FEMA 2019). The characteristics of the building structure, such as confined space, concentration of people, and electricity use, are inferred to contribute to this result. In addition, once a building with special functions catches fire, e.g., a museum or a subway station, it could cause immeasurable losses and casualties. For example, the fire of the Notre-Dame cathedral in Paris on April 15, 2019, according to estimates by Untec ("Union Nationale des Economistes de La Construction", "National Union of Construction Economists" in English), will cost €300 - €600 million in reconstruction costs (Tannous 2019), and the loss in literature and art is immeasurable. Therefore, there is a need to study building fires to minimize the loss that fire may incur to our society.

From the economical perspective and safety, fire simulation based on computing technology and study of aerodynamics is a good way to study building fires as shown by the previous researchers, e.g., by Xiao and Ma (2012) and Yang et al. (2012). To better cope with the increasingly severe climate conditions and fire protection requirements of special building functions, we conduct a literature review of the state-of-the-art (2015-2020) technology development in this field.

This article focuses on the latest original research in the field of building fires. Through reviewing peer-reviewed publications, the authors show the research progress in this field and propose constructive recommendations, to help researchers identify challenges and problems to address in future research in the field of building fire simulation.

BUILDING FIRE SIMULATION

Modern fire science began in 1970s by the research of fluid mechanics and fire safety (Emmons 1971). With the development of computing technology and computational combustion theories, three types of fire models have been gradually established and applied: 1) the field model, 2) the zone model, and 3) the network model (Yao et al. 1999).

The field model divides the fire space into a number of small control fields, and uses partial differential equations to solve each small control field based on the physical and chemical laws of the combustion process, and then obtains the temperature field, velocity field, and concentration field of the entire fire space. Field model has high calculation accuracy, but it has high requirements on computer hardware (e.g., CPU and memory) because the solution process is complex (Yao et al. 1999).

The zone model is based on the stratification of the gas in the fire room: the upper zone is the hot smoke layer, and the lower zone is the cold air layer. Tests and measurements found that the temperature and smoke concentration within each of the two layers did not change much. Therefore, the zone model divides a fire room into upper and lower zones. It is assumed that the physical state inside each zone is the same, and the changes only occur between the zones, between the zone and the boundary, and between the zone and the fire source (Forney and Moss 1994). Compared with the field model, the calculation of the zone model is simpler, and the application scenarios are more extensive. However, its calculation accuracy is lower, especially when it is applied to a space with a complex geometry, a strong fire source or a strong vent, the zone model is prone to calculation errors (Yao et al. 1999).

Finally, the network model uses the greatest simplification among the three models. It treats the entire building as a network, and each room in the building as a node in the network. It connects each room through the flow of air, and calculates the temperature and smoke concentration of the entire building based on the laws of physics and chemistry. The network model is suitable for continuous & large spaces and benefits from simple calculations. However, because each room is one of the nodes, it is mostly used in rooms with uniform air conditions (Yao et al. 1999).

The previous fire simulation research focused on the development of fire behavior in buildings. With the development of advanced technologies in other fields, such as Building Information Modeling (BIM), Agent-based Modeling (ABM), Internet of Things (IoT), etc., building fire simulation has incorporated broader connotations and functions. Building fire simulation discussed in this article refers to a method that uses various computer programs to simulate the growth of fire, the production and movement of combustion products, and human behavior related to escape in a building (Fahy 1985).

RESEARCH METHODOLOGY

In order to achieve the purpose of this paper, a three-step literature review method was adopted in this study.

Step 1: Use the keywords "building fire simulation," "building fire" and "fire simulation" to search for related papers in main literature source databases, including ScienceDirect, Google Scholar, and Emerald insight.

Step 2: Select the works from 2015 to 2020. This time range was chosen because the authors wanted to focus on the most recent research in this field.

Step 3: According to the research focus, the selected papers are classified into the following three sub-topics to be discussed: high-rise buildings and public buildings, joint consideration of multiple loads, and combination with other technologies.

