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## **ABSTRACT**

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As part of a Cybernetic Building Systems project at the NIST Building and Fire Research Laboratory, a whole building emulator called the Virtual Cybernetic Building Testbed (VCBT) has been developed. The VCBT combines simulation tools with commercial building automation system products in order to emulate the characteristics of a commercial building and its various systems and controls. The VCBT simulates in real time the building envelope, weather, the heating ventilating and air-conditioning (HVAC) system, the heating/cooling plant, the fire detection system, and the security system. The simulation is linked through a data acquisition system to commercial products for HVAC control, fire detection, access control and lighting control in order to study their performance and interactions.

This report describes a new simulation tool developed for the VCBT that combines a fire simulator called the Zone Fire Model with building shell and HVAC components derived from HVACSIM<sup>+</sup>. This new simulation tool is called the Zone Fire Model with HVAC components (ZFM-HVAC). Implementation of the ZFM-HVAC tool in the VCBT is described along with the results of emulation runs used to test its performance.

Key words: BACnet, building automation and control, building management systems, cybernetic building systems, fire models, fire simulator, ZFM-HVAC

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## ***1. INTRODUCTION***

As part of a Cybernetic Building Systems project at the Building and Fire Research Laboratory of National Institute of Standards and Technology (NIST), a whole building emulator called the Virtual Cybernetic Building Testbed (VCBT) has been developed. The VCBT combines simulation tools with commercial building automation system products in order to emulate the characteristics of a commercial building and its various systems and controls. The VCBT simulates in real time the building envelope, weather, the heating ventilating and air-conditioning (HVAC) system, the heating/cooling plant, the fire detection system, and the security system. The simulation is linked through a data acquisition system to commercial products for HVAC control, fire detection, access control and lighting control in order to study their performance and interactions. Simulation results are converted by the data acquisition system into electrical signals that appear to building automation system devices as input from real sensors. The control actions are captured and used by the simulation software to determine the response of the virtual building. The overall effect is that the building management system (BMS) controls the simulated building systems as if they were an actual building.

In 1983, a simple building emulator was constructed at NIST to demonstrate the basic concept of a building emulator. The first emulator had a model that was too simple for testing algorithms quantitatively. Later a contractor for the U.S. Naval Civil Engineering Laboratory, with assistance from NIST, built a second building emulator with greater sophistication [1]. Since then the work on building emulators has continuously evolved [2-7]. The resulting VCBT 1.0 simulator employed the program, HVACSIM<sup>+</sup> [8], which stands for HVAC SIMulation PLUS other systems to simulate the HVAC system components and simple building envelopes except for the BMS controllers. The VCBT has been used to study various types of building systems and technology including: interactions of HVAC system components with fire, HVAC system fault detection and diagnostics (FDD) technology [9], communication protocols for building automation and control networks (BACnet) [10, 11], and the sensor-driven fire model (SDFM) [12].

Since the VCBT 1.0 architecture was reported [7], several enhancements have been made including: a more advanced fire detection system panel, a biometric building access control system, newer HVAC controls, and a new simulation tool developed for the VCBT that combines a fire simulator called the Zone Fire Model with building shell and HVAC components derived from HVACSIM<sup>+</sup>. This new simulation tool is called the Zone Fire Model with HVAC components (ZFM-HVAC).

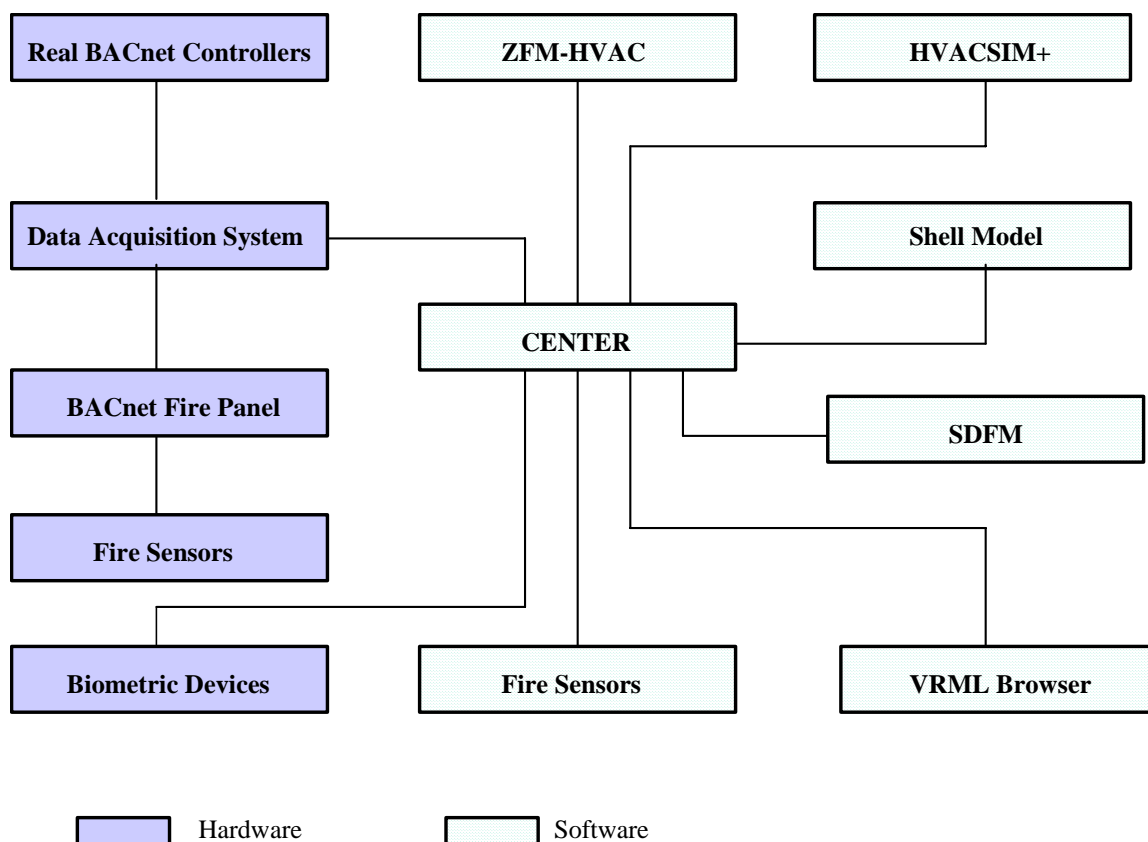
This report reviews the overall structure of the VCBT and describes the implementation of the ZFM-HVAC tool including results of emulation runs used to test its performance. Details of the ZFM components are published elsewhere [12]. Details of the HVAC components used in ZFM-HVAC will be described in this report.



## ***2. VCBT 2.0 ARCHITECTURE***

The architecture of the VCBT version 2.0 is shown schematically in Figure 1. The VCBT consists of a Center that provides an overall control and coordinating function of the other components, some of which are implemented in software and others are real building automation system devices. Simulated components include weather data, a simple building envelope model implemented using HVACSIM<sup>+</sup> called the Shell Model, a firefighter decision support tool called the Sensor-Driven Fire Model (SDFM), and a visualization tool that can depict the virtual building and its internal conditions implemented in Virtual Reality Modeling Language (VRML). Two options exist for simulating the building interior rooms and HVAC system. HVACSIM<sup>+</sup> is used if the research requires very detailed simulation of HVAC system components. ZFM-HVAC is used if the research requires investigating fires in the building. Fire detectors are represented by a combination of simulated output from detectors and actual fire detection hardware.

