Studying the Response of Building Systems to Fire Using a Virtual Cybernetic Building Test-Bed

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Abstract

As the ability to predict fire conditions in buildings using sensor signals improves, these predictions can be used to inform first responders about the building status and provide the possibility of using the building systems to contain the fire and aid in egress. While current fire models are used to predict the evolution of fire in buildings, the simulations do not include the interaction with actual building controllers and sensors. The NIST Virtual Cybernetic Building Test-Bed (VCBT) is designed to provide a method of coupling simulations of incidents such as fire to the response of actual building components such as HVAC controllers in multi-room, multi-floor buildings. This paper will give an overview of the VCBT and will provide descriptions of algorithms used to simulate heat, gas and smoke detectors. Methods for converting the sensor signals to provide information concerning fire conditions in buildings will be discussed.

Introduction

A major program of the Building and Fire Research Laboratory (BFRL) at the National Institute of Standards and Technology (NIST) is Enhanced Building Performance. One of the research thrusts in this program is designed to develop, test, integrate, and demonstrate open cybernetic Building Systems. The word "cybernetics" comes from the Greek word for "steersman" and is defined as the science of control and communication of complex systems. A Cybernetic Building System involves energy management, fire detection, security, transport systems, energy providers, one or more utilities, an aggregator, and numerous service providers, and information handling and complex control at many different levels. BFRL is developing standard communication protocols for open exchange of information among systems, fault detection and diagnostic methods and automated commissioning, smart multi-functional sensors, tools for protocol compliance testing and real-time monitoring, and a Virtual Cybernetic Building Test-bed (VCBT)[1] to help manufacturers develop and evaluate new products and systems.

Fire and smoke detection and control are important issues for buildings. A Sensor-Driven Fire Model (SDFM)[2] is being developed within the VCBT to examine the concept of extracting substantial information from building sensors about a fire event in real time and transmitting this information to first responders. Information such as fire location and size, smoke and visibility conditions, entrance and egress routes, the potential for structural collapse and the remote use of building systems to aid in the control of smoke and fire and aid in egress are being considered based on testing within the VCBT.

This paper will provide an overview of the VCBT. The algorithms used by the SDFM to extract information from fire sensors in a building will be described. An example of the kinds of information that could be transmitted to first responders will be discussed.

Virtual Cybernetic Building Test-Bed (VCBT)

The VCBT is a simulation-emulation environment that combines simulation of a building and its systems with the emulation of real commercial building components such as building system controllers. It provides a way to conduct tests in real time under a wide variety of controlled, repeatable conditions. The VCBT allows the introduction of actual components for hardware-in-loop testing in a realistic setting.

In its initial configuration, the VCBT can simulate a three-room, one-story building or a nine-room, three-story building. It consists of computer simulation programs running on several computers and actual HVAC controllers communicating with the programs. The airflow in the building simulation is dictated by the (real) response of these controllers to (simulated) building conditions. A schematic of the major functional elements of the VCBT is shown in Figure 1.

