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PRACTICAL APPLICATIONS OF FIRE MODELING IN INDUSTRIAL APPLICATIONS

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ABSTRACT

The use of computer based fire modeling tools in fire protection has become almost common place. The accessibility to computational power and the development of the necessary base knowledge of the fire phenomenon has led to the use of “performance-based” design and evaluation.
The development of technology and the widespread accessibility provide all users the opportunity to participate in performance-based design or evaluation. Using the fire modeling tools requires an appreciation of the environment in which they are being applied as well as an understanding of the limitations of the tools. The industrial environment presents many challenges to the application of fire modeling tools. For example, the fuel load may change frequently based on routine production and maintenance activities or the temperature in one area may vary greatly due to the presence of heated production equipment.
Examples of fire modeling applied to industrial cases are used to demonstrate practical application of some fire modeling tools in this environment.

INTRODUCTION

Fire modeling has become a common place tool readily available to all practicing engineers. As with all tools, the tool selected must be appropriate to the job. As we all quickly recognize, a curve template is not the appropriate tool to select for drawing a straight line.

There are many types of modeling. In the NFPA Fire Protection Handbook Beyler and DiNenno[1] classify models in two broad categories: (1) physical models and (2) mathematical models. Physical modeling includes full scale tests, the concept of conducting experiments using a reduced physical scale and the simplification of a complex phenomenon into a more manageable problem. Physical models and mathematical models are complementary. Often physical models are used to provide a better understanding of the relationships to be established in mathematical models while mathematical models may be used to help define the scope the of a physical test program.

Full scale testing is often impractical and prohibitively expensive. In scale modeling it is also necessary to maintain mechanical, thermal and chemical similarity in the reduced physical scale. The standard fire tests represent a type of modeling to represent one or a few components of a complex phenomenon. The adequacy of the physical modeling varies widely.

Mathematical models are subdivided into probabilistic models and deterministic models. Probabilistic models are designed to handle the random nature of the fire behavior. Deterministic models provide a determination of the fire growth and behavior in a well-defined physical situation.

DETERMINISTIC MODELS

My purpose in this presentation is to look at application of some deterministic models in the industrial environment. Deterministic models range from simple formulas expressing a singular characteristic of fire to complex computer software requiring extensive computing time on powerful computers.

The Society of Fire Protection Engineers is developing Engineering Guides to assist fire protection engineers in the application of fire models. Several of these guides have already been published. One of these guides, Assessing Flame Radiation to External Targets from Pool Fires[2], provides an example of the use of basic formulas to look at a specific fire characteristic. The guide presents four different methods for calculating the radiant heat transfer from pool fires to a target located outside the flame.

One of these methods is the ‘Point Source Model’. The incident radiative heat flux is given by:

$$q'' = \frac{Q_r \cos\theta}{4\pi R^2}$$

where

q'' is the incident radiative heat flux
Q_r is the total radiative energy output of the file
θ is the angle between the normal to the target and the line of site from the target to the point source location
R is the distance from the point source to the target

As done with all of the methods discussed in the engineering guide, the data requirements, assumptions, validation and limitations are identified.

The procedure provides formulas for calculation of the flame height based on the pool diameter and the heat release rate. Another expression is presented to calculate the radiative energy output based on the pool diameter and the total heat release rate of the fire.

An example of a computer based calculation procedure is the computer fire model DETACT-QS[3] developed in the 1980’s at the US National Bureau of Standards (now the US National Institute of Standards and Technology commonly referred to as NIST). The model was developed to calculate the response time of ceiling-mounted heat detectors/sprinklers and smoke detectors installed under large unobstructed ceilings. Another SFPE Engineering

Guide, Evaluation of the Computer Fire Model DETACT-QS,[4] provides information on the model, input data required, assumptions, and limitations.