Physical components of the VCBT include a variety of BACnet HVAC controllers from several manufacturers, a BACnet fire alarm panel, and a biometric building access control system. The hardware components are linked to the software components through a commercial data acquisition system. Key simulated values are converted by the data acquisition system into voltage or current signals that are wired to the building automation system devices and appear as sensor inputs. Control actions are captured by the data acquisition system and converted to digital values that are fed into the next step of the simulation. Figure 2 is a photo of the VCBT hardware.



**Figure 1.** Components of the VCBT distributed simulation environment.

## 2.1 Center

The Center is the heart of the VCBT. It is a computer program residing in a personal computer that uses the Common Object Request Broker Architecture (CORBA) [13] to provide communications between the distributed components of the VCBT. CORBA is a vendor-independent, object-oriented architecture that provides a way to link computer programs across a network.

Using the graphical interface of the Center, configuration data are entered and output data from the simulations are displayed. The inputs and outputs from the building control system hardware are also monitored by the Center. The VCBT runs in real-time in a distributed, multi-platform environment. As seen in Figure 1, the Center communicates with the building management system hardware through the data acquisition system. Other components of the VCBT communicate directly with the Center using CORBA.

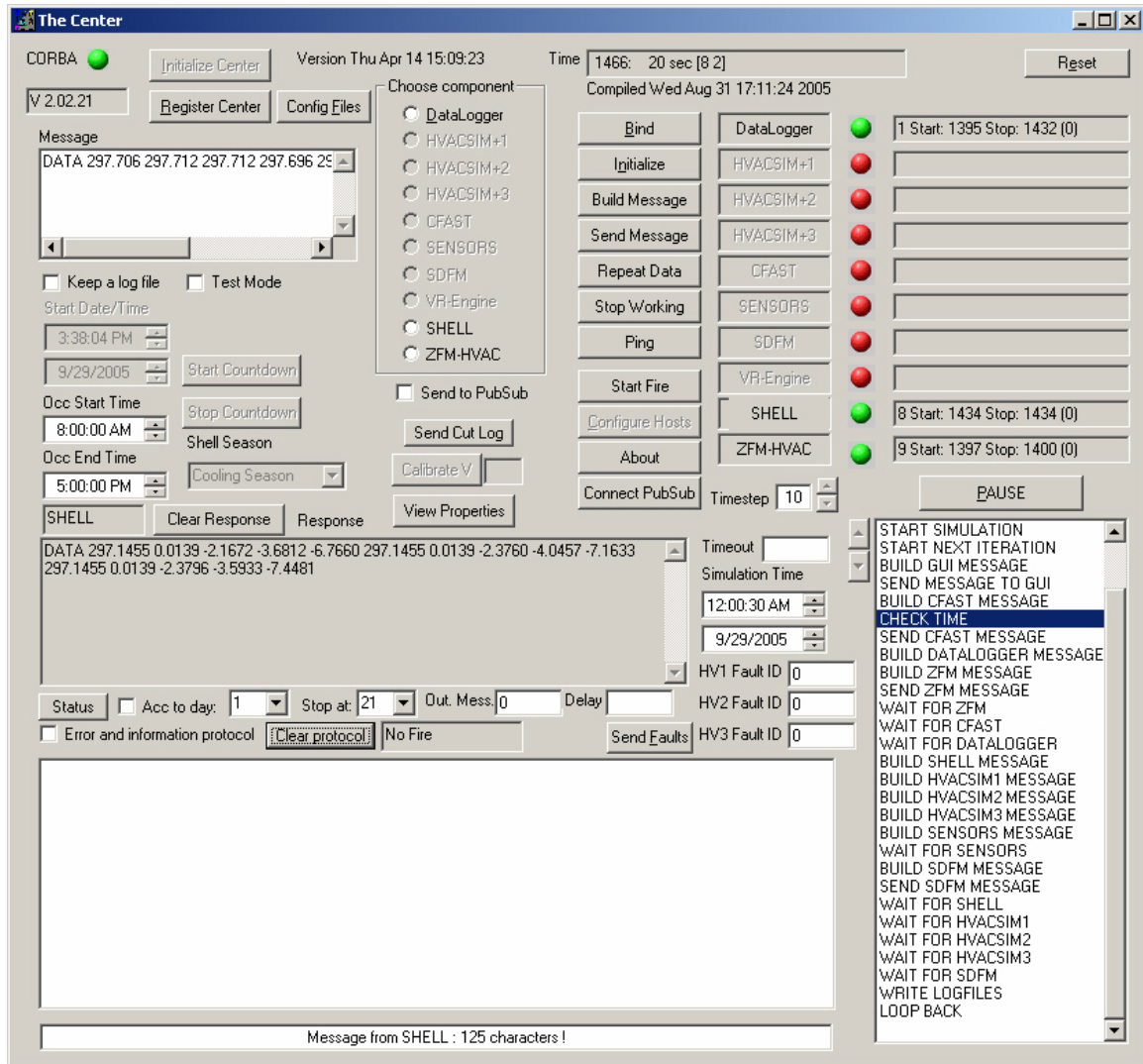


**Figure 2.** VCBT controller hardware, data acquisition system, fire-related devices including fire-panel, and biometric devices. Workstations for the VCBT controllers are not shown.

The Center controls the flow of data between all elements of the VCBT. It is also responsible for starting, initializing, and closing them. Individual components can be selected for use in a particular run of the VCBT, and the computer that these components will run on can be chosen at runtime. The Center runs on a 10 s cycle, during which data messages for each active component are created, transmitted, and any return messages evaluated. The amount of data currently being sent through the Center is only a fraction of its capability.

The Center is responsible for storing every piece of data that is transferred between the various components of the VCBT. This is done by first creating a list of the objects (i.e., a variable air volume (VAV) box or a room) which have properties (i.e., temperature, humidity, set points) associated with them. The properties of each object are then created, and linked to their parent objects. For each component of the VCBT, the subset of object and property combinations that the component uses is stored in a list associated with that

component. Separate lists are created for each component for data going to the component, and for data coming back from the component. The value of any property used in the VCBT can be viewed at the Center. Figure 3 is a screen image of the Center.



