Quantitative Assessment of Smoke Toxicity Hazards in Large Structures

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1. Introduction

In the last few years, toxicity has taken on the mistique in fire that cancer has in medicine. Fire statistics clearly tell us that most fire victims die from exposure to toxic fumes rather than from burns [1]. But while these toxic gases are the medical cause of death, how often are they really the direct reason for the fatality? If, for example, the person's escape path was cut off by excessive heat or blinding smoke, trapping the person for long enough for the gases to have their effect, would you not say that this heat or smoke was the reason that the fatality occurred? For if it had not been there, the person could have escaped. In such a case, reducing the toxicity without changing the heat or smoke production might not improve safety unless the additional survival time allowed for rescue of the trapped occupant. Thus, to make real progress in improving safety, we must gain an understanding of fire hazard and the interrelationships of the various factors which affect the development of hazard in building fires.

This is the primary motivation behind the ongoing work at the Center for Fire Research (CFR) on the development of hazard assessment methodologies; techniques which can be used to make quantitative predictions of the development of occupant hazards in building fires. The core method is based on computer simulation of specific fires in specific building geometries, systematically taking into account the material, combustion, fire growth and spread, building design, and occupancy factors which will impact the outcome of any fire scenario [2].

2. Fire Models

There are three general categories of fire modeling techniques; field models, zone models and network models.

Field models divide a space into a one, two, or three-dimensional network of relatively fine elements and, using the governing partial differential equation(s) of the phenomena of interest, calculate the conditions in each element as a function of time. These models provide very high resolution and detail but are computationally intensive; a simple combustion problem in a single compartment requiring significant time on the largest super computer. Thus, they represent an excellent research tool but generally are not too practical for problem solving.

Zone models divide each compartment into a small number of volumes, including at a minimum an upper layer, a lower layer and a fire plume region. These models work well in the compartments nearest the fire where stratified conditions exist because of the significant driving force of buoyancy. The turbulence normally associated with fires causes mixing within the layers which lead to conditions which are reasonably approximated by the uniform layer approimation of the zone models. These models are more computationally simple than field models and, given a good numerical solver routine, can run multiple compartment simulations in real time on a mid-sized mini computer.

Network models assume that conditions within each compartment are uniform in space. These models can be used to solve problems involving very large numbers of nodes (compartments) efficiently. At some distance from a fire the products are well mixed and are driven by the now-dominant forces of HVAC, stack effect, and wind. Network models are therefore well suited to this realm.

From this, it is clear that the most effective approach for treating the problem at hand is to marry the three techniques into a hybrid model which can provide the detail necessary for useful predictions while maintaining practicality for problem solving. In fact, this is probably the only approach with enough computational efficiency to be used for predictions in large structures due to the large number of compartments therein. Thus, the direction of our work is to use the zone model for the near-fire compartments where buoyancy and stratification are key phenomena. This model would include field model-type elements in special zones, as required (e.g., the zone which represents the ceiling material, where transient heat conduction requires a field equation analysis). Once beyond the distance where stratification is significant, the network technique will be used to map the distribution of products in the rest of the structure.

3. Current Status of Predictive Models

The major components of the strategy described above are already in place. The component which will simulate the near-fire compartment phenomena is called FAST [3,4]. FAST is based on the products of research which deals with the simulation of compartment fire processes. The initial version of FAST
is now undergoing testing and validation in its initial
version as refinements to its basic capabilities are being developed. One current refinement being studied will lead to simulations of the flow dynamics of the
initial smoke waves propagating across a ceiling and down corridors as previously mentioned.

The foundation for the network modeling of smoke transport throughout large, complex structures exists in the NBS model for smoke control systems analysis [5] and in similar models from France, England, Canada and Japan [6,7,8,9]. Network models for building evacuation simulations are also available from a number of sources [10,11]. Thus, the job at hand is to study these network models, and select the most appropriate ones (or assemble a new one using the best approaches from several), and link them together with a FAST-like model to form the complete package. One of the most critical activities here will be the definition of the boundary criteria where one technique ends and the next begins.