Based on data correlations from fire experiments, ceiling jet temperature and velocity predictions are calculated by the software. Then, based on heat transfer theory, the time for the heat detector/sprinkler or smoke detector is calculated. The input data required is

Height of ceiling above fuel
Distance of detector from center line of fire
Initial room temperature
Detector actuation temperature
Detector response time index
Total heat release rate time-dependent curve for fire

ZONE MODELS

The more complex fire models available today are identified as zone models and field models or computational fluid dynamics (CFD) models. Zone fire models define the fire environment in an enclosure using an upper hot region and a lower cool region (or zone) as shown in Figure 1. The models assume a uniform temperature and other fire effect characteristics across each zone. The interface between the two zones may move vertically during the fire.

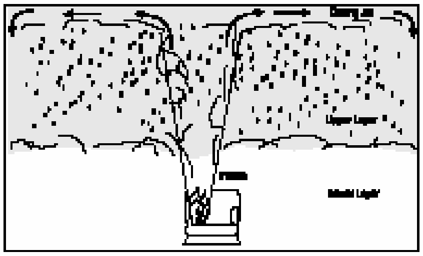

Figure 1

There are many zone fire models available[5] to the practicing fire protection engineer. One of the most widely used zone fire models in North America is CFAST[6] developed at NIST in the United States. Zone models provide an approximation of the conditions by the nature of the representation of the compartment(s). Although the results are an approximation of the conditions resulting from the fire effects, the user must determine if the results are acceptably accurate for the problem under consideration. Beyler and DiNenno state in the NFPA Fire Protection Handbook[7],

> "The extent to which zone models can be effectively applied in large open areas or tall structures is uncertain. The two-zone paradigm does not preclude their use in large or

> tall structures per se, but rather stretches the assumption of uniform properties within a zone."

The zone models commonly in use do not include combustion models. The fire is represented by a time dependent mass loss rate or heat release rate curve specified by the user. As the fire is the energy input into the system being evaluated, the similarity of the specified data to real world fire will impact the calculations and the model output.

The outputs from CFAST include:

Upper layer temperature
Lower layer temperature
Height of interface between layers
Boundary surface temperatures
Entrained mass flow in the plume
Heat release in lower layer, upper layer, out a vent
Mass flow from the plume into the upper layer
Radiation to a target
Species density
Radiative heat flux into the layer
Vent flow

COMPUTATIONAL FLUID DYNAMICS (CFD) MODELS

The technology of computational fluid dynamics has been in use for many fluid flow problems for at least 3 decades. Commercially available CFD software is now being used for the design and evaluation of many practical engineering problems.[8] CFD modeling the calculation of mass, momentum, and energy change in very small volumes (grid cells) within the total volume of interest. The number of cells can number in the thousands, tens of thousands or even millions. Figure 2 shows an example of such a grid.

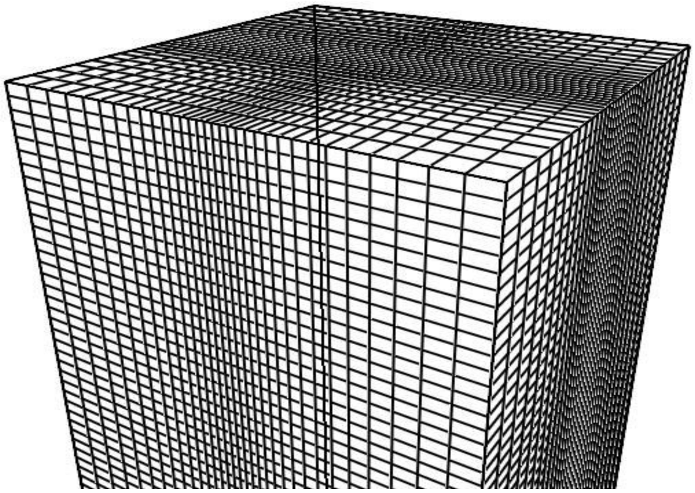

Figure 2

The complexity of the calculations as well as the detail in the geometric space requires extensive computing power. With the ever increasing power of personal computers, CFD models, also referred to as field models, have become available to the majority of practicing fire protection engineers.