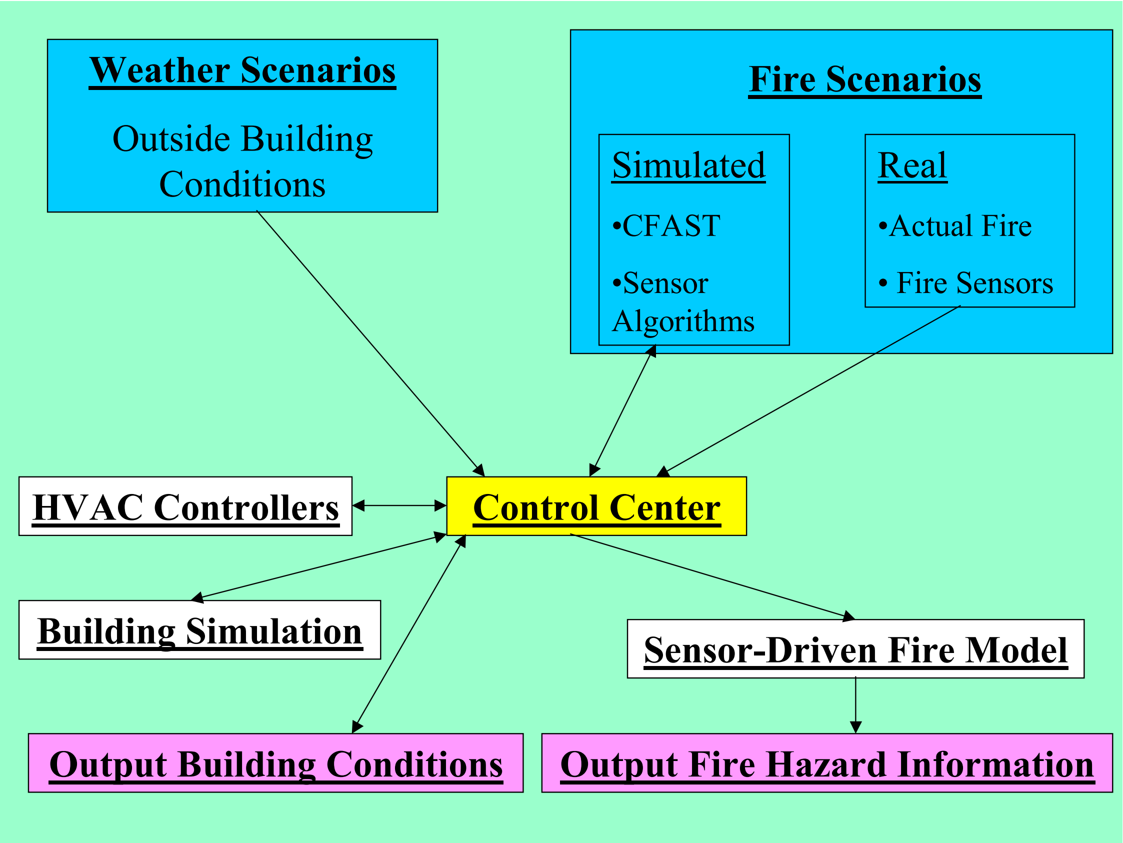

Figure 1 Block diagram showing the parts of the VCBT

The control center receives and distributes information from various components of the simulation. The top two blocks provide scenarios that allow the building systems to be studied in either normal or emergency modes. The Outside Building Conditions block supplies a weather scenario to the system. Temperature, pressure, humidity and wind conditions outside the virtual building are fed to the control center from a separate computer. The weather scenarios are preprogrammed and the building simulation will respond to the changing weather conditions.

Fire scenarios are available either as CFAST[3] computer simulations or as actual fires conducted in BFRL laboratories. The fire sensors can be commercial detectors if an actual fire is used or simulated sensors when CFAST supplies ceiling jet and smoke layer conditions for the sensor algorithms. Two-way arrows connect the simulated sensors and CFAST to the Control center to signify information traveling in both directions since these systems need to be supplied with current building conditions as well as supply their data. One-way information is used when the system uses a real fire. The Outside Building Conditions has a one-way arrow to the control center as nobody can change the weather.

The fire and weather information are sent to the building simulation that updates the building conditions and sends data through the control center to the HVAC controllers. The HVAC controllers respond to the changing building conditions and send their information about the changing HVAC flows back to the control center. The process then cycles as the weather/fire conditions change with time. The communication protocol that is used to communicate with the building hardware is BACnet[4].

