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A smoke detector activation algorithm for large eddy simulation fire modeling

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Abstract

This study chronicles the development and integration of a smoke detector activation algorithm (known as the SDAA) that describes the response time of a smoke detector into a large eddy simulation (LES) fire model [Roby RJ, Olenick SM, Zhang W, Carpenter DJ, Klassen MS, Torero JL. Smoke detector activation algorithm version 1 technical reference guide. NISTIR Report; 2006, in press]. Although the SDAA could be used with any CFD smoke movement model, the results here address specifically its application to the fire dynamics simulator (FDS). The fire model predicts the smoke concentration and velocity adjacent to the detector while an algorithm based on characteristic velocity-based lag times describes the transport of smoke into the sensing chamber of the smoke detector. The experimental data from a multi-room compartment fire were used for comparison and a series of benchmark studies provide a mechanism to establish the sensitivity of the model to the different input parameters. The SDAA was found to be very accurate in determining detector activation times for both high- and low-velocity smoke flows.

Keywords: Smoke detection; Detector delay time; FDS; Smoke detector response; Smoke detector activation algorithm

1. Introduction

Early detection of fire plays an important role in the life safety of building occupants. Proper modeling of activation times is essential for the design of alarm systems and for overall fire safety strategies. In recent years, modeling of smoke detector activation has become a very important research topic in fire safety engineering, as computer fire modeling allows for testing of the performance of a particular detection system design without the need for experimentation. Several approaches to modeling smoke detector activation have been proposed in the last few decades, and some are currently still used for fire safety design, most notably the temperature correlation method. In this study, a new smoke detector algorithm combined with two different characteristic lag time models (Cleary et al. [2] model and Heskestad [3] model) was studied and implemented into a large eddy simulation (LES) fire modeling code. These two detector models were compared with each other in a numerical wind tunnel over a range of different velocities. The models were also compared against experimental data from a multi-room compartment fire.

2. Background

Historically, smoke detectors are tested by UL and given a rating based on the smoke box test. The smoke box test is conducted at a fixed high velocity, while full-scale tests and real fire situations generally have much lower velocities at the time of detector activation. As a result, full-scale testing has demonstrated that detector alarms operate at a smoke concentration significantly higher than the value determined in the smoke box test. Therefore, smoke box ratings cannot properly be used to determine when the detector will activate in a real world fire situation, because at lower velocities the detector will not alarm when the threshold

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Nomenclature

Variables

Y	smoke mass fraction in sensing chamber (dimensionless)
δt	the characteristic filling time of the entire volume enclosed by the external housing, also known as the characteristic dwell time (s)
τ	the characteristic filling time of the sensing chamber, also known as the characteristic mixing time (s)
Δt	the total characteristic filling time of Heskestad's model (s)
L_P	the optical path length in meters (m)
κ_m	specific extinction coefficient (m^2/g)
U	velocity (m/s)
t	time (s)
L	characteristic length of the detector housing (m)
L'	characteristic length of the sensing chamber (m)
$\dot{m}$	mass flux (kg/s)
A	area (m^2)
Re	Reynolds number (dimensionless)
υ	viscosity (kg/ms)
α_1	dwell time coefficient (dimensionless)
α_2	mixing time coefficient (dimensionless)
β_1	dwell time exponent (dimensionless)
β_2	mixing time exponent (dimensionless)
ρ	density (kg/m^3)
dt	change in time (s)
I	light Intensity (dimensionless)
OD	optical Density (1/m)
OPM	obscuration per meter (%/m)
Z	distance from the wall (m)

Subscripts

s	smoke
o	internal
e	external

concentration is reached outside the smoke detector. Two methods were developed over the years to try to get around this problem: correlating the detector activation with temperature, and trying to account for the difference between the rated threshold of the detector and the actual smoke concentration outside the detector at alarm by modeling the transport of the smoke into the detector.

The earliest of these methods, the temperature correlation method, seeks to predict the smoke concentration at detector activation by relating the concentration to the temperature at the detector. This method is derived from experimental work in the 1970s of Heskestad and Delichatsios [4], who proposed a correlation between the temperature rise at the smoke detector and the amount of smoke at the detector location for a given fuel. For example, Heskestad and Delichatsios determined that for a particular fuel, an 11.1 °C temperature rise at the smoke detector could be correlated to activation of that smoke detector. This detector activation methodology was originally based in part on the fact that early fire models could more accurately predict the thermal layer than the smoke layer. However, considerable criticism of the accuracy of this correlation, particularly due to its fuel dependency, has been published in the peer-reviewed literature [5–12]. A fundamental flaw with the temperature correlation method has been the sometimes weak relationship between the development of smoke density in a fire and the development of a thermal layer. Despite its shortcomings, the temperature correlation method is still in use in some segments of the fire safety community almost 30 years after its introduction, because this method is easy to implement with any fire model [5–12].

As subsequent fire models became better able to predict the development of the upper layer smoke concentration with time, alternative detector activation methodologies that rely on smoke density at the detector rather than the temperature were developed. Heskestad [3] proposed the use of a threshold optical density to determine if adequate smoke concentration is present to activate a smoke detector. Heskestad observed that a smoke detector did not alarm when the threshold concentration of smoke reached the outside of the detector. Rather, he noted a delay in activation of the smoke alarm related to the velocity of the smoke at the detector. Therefore, his approach considered the fact that due to entry resistance (such as from insect screens and the geometry of the detector), the smoke concentration outside a detector may reach the alarm threshold much earlier than in the interior of the detector. Heskestad [3] proposed that this lag time (Δt) between when the smoke reached the detector and when the smoke penetrated the detector was a function of the free stream velocity (U) flowing past the detector and a characteristic length (L), which is the distance that the smoke has to travel through the detector.

The difficulty with applying Heskestad's approach is the need to predict both the smoke concentration and the smoke velocity at the detector. Although this approach can be used with some plume correlations where the local velocity can be estimated, it cannot be used with multi-room zone models, since zone models provide no information about smoke velocity. Thus, Heskestad's approach has not been available for use with zone models, the most common way of modeling fires prior to the advent of computational fluid dynamics (CFD) models. When the smoke velocity is known, Heskestad's approach has been shown to be adequate at sufficiently high velocities [13], but fails when the velocity is low [2]. For example, in the case of ceiling jets, Brozovsky [14] determined that Heskestad's