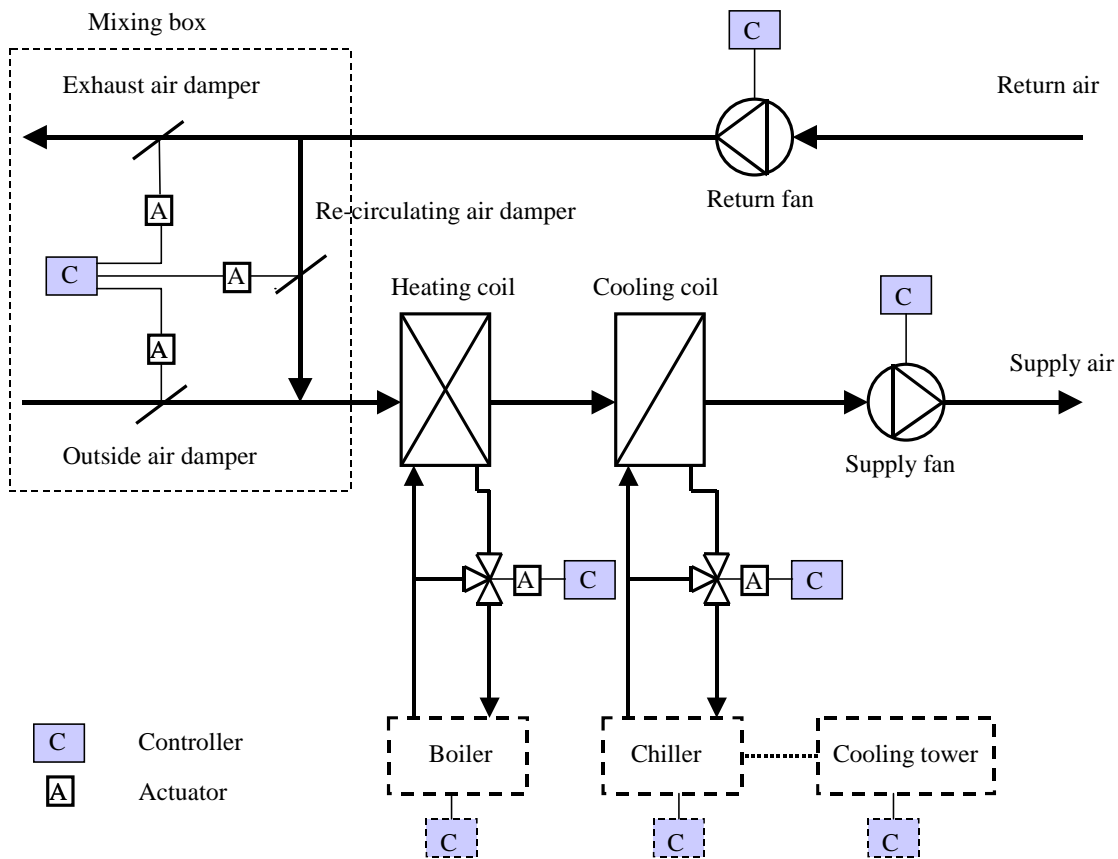
**Figure 3.** The Center Interface is used to link the components of a particular emulation and to control their interaction. In this example only the Datalogger, the ZFM-HVAC and the shell components are used.

## 2.2 HVACSIM<sup>+</sup>

HVACSIM<sup>+</sup> is a public domain computer simulation program developed by NIST for studying the dynamic interactions between building system components [8]. Most of the programs are written in Fortran 77. This program has been used extensively in the studies of fault detection and diagnostics (FDD) of building HVAC systems [9].

HVACSIM<sup>+</sup> links component type models together to build an HVAC system simulation. The component models used in the VCBT were originally developed during the course of ASHRAE Research Project 825 [14]. A typical virtual building simulation consists of the building zones (rooms), some single-duct Variable Air Volume (VAV) air-handling units, VAV terminal boxes, and the associated valves, coils, dampers, and sensors.

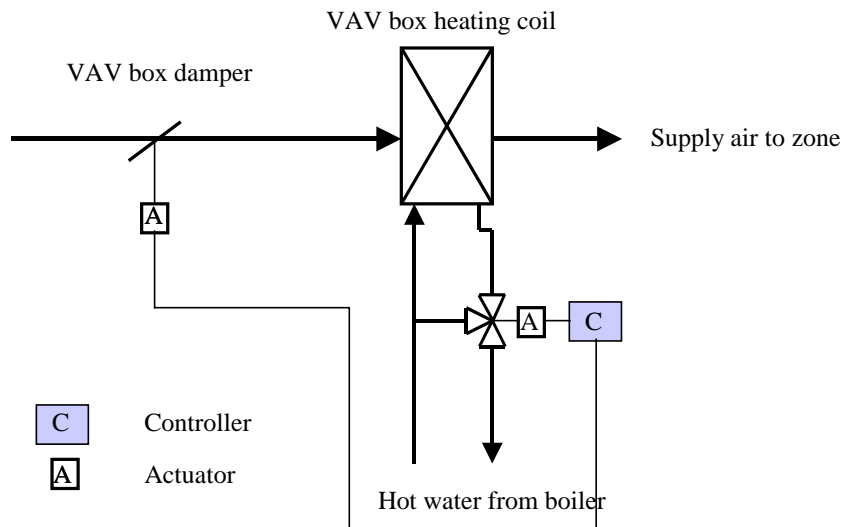
A schematic representation of a typical VCBT air-handling unit along with central plant facilities is shown in Figure 4. The figure illustrates the various dampers, valves, actuators, and fans that are to be controlled. The simulated sensor outputs that are to be used as inputs to the controllers for air-handling units are listed in Table 1. The component models of a central boiler, chiller, and cooling tower have not been utilized in the VCBT yet and are shown as dashed lines. Figure 5 is a schematic drawing of one of the single duct VAV boxes.



**Figure 4.** A schematic representation of a VCBT air-handling unit.

**Table 1.** Simulated sensor outputs for Air-handling unit control.

mixed air temperature
outdoor air relative humidity
outdoor air temperature
return air relative humidity
return air temperature
return air volumetric flow rate
supply air static pressure
supply air temperature
supply air volumetric flow rate



**Figure 5.** A schematic representation of the single duct VAV box.

### 2.3 Building Shell Model

The building shell model component of the VCBT is implemented using HVACSIM<sup>+</sup>. The building shell model simulates heat gain or loss through the building envelope surfaces (walls, ceilings, floors, doors, and windows) as a function of outside conditions such as air temperatures, solar intensities, and wind speeds. Conduction heat transfer functions are used for calculation of heat fluxes through composite multi-layered surfaces in which each layer material is assumed to have uniform properties [15]. By varying the input weather data, the climate effects due to building location can be observed.

Table 2 lists the variables associated with a typical building surface. The VCBT shell model has been enhanced to use ASHRAE WYEC2 hourly weather data [16]. The shell model assumes that weather conditions remain constant for 15-minute intervals. The 15-minute data are generated from the hourly values by interpolation. February, July, and October are selected as representatives of three weather patterns for heating, cooling, and swing seasons, respectively. Internal load variations and solar heat gains through windows and facades are not yet considered in the current ZFM-HVAC, but the temperature and humidity of outside air are accounted for.