The voltage outputs from fire sensors are sent to the SDFM once each update cycle for analysis to determine if a fire has started somewhere in the virtual building. Upon analysis, four different fire conditions are sent back by the SDFM. The first is a no-fire condition where all sensor signals appear normal. The second is a possible fire warning where one or more sensors are elevated above their normal levels but the estimated Heat Release Rate (HRR) is below a user determined threshold condition. The third is a fire warning that results when sensor signals have exceeded a manufacturer set point or the estimated HRR exceeds the user determined threshold condition. The fourth is a sensor failure warning. A block diagram of the Sensor-Driven Fire Model is shown in figure 3. The model consists of sensor algorithms to convert the analog or digital voltage signals from fire sensors to temperature, smoke, or gas concentration depending on sensor type, ceiling jet algorithms to calculate the HRR based on the sensor information, a zone fire model that uses the estimated HRR to calculate layer conditions in each room of the building, and algorithms that estimate hazard conditions in the structure based on layer temperature and depth.

When a fire has been detected, the SDFM will send fire location, size, smoke layer temperatures and heights, fire growth rate, and hazard warnings based on temperature and layer height for each location in the building to the control center. The control center could then transfer the information to emergency responders located at a firehouse or riding on a fire truck. The incident commander would use this information in planning or

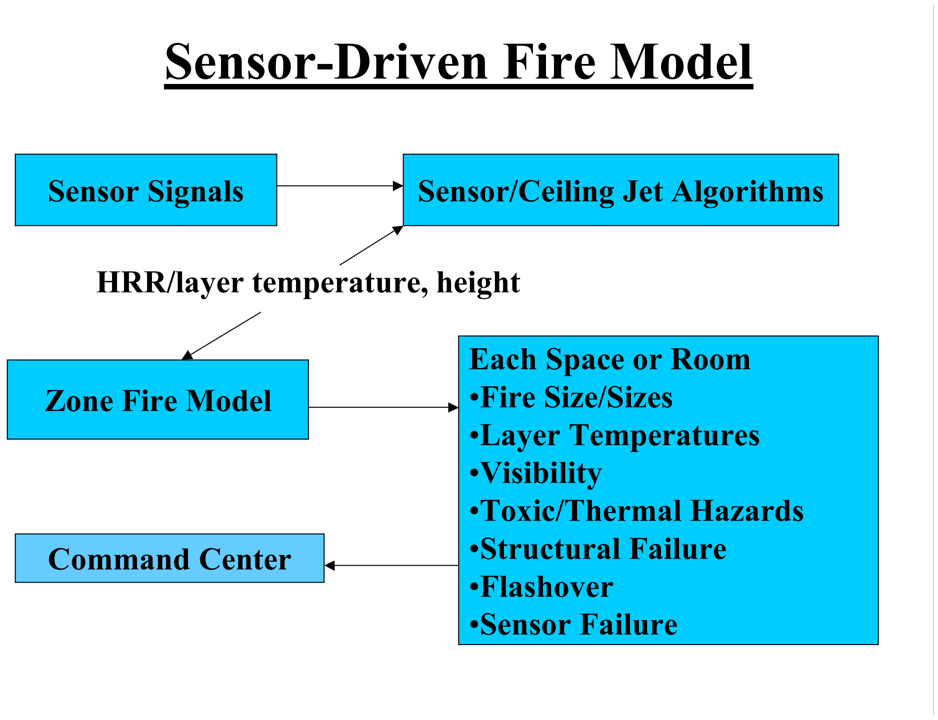

Figure 2 Block diagram of Sensor-Driven fire model

modifying a response prior to the arrival of the first responders. This information would provide first responders with the fire location and size and in conjunction with a database layout of the building, identify attack and egress routes for the building.

Fire Sensor Information

When a fire starts, hot gas rises to the ceiling as a fire plume, strikes the ceiling and flows along it until it reaches the walls where it turns and flows back toward the plume. The ceiling flow is known as the ceiling jet and the return flow forms a hot gas layer beneath the ceiling jet that is called the smoke layer.

