A METHODOLOGY FOR PREDICTING SMOKE DETECTOR RESPONSE

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ABSTRACT

A methodology for predicting smoke detector response with computational fluid dynamics is presented. The general phenomena associated with the overall smoke detection process are provided. The overall smoke detection process has been organized into five categories; ***property generation, bulk property transport, local property transport, sensor modulation,*** and ***alarm condition.*** Each component of the smoke detection process is discussed in terms of available methods for quantifying the associated variables.

INTRODUCTION

The accurate prediction of smoke detector response is an important consideration in assessing the performance of a detection system. As occupant and fire department notification can be dependent upon smoke detector response, more realistic objectives in terms of occupant evacuation times and fire department operations may be possible with reliable predictions of detector response. NIST's Fire Dynamics Simulator software, which is available for free and can be run on a PC, has removed some of the traditional barriers to using CFD in fire protection engineering. Therefore, the elements of a methodology for predicting smoke detector response with computational fluid dynamics are suggested. The objectives of this methodology are to provide a reference for predicting smoke detector response that can be used by fire protection engineers and practitioners as well as to serve as a stimulus for future research.

OVERALL DETECTOR RESPONE METHODOLOGY

Property Generation

The production of detectable properties by a fire is critical to predicting detector response. The most sophisticated and accurate predictive tool is of little value without proper inputs. Therefore, it is of primary importance to identify the combustion precursors or byproducts that influence the response of the sensor. In general terms, property generation is primarily influenced by the chemical composition of the fuel, local oxygen concentration, combustion mode, and heat release rate.

Characterizing the hazard in terms of a source of energy, mass, and relevant detectable properties is needed for inclusion in a CFD model. While, the energy and mass from a combustion reaction can be accounted for in CFD models such as NIST's Fire Dynamics Simulator, additional variables related to smoke detection such as particle size are not part of the prediction. Characterizing standard test fires used in approval testing such as

UL **217** and **UL 268** as well as the European Standard EN **54-7** for use with an appropriate CFD model could provide designers with the means to examine situations that vary from the geometry of these standard fire tests. **A** high degree of variability between two independent investigations of EN **54-7** test fire byproducts cited by Grosshandler [2] reveals that a comprehensive study is needed to properly characterize standard test fires for use with an appropriate CFD model.

Bulk Property Transport

Bulk property transport refers to the transport of combustion products from the fire to the detector location. **An** example of **bulk** property transport *could* involve buoyancy forces in the fire plume and momentum forces in the ceiling jet as shown in Figure 1.

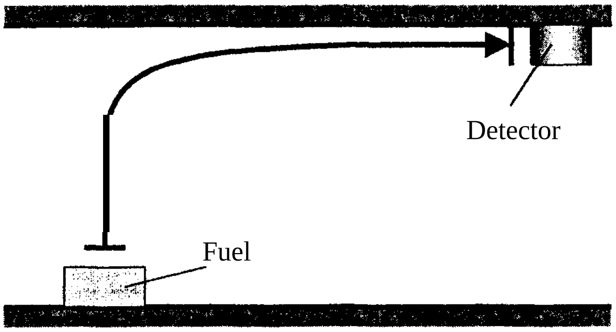

Figure 1 – Bulk property transport from fuel via lire plume and ceiling jet to detector location.

A variety of methods are available for establishing the environmental properties at the detector. Such methods may include, but are not limited to, experimental measurements, fire plume and ceiling jet correlations, or computer model simulations. Additional considerations for bulk property transport include agglomeration, deposition, dilution and sedimentation of the aerosol, as well as the geometry of the enclosure and relative positioning of the fire and detector.

The limitations of most ceiling jet correlations for use in predicting smoke detector response are that the resulting ceiling jet velocities and temperatures are independent of the specific fuel and have no vertical resolution. The fuel independence issue arises from most ceiling jet correlations being based on the total heat release rate. The lack of vertical resolution in ceiling jet correlations is the result of ceiling height and radial distance from the fire being the only geometric parameters in the correlations. The advantage to using CFD to predict ceiling jet conditions at the detector location is that the impact of fuel source can be accounted for with an appropriate combustion model and that spatial resolution of ceiling jet properties in all three coordinate directions is possible.