Although CFD modeling has been used for many fluid flow engineering problems, there are several CFD software packages being developed specifically for the fire problem. Within these packages there is much activity in advancing the understanding and capabilities for predicting flame spread and fire development.

The state of the art in combustion modeling still requires the user to approximate the fire source even though it may be a much more sophisticated approximation than that used in zone models.

EXAMPLE APPLICATIONS

Outdoor Transformer

One CFD model developed specifically for the fire problem is Fire Dynamics Simulator (FDS)[9] from the National Institute of Standards and Technology, U.S. Department of Commerce, USA. An accompanying program, Smokeview, allows easy visualization of the output from the FDS software.

FDS was used to look at the radiant heat flux from a transformer fire to an electrical substation. Figures 3 and 4 show the basic layout of the transformers and the electrical building wall.

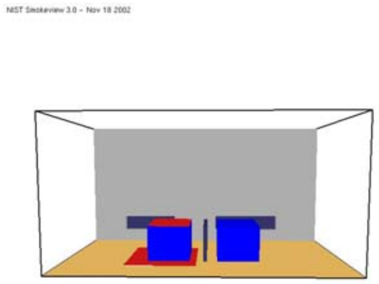

Figure 3

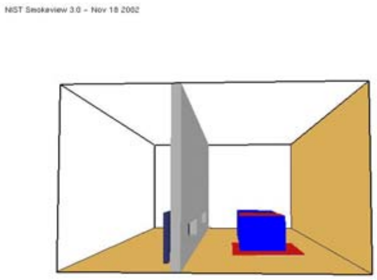

Figure 4

The blue cubes represent the transformers, each of which measures 3 meters x 3 meters by 2.5 meters high. The transformers are separated by a 2 meter space with a metal partition located near the center of the space. The metal partition is 25 mm thick and 3 meters long by 2.5 meters high (same dimensions as the transformers). The grey object represents a concrete building wall 3 meters from the transformers and 10 meters high. The 2 openings in the wall are windows located 1 meter above the ground level. Each window is 4.5 meters long and 1 meter high.

The dark grey object on the opposite side of the wall from the transformers is a metal panel 25 mm thick and 3 meters high located 0.5 meters from the wall (representative of switchgear inside the building).

The red area is the burning surface on top of and around the transformer. This represents a fire surface area of 22.0 m^2. Table 3-1.2 in the SFPE Fire Protection Engineering Handbook, 2nd Edition provides data for hydrocarbon transformer oil. This produces a fire with a maximum heat release rate of 1720 kW/m^2 or about 37,000 kW over 22 m^2. Based on a t^2 fire curve for a very fast developing fire, the fire reaches this total heat release in 75 seconds.

In this calculation the radiated energy flux (kW/m^2) was calculated at the surface of the surrounding objects, including:

Metal partition separating transformers
Adjacent transformer
Building wall
Metal panel on opposite side of wall

Figure 5 shows the calculation results at 60 seconds after the start of the calculation. The metal partition separating the transformers has a radiated energy flux of 25-30 kW/m^2. About the same value is shown on the concrete building wall. The circled area in Figure 4 is the metal panel on the opposite side of the concrete wall. The figure shows a calculated radiation flux of 15-20 kW/m^2 at this panel.