**Table 2. Building Surface Variables.**

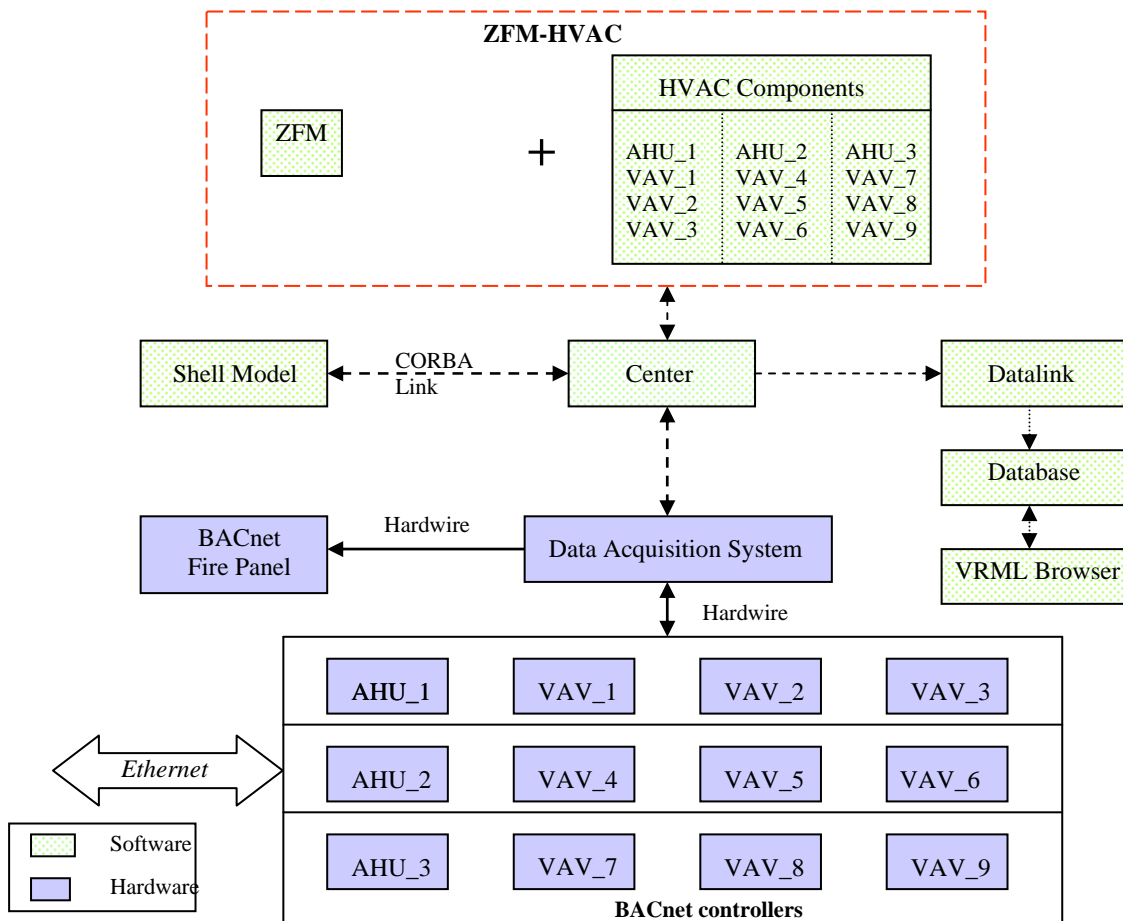
Variable	Description
<b>Inputs</b>	
TIA	Indoor air dry-bulb temperature
TMR	Mean radiant temperature
TOSINF	Outer surface temperature of unexposed wall
FAHADW	Shaded fraction of exposed surface
<b>Outputs</b>	
TIS	Inner surface temperature
SOLINT	Integrated solar influx on surface
<b>Parameters</b>	
IZN	Identification number of zone
ID	Identification number of surface
IEXPOS	Internal exposure 0 = within zone, 1= between zones, 2=exposed to sun
ISTR	Identification number of the construct
AS	Surface area
ORIENT	Azimuth angle of normal to surface & south
TILT	Tilt angle: flat roof=0°, floor=180°
GRF	Ground reflectivity
IROFS	Outer surface roughness index: 1=stucco, ...
ABSOS	Solar absorptance of outer surface
ABSIS	Short wave absorptance of inner surface
EMITIS	Emissivity of the inner surface
TRANSM	Transmittance of the glass window
SC	Shading coefficient of the glass window

## 2.4 Data Acquisition System

One of the computers used for the distributed simulation contains an interface card that communicates digitally with a commercial data acquisition system. This component is called the Datalogger in the system architecture. The simulated values that represent sensor inputs to the controllers are converted by the digital-to-analog converter of the data acquisition system into analog outputs represented by either DC voltages (0 to 5 V) or DC currents (4 to 20 ma). There is a capability to scale values to other ranges if needed. The output values of the BACnet controllers that represent inputs to the virtual building system component models are read by the digital voltmeter in conjunction with

multiplexing scanners. The output voltage range of each controller is in between 0 V and 10 V. Solid-state relay chips are employed for handling binary (digital) signals between a BACnet controller and the data acquisition system.

Figure 6 shows the relationship between the data acquisition system with other components of the VCBT. “Hardware” represents a pair of electrical wires. Other connections are digital communication using CORBA. After receiving data from the simulations, converting it into the analog values, and sending it to the controllers, the Datalogger waits 1 s, and then begins to read the controller outputs. The total cycle time is approximately 3 s to 4 s.



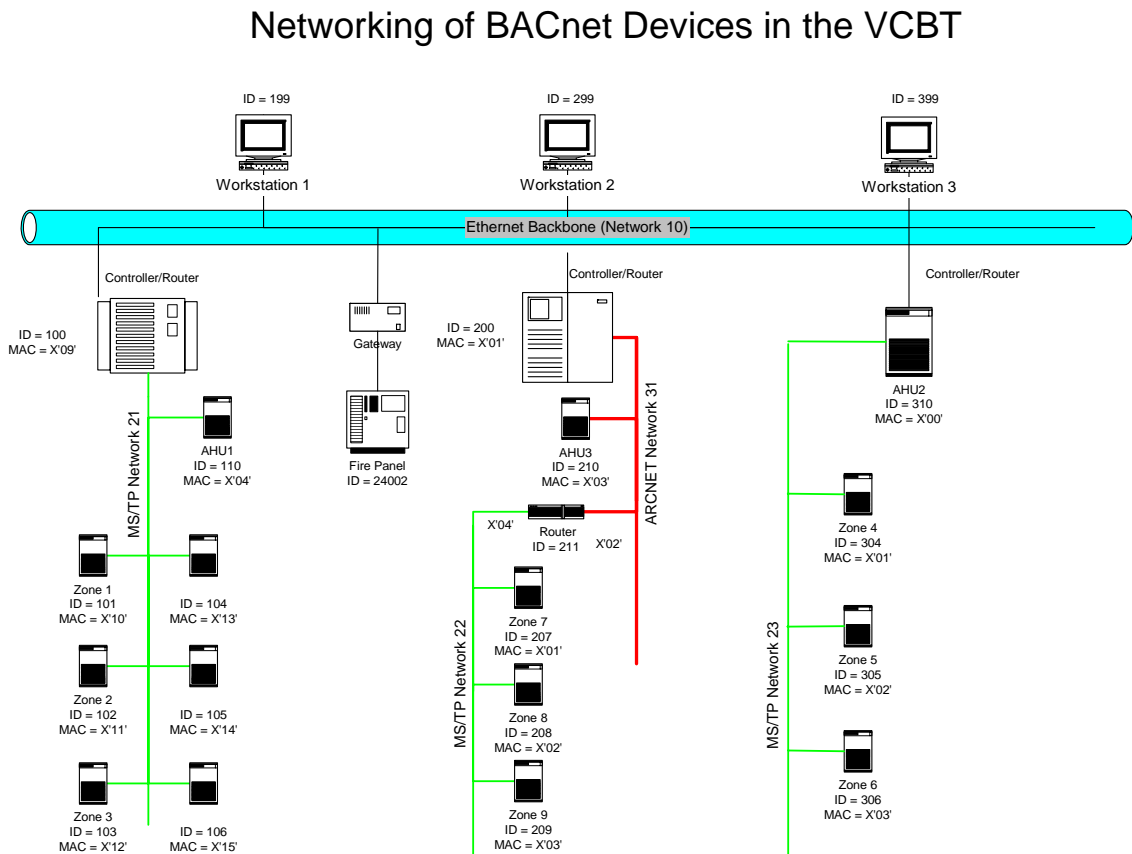
**Figure 6.** Relationship of the data acquisition system for ZFM-HVAC with other units.