Based on the above three sub-topics, the results and findings are classified and discussed as follows.

RESULTS AND FINDINGS

A total of 13 peer-reviewed papers were selected eventually, including journal papers and conference papers. These articles were selected because 1) they are research work in recent years and represent the latest research progress in this field, and 2) they foreshadow the research trend of building fire simulation. Table 1 shows the distribution of the number of selected papers over time and in each sub-topic area.

Table 1. Number distribution of selected documents

Year	2015	2016	2017	2018	2019	2020
High-rise buildings and public buildings	1		2		2	1
Joint consideration of multiple loads			1	1		1
Combination with other technologies				1	2	1

The results and findings of the above three sub-topic areas together constitutes the research progress of the building fire simulation field in this article from 2015 to 2020.

Building fire simulation for high-rise buildings and public buildings. High-rise buildings and public buildings (public buildings in this article refer to buildings for public use) have attracted the attention of researchers due to their high crowd density, long evacuation time and difficulty in rescue. However, high-rise buildings and public buildings have different characteristics and functions, so the focus of fire simulation research is correspondingly different.

For high-rise buildings, once a fire occurs, the smoke produced by the fire is more deadly than the high temperature. The temperature of the room decreases as the distance from the fire source increases, whereas the smoke quickly propagates vertically upwards through stairwells or vertical shafts (Bai et al. 2015). Smoke has two effects on the escape of occupants and the rescue by firefighters. One is that the smoke reduces visibility, and it is difficult to determine the correct route in the smoke. The other is that the smoke contains toxic gases such as carbon monoxide and particles, which can cause suffocation and death. Therefore, fire simulation for high-rise buildings mainly concerns the study of smoke flow in stairs or vertical shafts. Zhang et al. (2019) used a Large-Eddy Simulation (LES) method (a computing and modeling strategy for turbulent reacting flows (Gicquel et al. 2012)) to model the stairwell of a 21-story high-rise building, and analyzed the effects of fire location and heat release rate (HRR) on flow field and temperature distribution. Their study results showed that an increase in HRR leads to an increase in the velocity of the smoke stream. The temperature distribution in the vertical direction obeys the natural logarithmic distribution. The maximum temperature in the stairwell is linearly distributed with the location of the fire source, which means that under the same HRR conditions, a fire on a high floor has a lower maximum temperature than a fire on a low floor (Zhang et al. 2019).

In order to reduce the spread of smoke in stairs and vertical shafts, a strategy called positive pressure ventilation (PPV) was proposed and proved to improve the smoke conditions of stairs in a fire (Kerber and Walton 2005). By installing fans at the entrance of the stairwell, a large amount of airflow is introduced into the stairwell through the fans, thereby forming a high positive pressure zone in the stairwell, dissipating or preventing heat and smoke from entering the stairwell from the fire source. Panindre et al. (2017) simulated a high-rise building and measured the temperatures in different areas to detect the impact of the PPV strategy on wind-driven fires. The simulation confirmed the effectiveness of the PPV strategy to reduce the temperature of various areas of the building in a fire. As the wind speed that drives the fire increases, the performance of the PPV strategy decreases, indicating that the wind will increase the fire hazard. A comprehensive strategy that uses wind control devices (WCD) to reduce the impact of wind and uses PPV to disperse the combustion products in the fire is suggested in this study to minimize the temperature of the stairwell and ensure the safety of occupants and firefighters (Panindre et al. 2017).