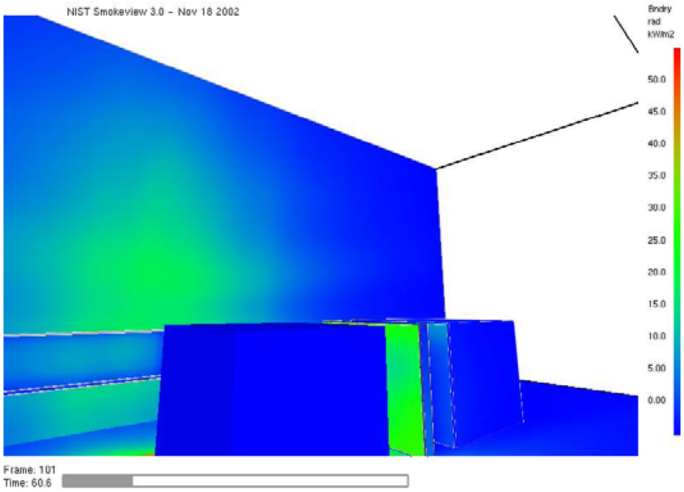

Figure 5

The values shown can be compared to data available in the literature to identify damage to different types of equipment and building components. A radiated heat flux of 12.5 kW/m^2 has been reported to be the minimum heat flux required for the piloted ignition of wood. At this level plastic will also melt. A value of 20 kw/m^2 has been reported to be the level at which cable insulation will begin to degrade. A value of 25 kW/m^2 has been reported to cause the spontaneous ignition of wood. At 30-35 kW/m^2 equipment can be damaged.

Without additional fire protection features, a transformer fire would be expected to damage the improperly separated transformer and equipment inside the building near the windows. This is about 1 minute after the fire starts.

Flammable Liquids Warehouse

This example was set up to look at the effect on the air movement under fire conditions with the ventilators at the roof. The air movement is of interest in consideration of the effectiveness of halon distribution with the expected fire growth and system response times.

The flammable liquids warehouse is shown in Figure 6. It is approximately 20 meters by 17 meters with a height of 5 meters at the peak. The walls are concrete and the roof is metal panel on steel truss. There are 4 ventilators located on the roof with 8 ventilation openings in the outside walls at floor level. The warehouse has a total flooding halon system that requires the activation of 2 heat detectors for halon discharge.

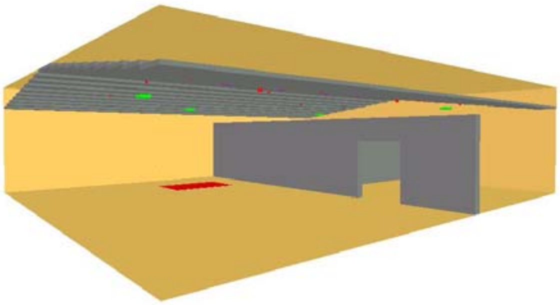

Figure 6

The air flow through the ventilators was calculated using the peak wind velocity of 14.4 m/sec recorded for the geographical region. The ventilator exhaust velocity of 6.7 m/sec was determined from a table[10] based on a typical ventilator. The air volume was then calculated to determine the inlet air velocity at the wall vents.

The combustibles range from triethylamine with a heat of combustion of 43.19 MJ/kg to acetone with a combustion of 25.8 MJ/kg. In addition there is storage of old paper files with an assumed heat of combustion of about 13 MJ/kg. These present significantly different fire growth potentials.

Two fires were characterized using heat release rates proportional to t^2. A fire involving triethylamine was developed using a growth time of 30 seconds to reach a peak heat release rate of 1771 kW/m^2. For the paper file fire a growth time of 300 seconds was used to reach a peak heat release rate of 1500 kW/m^2. The fire area was set at 6.9 m^2.

Under these conditions the heat detectors activated at the following times.

Detector	Liquid fire	Paper fire
1st	20 sec	130 sec
2nd	30 sec	145 sec

Halon would be discharged for a period of 10 seconds after the second detector activated. Air velocities within the warehouse were examined at the time of the start of halon discharge and 10 seconds after the assumed completion of halon discharge. Velocities of interest were around the fire plume and at the level of the halon discharge points.

Figure 7 shows the u (in figure right to left) velocity component in the xz plane near the center of the flammable liquid fire plume at 54 seconds (after discharge is completed) into the calculation. At the roof level the direction of this component is from left to right. In the center portion of this plane the direction is from left to right. At floor level there is very little movement.

