Performance-Based Fire Detection System Design for Water Curtain at Proscenium Opening of Stages

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Abstract

This study illustrates how a performance-based design approach using the computational fluid dynamics (CFD) tool Fire Dynamics Simulator (FDS) is adopted to facilitate the design of an appropriate fire/smoke detection system for a water curtain system at the stage proscenium opening in a theatre.

Keywords: performance-based design, FDS, tenability, water curtain, detection

Introduction

Fires occurring on the stage of a theatre could be deadly. The Chicago's 1903 Iroquois Theatre fire in which a fire started on the stage and finally caused more than 600 deaths is one of the most significant fire tragedies in history [1]. Since then codes and standards have been developed to regulate the fire protection at the stage area in order to minimize the fire life safety risk brought by a stage fire. In the 1929 edition of NFPA 101, it was the first time to explicitly require a fire-resistance curtain to be provided at the proscenium opening of a stage as an important means to limit fire/smoke spread throughout. Starting 1976 edition of NFPA 101, it is allowed to use a non-combustible opaque fabric curtain with a water deluge system protected on both sides in lieu of a fire curtain. In the most recent editions of codes/standards, from 1997 NFPA 101 and 2000 IBC to 2015 NFPA 101 [2] and 2015 IBC [3], the design requirements for the proscenium opening at a legitimate stage have been reinforced. Either a passive (i.e., a fire curtain or an approved water curtain) or an active means shall be provided to prevent fire/smoke from spreading to the adjacent seating area and the rest of the theatre so as to ensure safe evacuation and relocation of occupants.

In the past decades, a fire curtain, normally made of heavy iron or fiberglass, was typically used to protect the proscenium opening for a legitimate stage. With the development of advanced suppression and detection technologies, a water curtain is becoming a more preferred option since it helps minimize negative impacts brought by a fire curtain, such as reduced flexibility on the use of the proscenium opening, restriction on normal stage operations, complicated maintenance, etc. However, the application of a water curtain system, particularly the design of a fire detection system initiating the water curtain system, has not been explicitly regulated in the current codes and standards, e.g., IBC, and NFPA 72 [4], 101 and 5000 [5].

In accordance with 2016 edition of NFPA 72 Section 23.13.7, each space protected by an automatic fire suppression system actuated by the fire alarm system shall contain one or more automatic fire detectors installed in accordance with NFPA 72 Chapter 17, but no further regulations are provided on how the fire detection system shall be designed (e.g. timing of system activation). Therefore, a key design challenge is to design a well-functioning fire detection system so that the proposed water curtain system can be activated prior to the moment at which large amount of smoke and hot gases spread from the stage to the adjacent seating area to affect safe evacuation of occupants in the theatre. The design of such fire detection system varies with projects and is totally subject to designers and local authorities having jurisdiction (AHJ). In addition, there are other issues during the design process. For example, an automatic fire detection system using a combination of rate-of-rise and fixed temperature heat detectors is typically used for automatic activation of the water curtain system. According to the fire detector manufacturer data sheets, heat detectors are normally listed to be installed at a height of not greater than 9.144 meters (30 feet). Since stage opening height could often exceed 9.144 meters (30 feet), the use of such listed devices needs to be further evaluated. In accordance with NFPA 72 Section 17.6.1.2, if the fire detection system serving a proscenium opening water curtain is not designed in accordance with the prescriptive requirements, a performance-based design should be executed in accordance with NFPA 72 Section 17.3 to demonstrate an equivalency of the code intent.

Performance-Based Design Concept and Methodology

In this study, a proscenium opening with approximately 19.2 meters (63 feet) width and 11 meters (36 feet) height, at a stage with 23.2 meters (76 feet) height and 172 square meters (1,850 square feet) area, and located in an 800-seat theater, is proposed to be protected by a water deluge system. During events and shows, the size of this proscenium opening can be changed between a maximum of 19.2-meter (63-foot) wide by 11-meter (36-foot) tall and a minimum of 12.2-meter (40-foot) wide by 7.6-meter (25-foot) tall. An automatic fire detection system is provided at the stage area for automatic activation of the water deluge system. Due to the stage dimensions (exceeding 9.144 meters (30 feet) height) and application of a water curtain at the proscenium opening, a performance-based design is conducted using Fire Dynamics Simulator (FDS) modeling tool [6], as supplemental of NFPA 72 Section 17.6.1.2, to evaluate and demonstrate that the proposed fire detection system is able to timely detect a fire within the stage and quickly activate the proscenium water deluge system such that smoke and fire be contained within the stage area and a tenable environment be maintained within the adjacent auditorium seating area.