In addition to the high-rise buildings, another type of buildings that have attracted much attention from researchers are public buildings, such as subways, shopping malls, and museums. Most subways and shopping malls are equipped with escalators, and the spatial structure of escalators often becomes the fuse for fire outbreaks. If there is a fire source at the bottom of the escalator, due to the Coandă effect and chimney effect, the fire may spread to become uncontrollable in a short time (National Fire Chiefs Council (NFCC) (n.d.); Merci 2008). For example, in the 1987 fire at the King's Cross Station in London, a carton-sized fireball quickly spread from the bottom of the escalator to the ticket hall above within 3 minutes. In the end, the uncontrollable fire caused 31 deaths and more than 100 injuries (Simcox et al. 1992). Therefore, fire simulations for subways and shopping malls have also been a topic of concern for researchers in recent years. Zhang et al. (2019) simulated a real subway station and proposed *SITotal* (an indicator to measure the safety risk of the entire building after comprehensively considering the evacuation efficiency of multiple key escape areas of the building, such as doors and corridors) to measure the overall fire safety risk in order to determine the most dangerous fire scenarios among the four fire scenarios. The smaller the *SITotal* is, the more dangerous the fire situation is. Studies show that HRR has a huge impact on fire safety risks. When HRR increased by 50%, *SITotal* decreased by approximately 36%. Khan et al. (2017) conducted a fire simulation on a shopping mall with an area of 64 m^2, and explored the impact of HRR, mass density, soot yield, exit door width and number of exit doors on the evacuation time. The results show that the number of exit doors and the type of fuel (soot yield) have a great influence on the evacuation time. Under the same conditions, the number of escape doors was increased from 1 to 2, resulting in a reduction in the evacuation time from 780 seconds to 80 seconds. This is consistent with the conclusions of Bai et al. (2015) in the fire simulation study of high-rise buildings. Bai's research shows that adding an exit can reduce the escape time by 1/3.

Unlike other public buildings, the fire simulation of a museum must consider not only the safety of personnel, but also the protection of artworks, which means higher fire protection requirements. Caliendo et al. (2020) used computational fluid dynamics (CFD) to verify the fire protection and evacuation system of a multi-story historical building model. CFD results show that the spread of smoke is affected by factors such as the size and location of the fire, the geometry of the building, buoyancy, and the chimney effect. Equipped with fire rooms, fire detectors and a waiting area contribute to an effective fire safety plan for multi-story historic buildings (Caliendo et al. 2020).

Joint consideration of multiple loads during building fire simulation process. Buildings, when used, are subject to more than one load. In order to obtain a more realistic performance of a building in a fire, it is necessary to consider the coupling effect of multiple loads in the building fire modeling process. Post-earthquake fires and wind-driven fires have been the focus of researchers in recent years. The simulation of the post-earthquake fire mainly focuses on the damage of the non-structural components of the building, such as the sprinkler system, by the earthquake, which further affects the fire extinguishing system of the building when a fire occurs after the earthquake. Lu et al. (2020) used BIM and virtual reality (VR) to model a 19-story hospital fire rescue after the earthquake, and explored the impact of earthquake damage to non-structural components (sprinkler system damage and fallen debris in the case) on fire rescue. The results show that earthquake damage to non-structural components will make the rescue environment worse. The rescue time after considering the seismic damage of non-structural components is about 9 times of that otherwise (i.e., not considering the seismic damage of non-structural components). Therefore, the results of the study suggest that the impact of earthquake damage to non-structural components must be considered in the process of post-earthquake fire rescue modeling. Xu et al. (2018) proposed a simulation method to quantify the impact of sprinkler systems damaged by earthquakes on the spread of building fires. This method creates a high-fidelity fire dynamics simulator (FDS) model based on BIM, and predicts the earthquake damage of the sprinkler system based on the Federal Emergency Management Agency (FEMA) P-58 report and a developed tree data structure, and then quantifies the impact of the earthquake damage of the sprinkler system on the spread of building fires (Xu et al. 2018).

Another commonly considered coupling effect is the interaction of wind and fire, especially in high-rise buildings. The wind at the openings of the high-rise building expands the spread of the fire. da Silva et al. (2017) modeled the stairwell of a 21-story building and explored the influence of different air settings (open, semi-open, and close) on the fire behavior of the stairwell. Four indicators were recorded to measure the difference: "the air temperature in the walls, the air velocity settings at the vents, the smoke temperature through the fans, and the pressure through the exhaust fan" (da Silva et al. 2017). The results show that compared to the total area of the vents, the asymmetric setting of the vents has a greater impact on plume. In order to reduce the coupling effect of wind on fire, the research of Panindre et al. (2017) mentioned above verifies the effectiveness of the strategy of using wind control devices (WCD).