Two issues must be addressed in order to obtain detailed fire information from a fire sensor located in the ceiling jet. First, the response characteristics of the sensor must be determined such that the electrical signal that the detector delivers can be converted to a temperature or smoke or gas concentration. Once the signal has been converted, then algorithms for the ceiling jet and smoke layer must be used to transform the converted signal to a HRR. Three detector types, spot heat detectors, smoke detectors, and CO detectors are currently being investigated for use with the SDFM. The response characteristics for each type of detector are discussed below.

Response characteristics for heat detectors can range from the rapid response of a thermocouple to the relatively slow response of a thermistor. Typically, a Response Time Index (RTI) can be assigned to the detector and the first order differential equation that is used for fusible links can be used to model the detector[5]. For detectors with small values of RTI, the response characteristic can be ignored. Some thermal detectors may have offset times. An offset time is the time required for a detector to respond to a gas flow that has reached the outside of the detector housing. The offset time can be a combination of the flow time for the gas to reach the sensing element in the detector housing, a diffusion time in case the element is protected by a porous, thermally insulating material, and a minimum detectable signal required for the amplifying circuit to send a signal. Currently, the SDFM has only been tested against thermocouple measurements and so the thermal response characteristics for detectors have not been measured.

Response characteristics have recently been measured for smoke and CO detectors[6]. These detectors generally have offset times that can be velocity dependent. Smoke detectors can be represented with a single first-order differential equation and an offset time[7]. Many of the smoke detectors tested show strong velocity dependence at low flow velocities.

CO detectors can be represented with an offset time and either one or two first order differential equations[6]. While the two first-order differential equations generally provide a better representation of the detector than a single first-order differential equation, the difference is not substantial enough to warrant the extra computational problems in the SDFM. These detectors are only weakly dependent on velocity, which simplifies their use in the SDFM.

For smoke and gas concentration, the equation set used to model the detector response is:

$$\frac{dX(t)}{dt} = \left[X_e(t-\delta\tau) - X(t)\right]/\tau \tag{1}$$

$$\delta\tau = a u_e^{-c} \tag{2}$$

$$\tau = b u_e^{-d} \tag{3}$$

X(t) is the smoke or gas mass density in the sensing chamber of the detector, X_e is the smoke or gas mass density at the location of the detector, u_e is the flow velocity outside of the detector housing, $\delta\tau$ is the dwell or offset time for the flow to travel through the detector to the sensing chamber, τ is the mixing time in the sensing chamber, and a, b, c, and d are determined from the response time fits. For flow velocities above 0.1 m/s, $\delta\tau$ and τ become insensitive to velocity variations for the detectors tested and can be treated as constants.

For the CO detectors that are better represented by two first-order differential equations, a second equation is added

$$\frac{dX_s(t)}{dt} = \left[X(t) - X_s(t)\right]/\tau \tag{4}$$

X_s is the gas concentration at the electrochemical cell of the detector.

The response characteristics of detectors are of primary importance when fire conditions are changing rapidly. Failure to include these characteristics would lead to smaller estimates of HRR by the SDFM.

Ceiling Jet Theory

When a material begins to smolder, the natural airflow in the room may prevent a plume and ceiling jet from forming. As the HRR of the fire increases, a plume and ceiling jet will form. Once the ceiling jet flow strikes a wall, the return flow will mark the start of the formation of a smoke layer. The temperature, smoke, and gas concentrations in the plume and ceiling jet will be increased over the values predicted by unconfined plume and ceiling jet algorithms (algorithms that assume all entrainment is at ambient conditions) since the flow entrainment will now include a contribution from the smoke layer.

The zone fire model JET[8] was modified to include the ceiling jet algorithms for smoke and gas and the detector algorithms in order to test the predictive ability of the package. The CO detector experiments that were discussed in last year's meeting were modeled[9]. An additional feature that was included in the calculations was the time for the ceiling jet to reach the detector and the time for the layer to form. Using the measured response characteristics of the detector, the predicted CO concentrations using JET are in agreement with the measured values as shown in figure 3. Additional work using different geometries is required for a full verification of this calculation scheme.