## 2.5 Building System BACnet Controllers

Commercially available BACnet controllers make up the building automation and control system of the virtual building. The controller input and output connections are wired to a patch panels that provides connections to the emulator. Various BACnet communication networks [10, 11] connect the controllers to each other.

Figure 7 shows the network topology of the current BACnet system. For each local area network (LAN), the figure shows the type of network technology used and the BACnet network number. An Ethernet LAN serves as the backbone to the system. It connects three operator workstations and the supervisory controllers for the virtual building. These supervisory controllers provide scheduling capability, alarm processing, implementing reset schedules and also serve as routers to networks of unitary controllers. The unitary controllers reside on ARCNET or MS/TP LANs.



**Figure 7.** Network topology of the BACnet building automation and control system.

Products from three different control companies are used for HVAC controls. It is possible to monitor essential input and output values of all products from controller workstations using BACnet.

Air-handling unit (AHU) controllers in the virtual building provide supply fan control, return fan control, supply air temperature control, enthalpy economizer control, and supply air temperature reset. Appendix A provides an example BACnet object database for the controller for AHU 1. AI, AO, AV, BI, BO, and BV denote analog input, analog output, analog value, binary (digital) input, binary output, and binary value objects respectively. There is some variation in the BACnet object databases and control implementation details of the BACnet components. These differences reflect the fact that product features vary from manufacturer to manufacturer. The ranges of sensors and analog values in Appendix A correspond to design assumptions about the building equipment operating conditions. These can be varied by AHU or by zone.

Control of VAV boxes in the virtual building involves damper and reheat valve controls. The damper is controlled to modulate supply airflow to a zone, while the reheat valve coupled with the reheat coil enables the temperature of air supplied to the zone to be increased. Appendix B provides an example BACnet object database for a sample VAV box controller.

Appendices A and B illustrate the kind of detailed information that is available through a BACnet interface to the VCBT. They also provide the object identifier details needed to access the data using BACnet messages and the scaling details of the connection to the data acquisition system. Proportional-integral control is used for most local loops.

Some AHU and VAV box control strategies implemented in controllers are briefly described below.

### Supply Fan Control

A typical, pressure-independent VAV system maintains a constant pressure at the VAV box inlets by sensing and controlling the static pressure at the supply duct. The supply fan controller with a proportional-integral (PI) algorithm receives the static pressure sensor output and sends the control output to a variable frequency motor controller to vary the supply fan speed.

The PI control is a feedback control to minimize the error signal  $e(t)$ .

$$e(t) = SP - MV(t)$$

where  $SP$  = set point

$MV(t)$  = measured value

$t$  = time

A popular PI algorithm is expressed [17] as:

$$u(t) = u_0 + K_c \left[ e(t) + \frac{1}{\tau_I} \int_0^t e(t^*) dt^* \right]$$

where  $u(t)$  = controller output

$u_0$  = bias value

$K_c$  = proportional gain

$\tau_I$  = integral time or reset time

$t^*$  = dummy variable of integration

### Return Fan Control

The airflow rates of the supply and the return systems are measured at the airflow stations. The return fan speed is controlled to maintain a constant flow rate difference between the supply airflow rate and the return airflow rate. A PI algorithm is employed.

### Supply Air Temperature Control

The supply air temperature controller receives the sensor output from the supply air temperature sensor, and determines the appropriate positions of the cooling coil valve, heating coil valve, and mixing box dampers. It is assumed that outside air, exhaust air, and re-circulating air dampers are linked together to be controlled by a single controller output signal. Whenever the supply fan is on, the cooling and heating coil valves operate in conjunction with mixing box air dampers to maintain the set point value of supply air temperature. A PI controller is used.

### Enthalpy Economizer Control

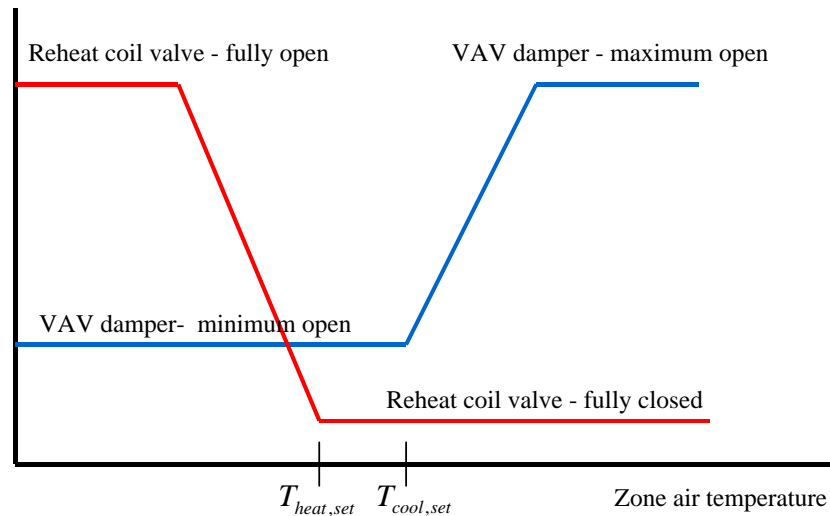
The sensor outputs from the outside air temperature, outside air relative humidity, return air temperature, and return air relative humidity sensors allow the enthalpy economizer controller to determine the damper openings. When the outside air enthalpy is greater than the return air enthalpy, the outside air damper is closed to its minimum position, and the cooling coil provides the required cooling. When the outside air enthalpy is less than the return air enthalpy and the outside air temperature is greater than the supply air temperature, the outside air damper is fully open, and the cooling coil supplements the required cooling.

### Supply Air Temperature Reset

Based upon data from individual zone VAV boxes, the set point for supply air temperature can be reset to satisfy the maximum cooling demand required each zone during cooling season.

### VAV terminal box controller

The airflow rate of a VAV terminal unit is governed by the damper opening. The reheat coil provides heating. The amount of heat is determined by the reheat coil valve opening. Typically the VAV terminal box controller controls the VAV box with a reheat coil in the way as shown in Figure 8. The zone temperature,  $T_z$ , is to be maintained near the set points ( $T_{cool,set}$  for cooling and  $T_{heat,set}$  for heating).



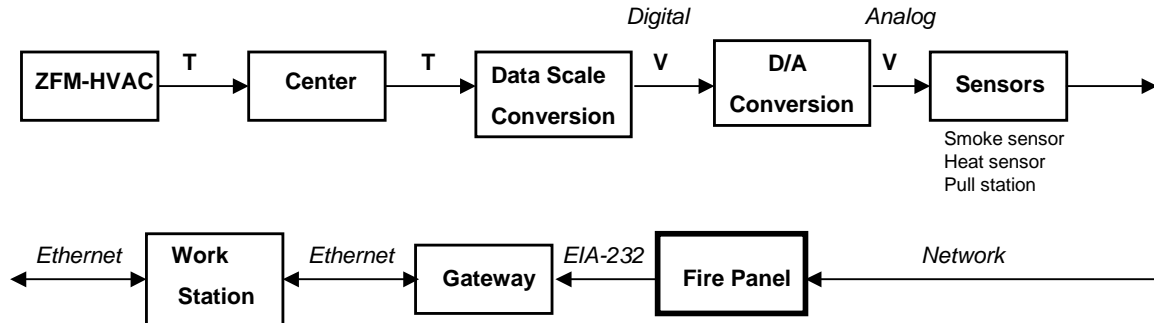
**Figure 8.** VAV box control

- When  $T_z \geq T_{cool,set}$ , the damper opening modulates linearly until the maximum opening is reached.
- When  $T_z < T_{cool,set}$ , the damper opening is at the minimum.
- When  $T_z \geq T_{heat,set}$ , the reheat coil valve is fully closed.
- When  $T_z < T_{heat,set}$ , the reheat coil valve modulates linearly until the maximum opening is reached.