Combination of building fire simulation methods with technologies in other fields. Conventional building fire simulation is limited to studying the spread of fire in buildings and the critical factors affecting the spread of fire. The development of technology in other fields provides new tools for building fire simulation. The introduction of these advanced technologies has expanded the functionality of building fire simulation tools. In recent years, numerous building fire management systems that integrate fire development simulation, building visualization, and evacuation guidance have been proposed. For example, Mirahadi et al. (2019) integrated the BIM based on the industry foundation classes (IFC) data structure with ABM and FDS, developed a tool for optimizing building evacuation performance, and applied it to a two-story office building with 59 compartments. The case results show that compared with the current safety indicators, the new framework has obtained a more comprehensive evacuation safety assessment. Similarly, Sun and Turkan (2020) integrated BIM, FDS and ABM to develop a framework for fire development simulation and evacuation scenarios development, and applied this integrated simulation framework to case studies. Chou et al. (2019) used Bluetooth sensors to obtain information on the fire scene (including fire location, occupant's location, and firefighter's location), combined them with path optimization algorithms, to provide firefighters with the best fire rescue path planning. Their experimental test results confirmed the effectiveness of this rescue path planning system. Chen et al. (2018) solved the data integration problem of BIM, FDS and IoT, and proposed a visualized fire rescue system with real-time monitoring, early warning, and evacuation guidance functions to help improve the safety of occupants and firefighters.

SYNTHESIS AND ANALYSIS

Although the reviewed literature is classified into three sub-topics for discussion, the research content of many literatures involves two or more sub-topics, as shown in Table 2. In building fire simulation, complex scenarios are considered in the literature to respond to the actual building fire prevention requirements. Building fires in reality are affected by many factors. For example, the fire simulation of a high-rise building must consider not only the vertical spread of smoke along the stairwell, but also the effect of the wind at the openings of the building on the fire; the fire simulation of a shopping mall on an earthquake zone must consider not only the size of the escalator and the layout of the exits, but also the probability and degree of earthquake damage to non-structural components such as sprinklers. In view of the complex building fire in reality, the simulation of fire alone cannot meet the requirements of building safety. Advanced technologies in other fields provide the possibility to expand the function of building fire simulation. Through the integration of BIM, FDS, ABS model data and the use of sensors such as Bluetooth, a building fire management system that integrates monitoring, early warning, fire analysis, fire extinction and evacuation guidance is the research trend of building fire simulation in the near future. This type of management system is designed to achieve all-round management of building fires and minimize the losses caused by fires.

Table 2. Interaction of the investigated literature in subtopics

The investigated literature	Sub-topic A	Sub-topic B	Sub-topic C
Panindre et al. (2017)	√	√	
da Silva et al. (2017)	√	√	√
Xu et al. (2018)		√	√
Lu et al. (2020)	√	√	√

Note: Sub-topic A is "building fire simulation for high-rise buildings and public buildings", sub-topic B is "joint consideration of multiple loads during building fire simulation process", sub-topic C is "combination of building fire simulation methods with technologies in other fields".

CONCLUSIONS AND FUTURE WORK

This article reviews 13 journals and conference papers published in the field of building fire simulation from 2015 to 2020. The result indicates that high-rise buildings and public buildings have received more attention in recent years due to their characteristics and special functional requirements. Joint consideration of fires and other loads and the combination of advanced technologies in other fields with building fire simulation technologies are the future research trends. In future work, investigating the feasibility and configurations of a building fire management system that integrates monitoring, early warning, fire analysis, fire extinction and evacuation guidance is worthy of consideration.

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