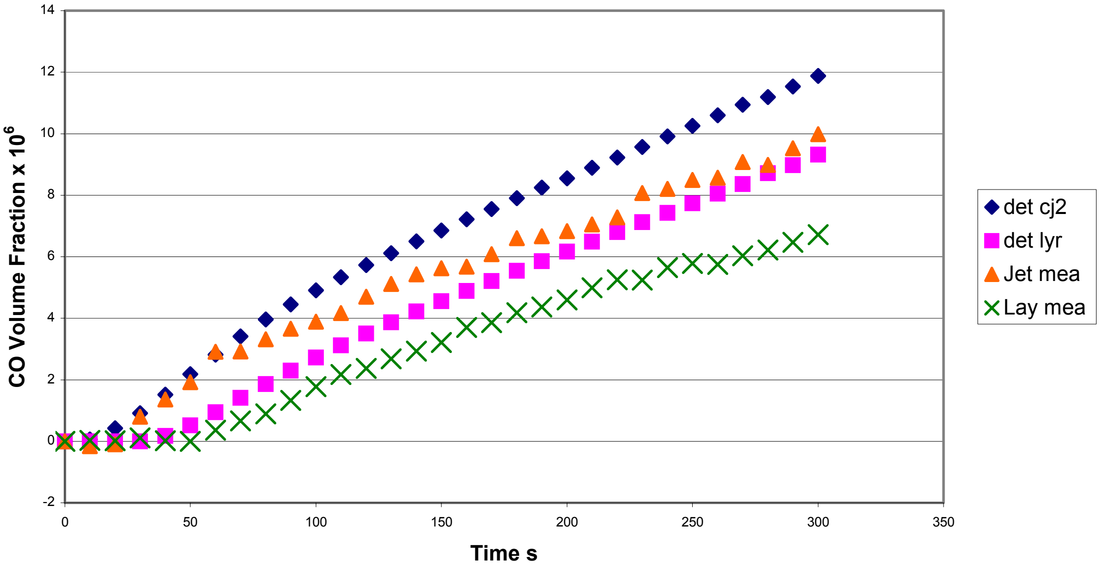

Figure 3 Comparison of predicted values of CO volume fraction in the ceiling jet (cj2) and the smoke layer with the measured values from the CO detectors. The experiment used a small burner with a 2.0 Lpm flow rate of propene. The ceiling jet value was

obtained 0.6 m from the axis of the burner. The top of the burner was located 2.19 m beneath the ceiling

The SDFM is designed to use these algorithms to solve for detector response in the ceiling jet. The major difficulty associated with the use of the algorithms is that they must be solved for HRR. This solution is easy as long as a smoke layer is absent but becomes quite complicated when the properties of the smoke layer must be included. The solution is no longer analytic and numerical methods must be used to obtain a solution.

Algorithm Application

The computational sequence to estimate room conditions when a fire is detected is as follows. Sensor signals in volts have been corrected using the response characteristic of the detector and used as an input into the unconfined ceiling jet models. If the resulting HRR meets threshold conditions for a detected fire, the HRR is used by a modified version of CFAST to compute smoke layer temperature, smoke concentration, and CO concentration for each room of the structure. The layer conditions are then used to determine visibility and hazard conditions in the structure.

On subsequent building cycles, if a layer has developed in the fire room, algorithms that include the layer entrainment are used to estimate the HRR rather than the unconfined algorithms. All the other steps in the calculation sequence are the same.

An example of the type of information that can be made available to first responders is shown in figure 4. The figure shows a Smokeview[10] rendering of a SDFM output of a computer-generated fire scenario using CFAST in the VCBT. The display would provide a responder with the location of the fire (inverted cone), smoke layer heights, and warning conditions (color of smoke layer keyed to a particular hazard condition) for every room in the structure.