## 2.6 BACnet Fire Panel

The old BACnet fire panel has been replaced with a new advanced fire panel. The previous fire panel could monitor addressable smoke detectors that were triggered by

on/off operation. The new product can obtain analog values in voltage from addressable smoke detectors and heat sensors. First responders can monitor the information in the fire panel remotely using BACnet via Ethernet. In the virtual cybernetic building emulation, zone temperatures and zone smoke concentrations are generated by ZFM-HVAC, transmitted to the data acquisition system, converted into analog data in voltage, sent to sensors, and sent to the BACnet fire panel as shown in Figure 9 where T and V denote the temperature and the voltage, respectively. When a zone/zones condition is in an alarm state due to fire, the fire panel provides alarms.



**Figure 9.** BACnet fire panel and ZFM-HVAC

## 2.7 Biometric Devices for Security

Biometric devices for eye recognition and hand recognition as security measures for door entry have been added to the VCBT [18]. All implemented devices are fully compatible with the BACnet protocol.

## 2.8 Sensor-Driven Fire Model (SDFM)

The sensor-driven fire is described elsewhere [12].

## 3. ZFM-HVAC

In the previous version of the VCBT, fire simulation was performed using the Consolidated Model of Fire Growth and Smoke Transport (CFAST) [19], and building HVAC system simulation was done using the HVACSIM<sup>+</sup> program separately. Communication between CFAST and HVACSIM<sup>+</sup> was accomplished by exchanging data through the Center using CORBA. CFAST and HVACSIM<sup>+</sup> had their own independent equation solving routines.

The new program called ZFM-HVAC is a computer program that combines a newly developed zone fire model, ZFM, and the building HVAC components based on HVACSIM<sup>+</sup>.

The primary purpose of developing the combination program, ZFM-HVAC, is to organize all the computations under a single solver to ensure convergence to the proper solution. This consolidation will also aid in making the simulation expandable to large buildings.

### **3.1 Zone Fire Model (ZFM)**

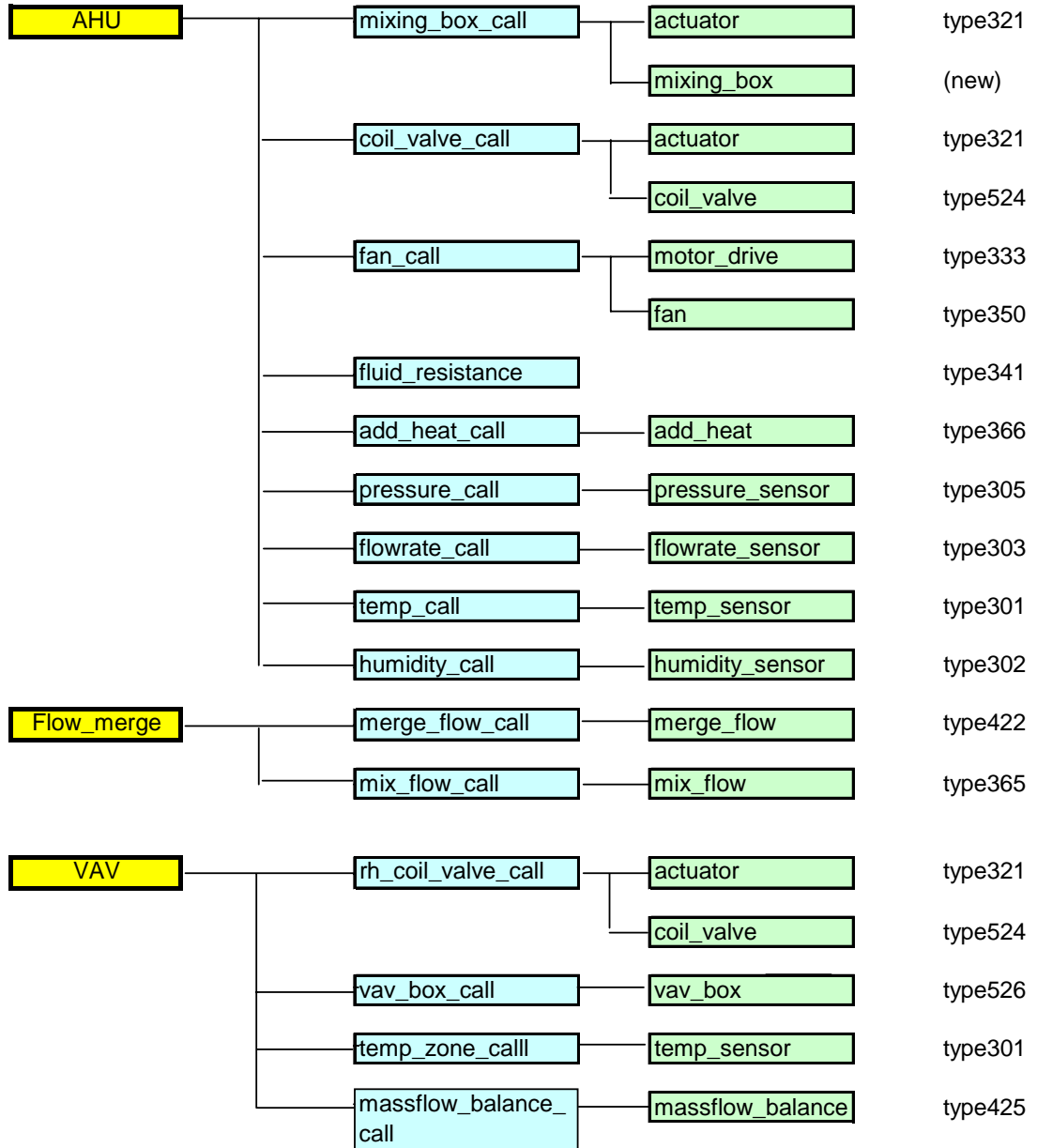
The zone fire model is described elsewhere. An early version can be found in reference [12].

### **3.2 HVAC Components from HVACSIM<sup>+</sup>**

A building HVAC system delivers conditioned air to building zones. The virtual HVAC system determines pressures, flow rates, temperatures and humidity values, while the controllers provide control signals. As mentioned previously, HVACSIM<sup>+</sup> solves a system of non-linear equations simultaneously; however HVAC-side equations of the ZFM-HVAC are solved sequentially. This sequential solving method was chosen, because there are many variables to be solved in the HVAC-side. The ZFM-side equation solver solves simultaneously only for zone/room-related variables such as layer temperature, pressure, density, and combustion product concentrations. Fire is modeled as a two-layer environment with a hot upper smoke layer and a cool lower layer. The time scale for these zone/room variables to change is short compared to the response of an HVAC system. The variables determined by HVAC-side are treated as pseudo-steady state variables due to the fact that most HVAC motor-driven actuators respond very slowly to control signals and final element components such as coils, and dampers are connected to the motor-driven actuators.