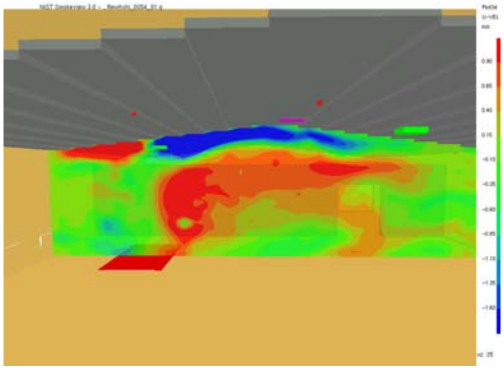

Figure 7

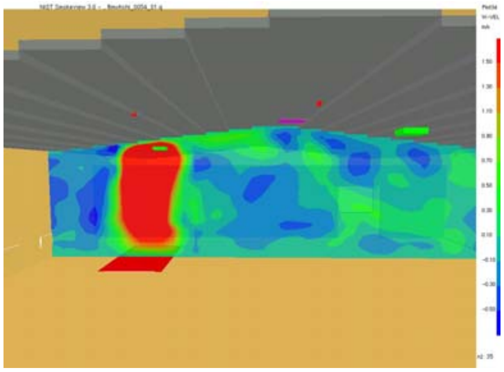

Figure 8

Figure 8 shows the w (vertical) velocity component in the same plane at the same time frame. The direction of the vertical component is upward immediately over the fire (the fire plume). There is little movement adjacent to the fire plume. The direction of movement away from this area is in the downward direction. However, there is little movement in the vertical direction near the floor level.

Figures 9 and 10 show similar velocity components for the paper fire at 175 seconds into the calculation. This is also shortly after the end of the halon discharge. The general layout looks similar to that shown in Figures 7 and 8.

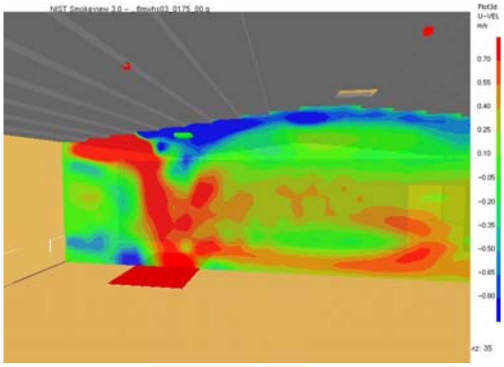

Figure 9

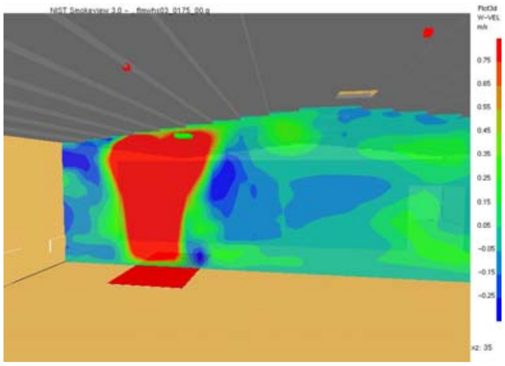

Figure 10

In both fire scenarios there is a well developed fire at the time the halon discharge would take place. The air movement is away from the fire at the level of discharge with no strong return air movement towards the base of the fire where the fuel is located. Early in the discharge halon would be carried away from the location of the fire resulting in greater quantities of halon in areas remote from the fire. The concentration of halon at the fire plume would be significantly less than the average concentration over the entire volume.

CONCLUSION

The many fire modeling tools available to the practicing fire protection engineer can be used successfully to identify problems in design concepts. These tools allow this type of evaluation to take place in the design process to assure the best results for the fire protection money invested.

Where this type of evaluation has not been included in the design process or where conditions have changed, these tools can still be used to determine the extent of existing fire hazards and fire hazard control.

The selection of the proper tool through understanding the proper application is important. The selection must consider the limitations of the application, the availability of reliable input data, and the ability to use the output from the calculation.

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[2] SFPE Task Group on Engineering Practices, “Assessing Flame Radiation to External Targets from Pool Fires”, Society of Fire Protection Engineers, Bethesda, MD, USA, June, 1999

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[4] SFPE Task Group on Computer Model Evaluation, "Evaluation of the Computer Fire Model DETACT-QS", Society of Fire Protection Engineers, Bethesda, MD, USA, December, 2002

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