Discussion

The determination of characteristics for several commercial CO and smoke detectors provides a necessary background for moving ahead in the development of methods to extract fire information from analog or digital detector signals. There is still a large amount of work to be done with detectors. Information about detector saturation and survivability need to be investigated. Changes in response due to detector orientation to the ceiling jet flow needs to be determined. Detector characteristics for current commercial spot heat detectors need to be measured.

When using smoke or gas algorithms, specific information about the heat of combustion of the fuel, radiative fraction, and the yield fractions for smoke and gas must be known. For smoke detectors, particle size also plays a role in the signal output. In using a SDFM to analyze building fires, one or more generic types of fire properties would have to be developed in order to make use of these types of detectors. Heat detectors are much simpler as only the radiative fraction needs to be known.

Additional building system controls such as a chiller unit and an elevator are being added to the VCBT. The version of CFAST used in the VCBT will be upgraded to include ceiling jet algorithms for CO and smoke. The Detector algorithms will be rewritten to include the recently measured detector characteristics. A long-term goal for the VCBT is to improve the flexibility to change building designs. Currently, only a three-room, single floor or a nine-room, three floor building can be simulated. The next generation VCBT will support the capability to change building configurations.

The VCBT at NIST provides a platform to investigate and test new technology in a simulated building environment that contains commercial building controllers. If it proves useful for emergency responders to have the capability to remotely control building systems, the VCBT should provide a structure for developing and testing the communication methods required for this to happen.

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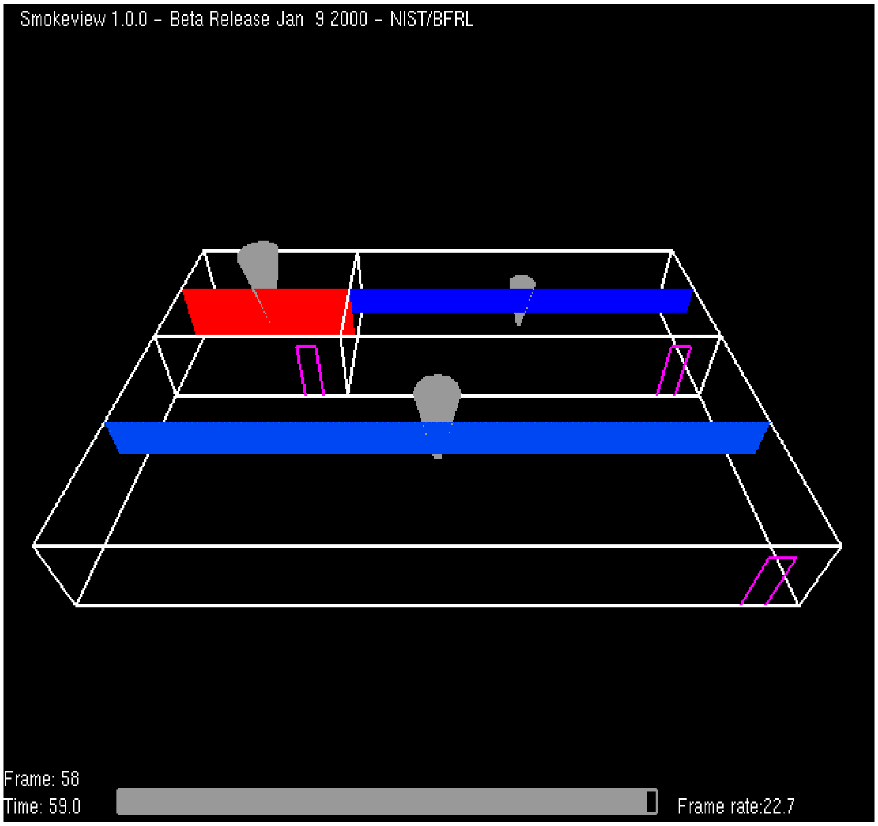

Figure 4 Three-room simulation of a fire that started in the small room. The colored slices represent the layer depth with the red color indicating flashover conditions and the inverted gray cones showing the presence and size of fires in the rooms. The visualization is done using NIST Smokeview.