Stage Fire Detection System Design

To avoid a false alarm from activating the water deluge system to damage the property, a combination of rate-of-rise and fixed temperature heat detectors are proposed as shown in Table 1. At least one heat detector in each of the two heat detection series (Series A and B) needs to be initiated in order to actually activate the proscenium water deluge system. One pair of heat detectors will be installed at the top of the stage and the other pair of heat detectors will be provided at 0.6 meters (two feet) above the stage opening.

Table 1. Stage Fire Detection System Design.

Devices	Operating Temperature	Location
Heat Detectors	A rate of temperature increase at 8.4 °C/min (15 °F/min) and a fixed temperature of 57 °C (135 °F)	Stage Opening
Heat Detectors	A rate of temperature increase at 8.4 °C/min (15 °F/min) and a fixed temperature of 71 °C (165 °F)	Stage Top

The following Fig. 1. displays the layout of the heat detectors.

In addition to the stage fire detection system design, the following design information associated with the stage fire detection system is included in the FDS modeling analysis.

- Eight (8) stage roof vents are provided in accordance with 2015 IBC Section 410.3.7.1. A fusible link with an activation temperature of 71 °C (165 °F) is provided for all eight vents.
- Hanging equipment and decoration located permanently in the stage are included to take into account the effect of objects/barriers blocking smoke and hot gases spread.
- A transverse proscenium portal is either hangered under the stage ceiling or placed at the stage opening that minimizes the stage opening from 19.2 m by 11 m (63’ by 36’) to 12.2 m by 7.6 m (40’ by 25’).

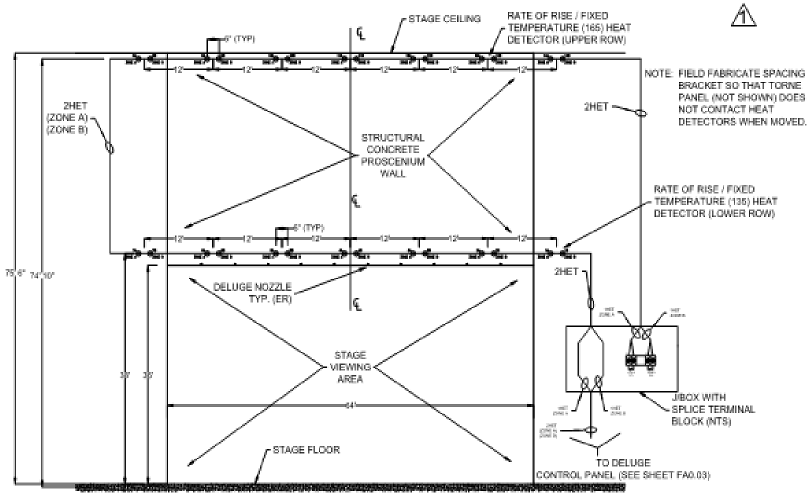

Fig. 1. Location of rate-of-rise and fixed temperature heat detectors.

Evaluation Criteria

In order to evaluate the proposed stage fire detection system design serving the stage proscenium water deluge system, it is necessary to establish baseline evaluation criteria. Table 2 lists the evaluation criteria used in FDS modeling analysis in order to determine if the proposed stage fire detection system would be able to achieve quick activation and initiate the stage proscenium water deluge system to protect stage opening in an event of a fire within the stage area.

Table 2. Evaluation Criteria.

Parameter	Description of Criterion	Value of Criterion
Activation of Heat Detector	At least one heat detector from each heat detection series A and B activated in order to initiate the proscenium water deluge system	One HD on series A One HD on series B
Tenability	Smoke layer maintained at least 1.83 meters (6 feet) above the highest seating level [2, 3]	1.83 meters

Modeling Analysis Assumptions

The following key assumptions were included in the FDS modeling analysis of the proposed stage fire detection system design.

- An ambient indoor temperature of 20 °C (68 °F) was used to provide a conservative analysis on temperature measurement and activation time of the heat detectors.
- Thermocouples were placed in the FDS model at or immediately next to the heat detectors to measure the temperature increase rate.
- A fast-growth medium fire with a heat release rate of 5,275 KW (5,000 Btu/s) and a fast-growth large fire with a heat release rate of 21,100 KW (20,000 Btu/s) were used to evaluate the proposed stage fire detection system design. This assumption is to achieve more conservative analysis results when evaluating the effects of smoke spread through the unprotected stage opening to the adjacent auditorium seating area prior to activation of the stage proscenium water deluge system over the course of the simulation.