Each of these component models is currently being used independently within its own area of applicability, and some have been compared to experimental data [3,12]. While such comparisons are useful in demonstrating the ability of a model to predict a specific case, a more rigorous approach is necessary before any conclusions can be drawn about the predictive accuracy of any of these models in general. This subject will be covered in more detail below in the section on validation.

3.1 Modeling in the Stratified Region

FAST is a zone model which predicts the generation and transport of heat, smoke and a number of gas species throughout multiple, interconnected compartments of a structure. It is used in the compartments near the fire where buoyancy driven, stratified flows predominate.

As input, it requires information on the structure such as room and connecting vent dimensions, physical and thermal properties of the enclosing materials, and specifications of the fire. The fire is specified in terms of the mass loss (or heat release) rate, heat of combustion and yields (mass conversion fractions) of smoke and the species of interest. Additions to be incorporated soon, include the enhancement of fuel generation by radiation feedback from the upper layer (for modeling flammable liquids and horizontal slab solids) and a submodel to predict the burning of furniture items from data on component materials and geometry based on the work by Dietenburger [13].

Outputs include detailed time histories of temperature, smoke, and gases for each layer (and the position of the interface between layers) for each compartment along with mass flow rates through vents and boundary surface temperatures.

3.2 Modeling in the Fully Mixed Region

As mentioned above, far from the fire the conditions in each compartment will be relatively uniform and the flows will be driven by the pressure differentials established by HVAC systems, stack effect and wind. This situation lends itself to network modeling where each compartment is considered to be at one temperature and pressure. An example of such a model is the NBS Smoke Control Program [5]. Here, each compartment can be specified with a net supply rate, a net exhaust rate, and with flow or leakage paths between spaces. Mass flow rates between spaces are thus obtained and the distribution of smoke and gases by these flows is predicted.

Thus, by combining these two types of models, the spread of heat, smoke and gases can be predicted for the course of the fire over the entire building.

3.3 Modeling the Evacuation of Occupants

Another use of network modeling is in the simulation of occupant evacuation. Here, starting locations are specified along with a defined evacuation route in terms of nodes and arcs. Each arc has a length and a walking speed associated with it and the speed can be a function of local enviornmental conditions at the time a person moves over it. Nodes can be specified with delays such as for initial notification (starting node), activity delays, or waiting to get through a door as a function of the number of persons at a node at a given time. Nodes could also be programmed to account for decisions such as to take another route as a function of environmental conditions at that point of the fire. An example of such a model is one developed by Kisko and Francis at the University of Florida on a CFR Grant [10].

When run in conjunction with or subsequent to the fire model, cumulative exposure to combustion products (dose) can be determined since the exposure conditions for each compartment are known. From the recent work in the U.S. on the biological effects of combinations of pure gases on lethality [14] and by the Japanese for incapacitation [15,16], interpretation of these exposures in terms of the expected effect is becoming possible.

3.4 Modeling Fire Protection Systems

Currently, it is possible to predict accurately the operation of heat-activated devices (heat detectors and sprinklers) as a function of predicted conditions in the room of origin [17]. Estimates of the operating times of smoke detectors as a function of soot mass concentration or number concentration can be made with less accuracy for optical and ionization types respectively.

Modeling the extinguishment process by sprinklers is not as advanced and may not be practically achieved for a few more years. Work on this is ongoing at NBS and Factory Mutual Research Corporation in the

U.S.

As was discussed above, modeling the impact of smoke control systems should be possible since network models which will form the basis for the fully-mixed fire model were originally developed for this purpose.

4. Validation

In order to be useful in a practical sense, models must be validated. That is, we must be able to establish the statistical accuracy of the predicted quantities. This requires much more than simply making direct comparisons with selected experimental results. Thus, CFR, in conjunction with the Center for Applied Mathematics (CAM) of the National Bureau of Standards has established a project to develop techniques to be used for this purpose.