The aerosol dynamics processes of interest to smoke detection are agglomeration, deposition and sedimentation. The significance of each process is described and the importance of including aerosol dynamics sub-models into CFD predictions.

The ability to account for particle size in a CFD study of aerosol entry in smoke detectors is important with respect to agglomeration and sedimentation. As smoke particles are transported from the fire to the detector location they will interact with other particles, solid surfaces, and gaseous products. Aerosol agglomeration is particles colliding with other particles as a result of Brownian motion. Agglomeration of particles results in larger particle size and a decrease in number concentration. If agglomeration is ignored in a CFD calculation the particle size at the detector location will be under-predicted and the number concentration will be over-predicted relative to the actual phenomena.

Aerosol deposition is the result of particles adhering to solid surfaces. Deposition results in a decrease of number concentration and mass concentration. If deposition is ignored in a CFD calculation the number concentration and mass concentration will be over-predicted relative to the actual phenomena. Aerosol sedimentation is the result of particle weight overcoming local buoyancy forces.

Sedimentation results in a decrease in number concentration and mass concentration. If sedimentation is ignored in a CFD calculation the number concentration and mass concentration will be over-predicted relative to the actual phenomena.

Local Property Transport

Local property transport refers to transport of combustion products from the detector location to the sensor. The objective is to describe environmental conditions inside the detector (at the sensor) in terms of conditions external to the detector. Local property transport is dependent upon the geometry of the detector of interest as well as the ceiling jet properties at the detector location. Quantifying such parameters requires the development of functional relationships between quantities measured at the detector location and quantities at or near the sensor. CFD modeling can be used to examine the interaction between a ceiling jet flow and specified detector geometry. Previous studies [4,5] have demonstrated the viability of using CFD to examine aerosol entry.

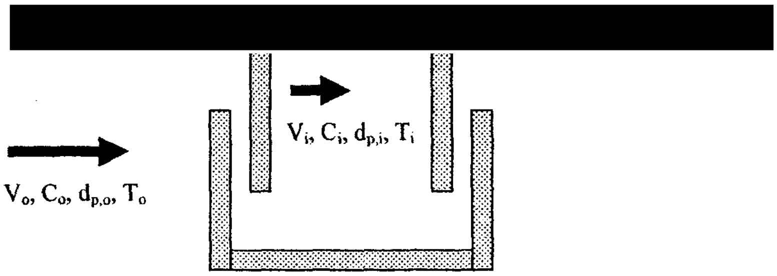

Figure 2 -- Example sectional view of local property transport from outside to inside a detector for a sensor influenced by velocity, aerosol mass concentration, aerosol particle size, and gas temperature.

In the case of spot-type smoke detectors, the geometry of the detector influences the ability of combustion byproducts to enter the detector and reach the sensor. An example of a flow field distribution within an arbitrary detector profile from a computational fluid dynamics simulation is illustrated in Figure 3.