Most component models used in the HVAC-side of ZFM-HVAC originated from ASHRAE 825-RP by Norford and Haves [14] as “TYPE” routines. Brief descriptions of the models will be made based upon the report and the computer source code. Figure 10 shows a number of routines involved in the HVAC-side of ZFM-HVAC. Slightly modified HVAC component models of HVACSIM<sup>+</sup> are used except that the mixing box component model is greatly simplified and smoke mixing is added. The routine for merge flow (Type422) was also modified to add smoke mixing. Completely new routines for determining calculation sequences were developed solely for ZFM-HVAC using Fortran 90. At present, input data structures similar to HVACSIM<sup>+</sup> are used. The equations that are valid within their operating limits are presented below. Beyond the limits, the equations may not be valid. Special treatments are provided in the computer code for the equations in invalid regions.

## Relationship of HVAC-Side Subprograms



**Figure 10.** Routines involved in the HVAC-side of ZFM-HVAC.

### 3.2.1 Actuator (Type321)

The motor-driven actuator model calculates the position of a constant speed, motor-driven actuator accounting for hysteresis, crank geometry and range mismatch. Detailed description can be found in reference [14].

At each time step, the dimensionless actuator drive shaft position,  $\theta(t)$ , moves to next position according to the demand position,  $\theta_D(t)$ , and the state of movement of the motor. The possible states of the motor are backward motion ( $\delta = -1$ ), stationary ( $\delta = 0$ ), or forward motion ( $\delta = +1$ ).

The maximum change of position during one time step,  $\Delta\theta_{\max}$ , is:

$$\Delta\theta_{\max} = \frac{\Delta t}{\tau_f}$$

where  $\Delta t$  is the duration of time step, and  $\tau_f$  is the time required for the actuator to travel its full range from  $\theta = 0$  to  $\theta = 1$ .

Three cases can be considered:

If the actuator motor was stationary at the previous time step ( $\delta(t-1) = 0$ ), the new position remains at the previous position ( $\theta(t) = \theta(t-1)$ ) and no movement occurs ( $\delta(t) = 0$ ).

If the actuator motor was moving either forward or backward ( $\delta(t-1) = +1$  or  $\delta(t-1) = -1$ ), and  $|\theta_D(t-1) - \theta(t-1)| \leq \Delta\theta_{\max}$ , the actuator moves to new position as demanded at the previous time step ( $\theta(t) = \theta_D(t-1)$ ) and the actuator motor stops ( $\delta(t) = 0$ ), if the demand position is attained.

If the actuator motor was moving ( $\delta(t-1) = \pm 1$ ), but it could not reach the demanded position during the current time step ( $|\theta_D(t-1) - \theta(t-1)| > \Delta\theta_{\max}$ ), the motor continues to move by  $\Delta\theta_{\max}$ . The new position is

$$\begin{aligned} \theta(t) &= \theta(t-1) + \Delta\theta_{\max}, \text{ if } \theta_D(t-1) \geq \theta(t-1) \\ \theta(t) &= \theta(t-1) - \Delta\theta_{\max}, \text{ if } \theta_D(t-1) < \theta(t-1) \end{aligned}$$

The motor moving direction at the end of previous time,  $\delta_e(t-1)$ , becomes

$$\delta_e(t-1) = 1, \text{ if } \theta_D(t-1) \geq \theta(t-1)$$



$$\delta_e(t-1) = -1, \text{ if } \theta_D(t-1) < \theta(t-1)$$

The new motor moving direction at the current time,  $\delta(t)$ , is determined considering whether the motor was moving in the direction required to reduce the position error at the end of the previous time step. If the motor was in the desired state at the end of the previous time step, no change of state is made ( $\delta(t) = \delta_e(t-1)$ ).

The rotational motion of a motor-driven actuator matches the rotation motion of a damper, but most of valves need translational motion of the valve stem either by means of a screw thread or by a crank. When a valve is driven by a screw, the relationship between the dimensionless rotation position,  $\theta(t)$ , and the dimensionless translational position,  $y(t)$ , is linear. Thus, simply

$$y(t) = \theta(t)$$

However, if a crank on the drive shaft is used, non-linearity needs to be considered. Figure 11 illustrates a motor-driven actuator with a crank on it along with a flow valve and a linkage. The length of the crank,  $R$ , the angular range of the crank,  $\alpha$ , the total vertical displacement due to the cranking,  $Y$ , and the length of linkage,  $L$ , are given. The vertical displacement of the crank,  $\tilde{y}$ , corresponding to the angular position,  $\tilde{\theta}$ , is determined ignoring any bending of the linkage under the assumption that  $L \gg R$ .

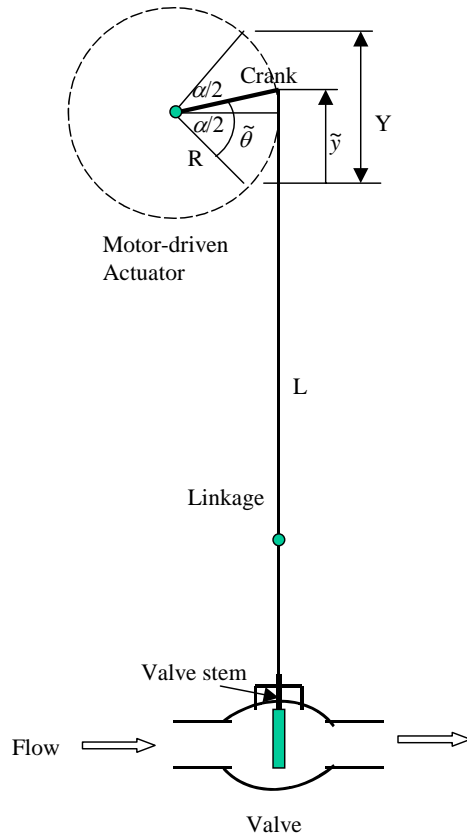
From the figure,

$$Y = 2R \sin(\alpha/2)$$

$$\tilde{y} = R \sin(\alpha/2) + R \sin(\tilde{\theta} - \alpha/2)$$

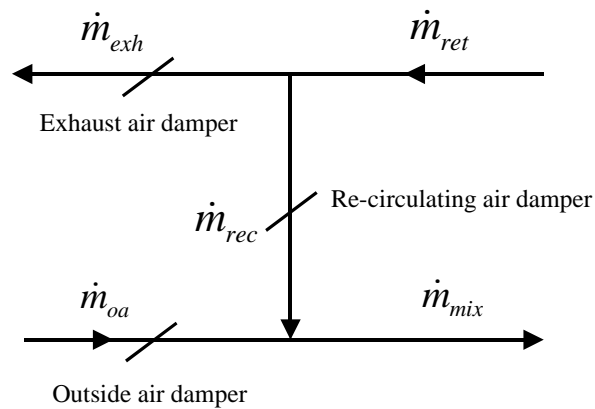
Defining  $\theta = \frac{\tilde{\theta}}{\alpha}$  and  $y = \frac{\tilde{y}}{Y}$ , the relationship of  $\theta(t)$  and  $y(t)$  is determined.

$$y(t) = \frac{1}{2} + \frac{\sin(\alpha(\theta(t) - 1/2))}{2 \sin(\alpha/2)}$$



**Figure 11.** A crank of motor-driven actuator, a linkage, and a flow valve.

### 3.2.2 Mixing box



**Figure 12.** An air-handling unit mixing box

The mixing box of an air-handling unit consists of an outdoor damper, an exhaust damper, and a re-circulating damper as shown in Figure 4. Only one damper actuator is employed to control three dampers in responding to the PI control signal from the BMS

While the exhaust and outside air dampers are closing/opening in phase, the re-circulating damper is opening/closing.