Interestingly, the ease of validating a model against test data is in many ways inversely proportional to the complexity of the modeling technique used. That is, comparisons are most direct for field models since they produce values of physical quantities at a specific point in space which corresponds directly to the location where a quantity was actually measured in an experiment. Zone models, on the other hand, produce what corresponds to a bulk average value within a layer. The average must be derived from experimental data by averaging some number of measured values within a layer which is continuously changing in volume. Since the measurements are taken at fixed points, one must determine according to an operational definition of layer interface location (which itself must be applied to the data) when they are within one layer or the other. Differences between measured and predicted values can be attributed to the poor quality or accuracy of the data, the paucity or low frequency of the data, the somewhat arbitrary definition of layer interface location, the poor performance of one or several of the predictive algorithms which make up the overall model, or a combination of any one or all of these.

5. Managing the Output

The output produced by models is in much the same form as data from large-scale fire experiments. That is, they give temperatures, flows, smoke densities, gas concentrations, radiant flux, etc. at fixed time intervals over the course of the simulation. The difference lies in the fact that fire experiments are expensive and time consuming to run, so their number is generally limited to a few, carefully selected scenarios.

Model runs, on the other hand, are easy to set up and inexpensive to produce, so the limitation with models is the ability to analyze and understand the large amount of data which is so readily available. Thus, it is critical that the models be provided with the capability of presenting their data in a way which is most easily understood, consistent with the purpose for which the model is being used.

Many applications will involve quantitative comparisons among numbers of model runs where parameters of interest have been varied. Here, general graphic techniques where X-Y plots of predicted variables can be presented from one or more runs on a single graph would be useful.

Such a capability is provided for FAST with a program called Fastplot (described in the Appendix of Ref. 1). For a more qualitative understanding of what would happen throughout an entire facility (especially a complex one) for a given set of conditions, this kind of presentation may not be appropriate. The large number of plots would lead to a confusing and unclear picture of the sequence of events.

To address this latter problem, we are developing a computer graphic technique which presents the information provided by the model in a two- or three-dimensional pictorial format along with graphical or tabular presentation of key quantities. This pictorial representation includes color coded hazard information which is also keyed to the data to show the relative contribution of a given parameter to the hazard condition present. In this way, key information is presented to the user in an easily understood manner similar to watching an experiment. Critical events can be noted during the graphical presentation and analyzed later by using the data graphics routines. With the evacuation sub-model, the graphics output can include occupants' progress displayed along with the environmental conditions to show either successful evacuation or the time, location, and condition which ultimately prevents escape. Mitigation strategies are then apparent to delay the onset of the limiting condition sufficiently to allow successful evacuation.

6. Use of Models for Hazard Analysis

The potential uses for these techniques are as varied as the potential users. Initially, we feel that the primary uses will be in the areas of fire investigations and analysis of the contribution of material toxicity relative to other fire hazards. In the former, the models can be used to sort out the most likely scenario from several possible theories of origin and spread indicated by the evidence. In the latter, the models show all of the relevant hazard considerations and their interrelationships in a way which cannot be analyzed by any other means. In both cases, the growth in litigations associated with fires will likely provide the motivation to invest in these new technologies.

As confidence in these techniques grows through validation and successful application in these areas, we hope that codes will begin to shift toward acceptance of compliance equivalency based on a calculated hazard analysis, and eventually to a performance base. Once this begins, the design community will be able to begin using models to improve safety and reduce the cost of fire protection through design trade-offs and elimination of redundancy.

Since any evaluation of the impact of the combustion toxicity of materials and products requires a knowledge not only of the potency but also of the time of exposure and the resulting inhaled dose, these models represent the only scientifically defensable approach. This is particularly true for large structures where time scales for both transport processes and evacuation are long.

The technology to do all of the things discussed in this paper is available today and with a dedicated effort can be implemented within a few years. The key to achieving this goal is cooperation among the research, regulatory, and manufacturing communities to support the effort financially, and with the exchange of data necessary to make this all work.

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