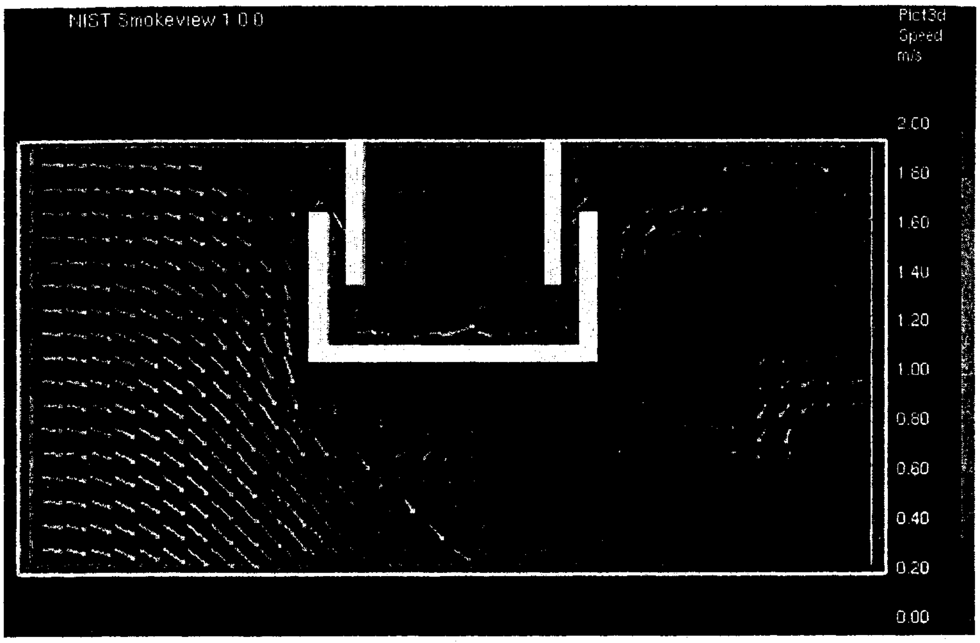

Figure 3 -- Flow field distribution for an arbitrary 2 dimensional detector profile subjected to a steady state inlet velocity of 1 m/s at ambient conditions. The simulation was performed with NIST's FDS program using the Direct Numerical Simulation technique for a physical domain of 0.3m long by 0.15m high and a computational domain of 144 by 72 grid cells.

The characteristic length used in Heskestad's lag time model *[3]* and Cleary's pipe flow/ mixing chamber model [1] are examples of how local property transport can be accounted for in predictive methods involving spot-type smoke detectors. Air sampling type detection systems involve a piping network and filtration process that must be accounted for in any type of performance assessment. The concept of local property transport does not apply to beam-type detection units as there are no physical obstructions inherent to the unit that prevents combustion byproducts from encountering the sensing path length.

Sensor Modulation

The interaction between the environment of the sensor and the current in the sensor circuit are accounted for in the sensor modulation component. The objective is to describe sensor circuit current in terms of parameters that influence the measured current. An example of a general expression for a sensor that responds to particle size, aerosol number concentration, velocity, and temperature would be

$$I_s = f\left(d_p, N_c, v, T\right)$$

Quantifying sensor circuit current as a function of the influencing parameters is admittedly a large task. However, appropriate small-scale testing could provide sufficient data for use in an overall predictive methodology.

Alarm Condition

The alarm condition for most smoke detectors is a threshold value of current in the sensor circuit. For ionization-type smoke detectors an alarm condition exists when the current in the sensor circuit decreases below a threshold value. For photoelectric type smoke detectors an alarm condition exists when the value of the current in the sensor circuit increases beyond a threshold value. This threshold value can be described in terms of the alarm current.

For some populations of smoke detectors the threshold value relates to an instantaneous value in time. However, for some other populations of smoke detectors signal verification is used which introduces additional time delays until occupant notification. In the case of addressable systems, smoke detectors are polled by a fire alarm panel in a regular time interval. The signal verification may require that an alarm condition exists for a certain number of consecutive polls. In addition to signal verification, time delays can also result from the time between the alarm condition and the activation of audible and visual peripherals such as alarm horns and strobe lights.

CONCLUSIONS

The ability to accurately predict smoke detector response is crucial in the assessment of occupant life safety in buildings. While simplistic methods exist for predicting smoke detector response, such as the temperature rise analogy, the underlying phenomena of the overall smoke detection process are not fully addressed by such methods. However, by treating the overall smoke detection process as a collection of related components for use with computational fluid dynamics modeling it is possible to focus research efforts towards the development of improved predictive methods.

There are several areas of improvement needed before such an overall methodology would be feasible for routine use by fire protection engineers and practitioners. Such improvements would be:

- Inclusion of an aerosol dynamics sub-model in a CFD code that includes the phenomena of agglomeration, sedimentation, and deposition.

- Particle size and number concentration as additional variables in a CFD code.

- Characterizing detection hazards as a source of energy and mass that is compatible with the aerosol dynamics sub-model of a CFD code.

- Characterizing sensor modulation in terms of relevant combustion byproducts.

Additionally, appropriate full- and bench-scale testing can provide the required metrics for detector performance as well as verification of the resulting CFD simulations.

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