Modeling Analysis Scenarios

In ordert to perform a thorough analysis, multiple fire scenarios were evaluated in the deterministic computer fire modeling analysis for the proposed fire detection system design, including fires occurring at various locations on the stage a well as fires in various sizes.

Performance-Based Modeling Analysis Results

Fig. 2. through Fig. 4. show how smoke quickly spreads out of the stage area and cause the adjacent auditorium seating area to become untenable within a short period (6-7 minute).

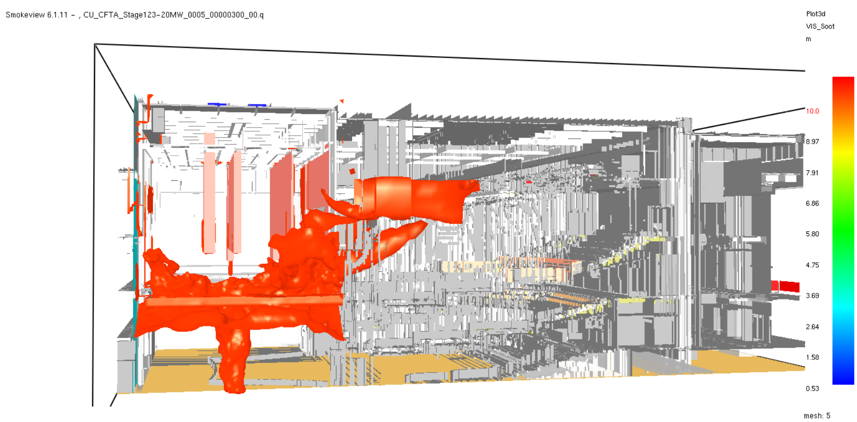

Fig. 2. 21,100 KW (20,000 Btu/s) Design Fire - Isosurface indicating smoke layer height (visibility at 10 meters) at 300 seconds.

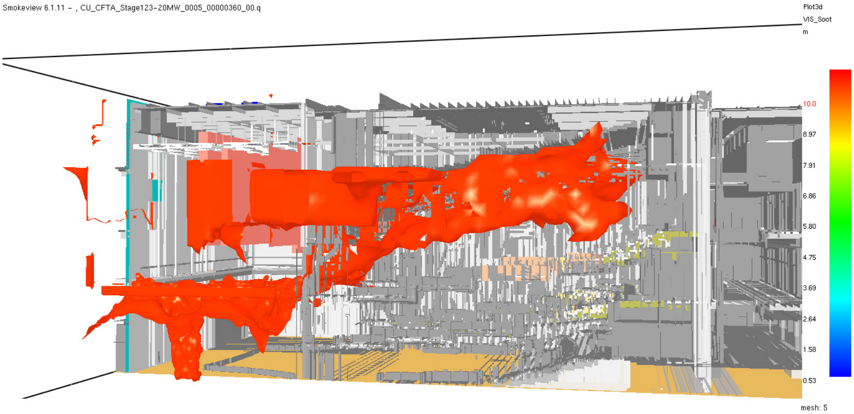

Fig. 3. 21,100 KW (20,000 Btu/s) Design Fire - Isosurface indicating smoke layer height (visibility at 10 meters) at 360 seconds.

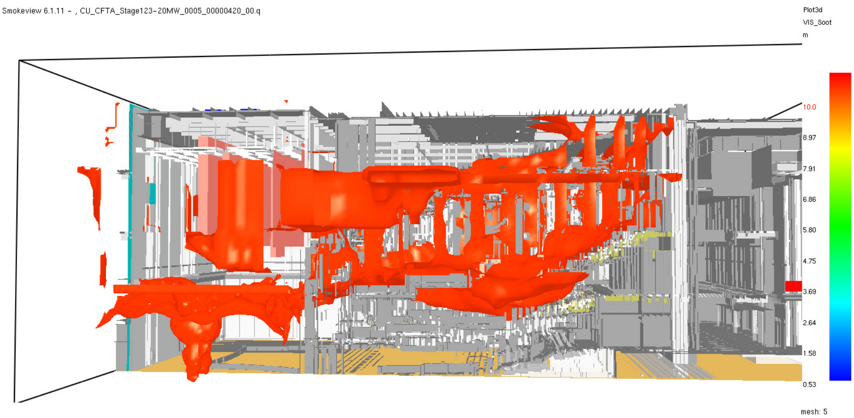

Fig. 4. 21,100 KW (20,000 Btu/s) Design Fire - Isosurface indicating smoke layer height (visibility at 10 meters) at 420 seconds.

Based on the FDS modeling analysis outputs as shown above, if the proposed stage fire detection system is able to detect a fire (small to large fires) at the stage area within 300 seconds (5 minutes) after ignition of a design fire, the stage proscenium water deluge system will be activated to contain smoke and/or fire within the stage area and a tenable environment will be maintained within the adjacent auditorium seating area.

The following graph provides FDS modeling analysis results of thermocouple measurements showing the temperature changes of the stage heat detectors along with the time.

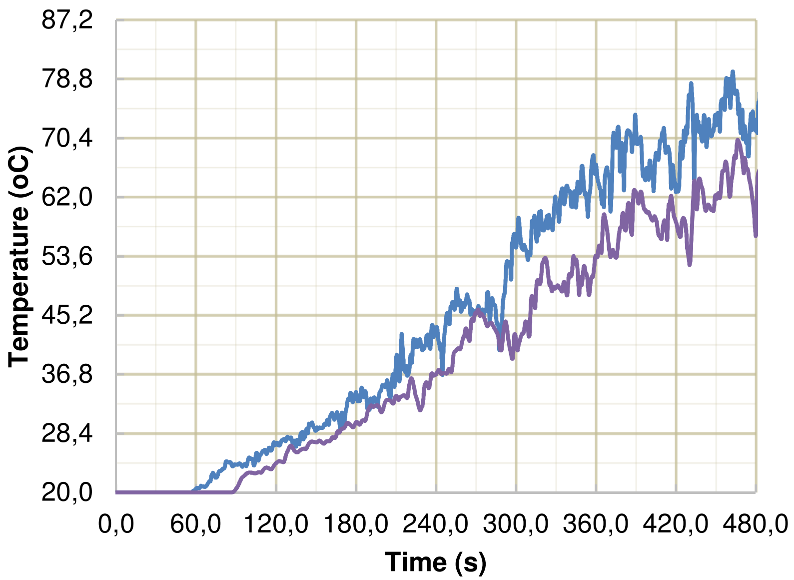

Fig. 5. Thermocouple measurement of heat detector temperatures at the top of stage.

The FDS thermocouple measurement outputs in Figure 5 indicate that the first pair of heat detectors located at the top of the stage has a rate of temperature increase more than 8.4 °C/min (15 °F/min) at 240-270 seconds (4-4.5 minutes) after ignition of design fires. Therefore, the proposed stage fire detection system is able to detect a fire at the stage area within 300 seconds (5 minutes) to activate the stage proscenium water deluge system, and thereby the adjacent auditorium seating area will have a tenable environment for safe evacuation and relocation of audiences.

Conclusion and Outlook

The simulation results have proved the effectiveness of the design, i.e. with the proposed fire detection system, the water curtain system can be timely activated hence the tenability in adjacent seating area can be successfully maintained. In addition, it is discovered that the rate-of-rise detection is more sensitive in response to fire than the fixed temperature detection. Therefore, the proposed stage fire detection system design is considered to meet the intent of the code (2015 IBC Section 410.3.5, 2015 NFPA 101 Sections 12.4.6.7.1 and 12.4.6.5.1.1, and 2016 NFPA 72 Section 17.3).

To conclude, through this study a deficiency in current codes and standards is identified: current codes and standards only provide regulations for a water curtain system design, but do not provide any guidelines for the fire detection system design on timing of system actuation. This deficiency might cause the late activation of a water curtain system, hence might cause loss of tenability in auditorium to affect safe evacuation of audiences. It is recommended that, based on this study, future edition of codes and standrads should amend relevant sections to indicate that the fire detection system serving a proscenium opening stage proscenium opening water curtain system shall be designed to activate earlier such that the adjacent auditorium seating area can remain tenable for safe evacuation and relocation of audiences. Meanwhile, through this study, an engineering performance-based design methodology with the aid of computer modeling tools is recommended as an appropriate approach to resolve design challenges and achieve prescriptive code requirements for a water curtain detection system at the proscenium opening of legitimate stages.

References

[1] *https://en.wikipedia.org/wiki/Iroquois_Theatre_fire*, retrieved on May 4th, 2017

[2] National Fire Protection Association, "*2015 NFPA 101: Life Safety Code*".

[3] International Code Council, "*2015 International Building Code*".

[4] National Fire Protection Association, "*2016 NFPA 72: Fire Alarm and Sigling Code*".

[5] National Fire Protection Association, "*2015 NFPA 5000: Building Construction and Safety Code*".

[6] National Institute of Standards and Technology, "*Fire Dynamics Simulator*", 2016.