This mixing box model used in ZFM-HVAC is a simplified model that differs from the model used in HVACSIM<sup>+</sup>.

The return (or extracted) air mass flow rate,  $\dot{m}_{ret}$ , is assumed to be

$$\dot{m}_{ret} = (1 - \beta)\dot{m}_{mix}$$

where

$\dot{m}_{mix}$  = mixed air mass flow rate from the mixing box

$\beta$  = fractional factor of air flow leakage in the air delivery system

Then the exhaust air mass flow rate,  $\dot{m}_{exh}$ , and the mixed air mass flow rate are expressed by

$$\begin{aligned}\dot{m}_{exh} &= \dot{m}_{ret} - \dot{m}_{rec} \\ \dot{m}_{mix} &= \dot{m}_{oa} + \dot{m}_{rec}\end{aligned}$$

where the subscriptions *rec* and *oa* represent re-circulation and outside, respectively.

Assuming that the outside air mass flow rate is proportional to the outside air damper fractional opening,  $\alpha$ ,

$$\begin{aligned}\dot{m}_{oa} &= \alpha\dot{m}_{mix} \\ \dot{m}_{exh} &= (\alpha - \beta)\dot{m}_{mix}\end{aligned}$$

The mixed air temperature,  $T_{mix}$ , becomes

$$T_{mix} = \frac{c_{p,oa}\dot{m}_{oa}T_{oa} + c_{p,rec}\dot{m}_{rec}T_{rec}}{c_{p,mix}(\dot{m}_{oa} + \dot{m}_{rec})}$$

where  $c_p$  is moist air specific heat.

The smoke concentration in the mixed air flow,  $C_{mix}$ , can be computed in terms of the smoke concentration of the return air flow,  $C_{ret}$ , since the outside air is smoke-free.

$$C_{mix} = C_{ret}(1 - \alpha)$$

### 3.2.3 Temperature Sensor (Type301)

Temperature sensor is modeled by a first-order differential equation with a single time constant,  $\tau_t$ .

The sensor output signal,  $c_o$ , is give in terms of modified temperature input,  $c_i$ .

$$c_i = \frac{T_i - T_{offset}}{G_t}$$

$$\tau_t \frac{dc_o}{dt} + c_o = c_i$$

where

$T_i$  = temperature input

$T_{offset}$  = offset for the minimum allowable temperature

$G_t$  = temperature sensor gain

The differential equation is solved analytically at each time step,  $\Delta t$ .

$$c_o(t) = [c_o(t-1) - c_i]e^{-\Delta t/\tau} + c_i$$

The output sensor signal is bound between the maximum and minimum values. For each air-handling unit, there are four temperature sensors for the supply air, return air, mixed air, and outside air temperatures. These sensor outputs are inputs to the air-handling unit controller. One temperature sensor is also used in the return air duct of each zone to provide the input signal to the VAV controller for the zone.

### 3.2.4 Humidity Sensor (Type302)

Humidity sensor is modeled by a first-order differential equation similar to the temperature sensor model.

The sensor output signal,  $x_o$ , is give in terms of modified humidity input,  $x_i$ .

$$x_i = \frac{h_i - h_{offset}}{G_h}$$

$$\tau_h \frac{dx_o}{dt} + x_o = x_i$$

where

$h_i$  = humidity ratio

$h_{offset}$  = offset

$G_h$  = humidity sensor gain  
 $\tau_h$  = humidity sensor time constant

There are two humidity sensors for the return air and outside air for each air-handling unit.

### 3.2.5 Flow rate Sensor (Type303)

A first-order differential equation is used to model the flow rate sensor. The sensor output signal,  $F_o$ , is give in terms of modified flow rate input,  $F_i$ .

$$F_i = \frac{\dot{m}_i - \dot{m}_{offset}}{G_m}$$

$$\tau_m \frac{dF_o}{dt} + F_o = F_i$$

where

$\dot{m}_i$  = mass flow rate input  
 $\dot{m}_{offset}$  = offset  
 $G_m$  = flow rate sensor gain  
 $\tau_m$  = flow rate sensor time constant

There are two flow rate sensors for the supply air and return air for each air-handling unit.

### 3.2.6 Static pressure Sensor (Type305)

The static pressure sensor output signal,  $P_o$ , is give in terms of modified static pressure input,  $P_i$ .

$$P_i = \frac{p_i - P_{offset}}{G_p}$$

$$\tau_p \frac{dP_o}{dt} + P_o = P_i$$

where

$p_i$  = static pressure input  
 $P_{offset}$  = offset  
 $G_p$  = pressure sensor gain

$\tau_p$  = pressure sensor time constant

Only one static pressure sensor for the supply air is employed for each air-handling unit.

### 3.2.7 Motor drive (Type333)

The motor drive receives a demanded fractional speed signal,  $\omega_d$ , from the BMS to determine the actual rotational speed,  $\Omega_a$ , of an ideal motor of a fan. Motor dynamics, drive hysteresis, and non-linearity are neglected. Power consumption or efficiency is not considered.

The actual fractional speed,  $\omega_a(t)$ , is determined depending on the difference between current fractional demanded speed,  $\omega_d(t)$ , and previous actual fractional speed,  $\omega_a(t-1)$ .

$$\omega_a(t) = \omega_a(t-1) + \Delta\omega_{\max}, \text{ if } \omega_d(t) \geq \omega_a(t-1)$$

$$\omega_a(t) = \omega_a(t-1) - \Delta\omega_{\max}, \text{ if } \omega_d(t) < \omega_a(t-1)$$

where  $\Delta\omega_{\max}$  is the maximum change in fractional speed in one time step given by

$$\Delta\omega_{\max} = \frac{\Delta t}{T_{\text{trav}}}$$

The travel time,  $T_{\text{trav}}$ , is the time required for the motor drive to travel from lower to upper limit.

With a given maximum rotational speed,  $\Omega_{\max}$ , the actual rotational speed is determined.

$$\Omega_a(t) = \omega_a(t)\Omega_{\max}$$

At each air-handling unit, two motor drives are connected to the supply fan and the return fan, respectively.

### 3.2.8 Fan (Type350)

The fan model calculates a pressure rise,  $\Delta p$ , in terms of the dimensionless flow,  $C_f$ , defined by

$$C_f = \frac{\dot{m}}{\rho\Omega D^3}$$

where

$\dot{m}$  = mass flow rate  
 $\rho$  = density of air  
 $\Omega$  = rotational speed  
 $D$  = diameter of fan blade

The dimensionless pressure head function,  $f_h$ , is obtained from dimensionless fan performance curves, and can be represented by the 4<sup>th</sup> order polynomials.

$$f_h(C_f) = a_0 + a_1C_f + a_2C_f^2 + a_3C_f^3 + a_4C_f^4$$

Coefficients,  $a_i$ , are determined empirically. In the valid region of the performance curves, the pressure rise is expressed by

$$\Delta p = 0.001\rho \Omega^2 D^2 f_h$$

Fan efficiency,  $\eta$ , is also represented by the 4<sup>th</sup> order polynomial equation as

$$\eta = e_0 + e_1C_f + e_2C_f^2 + e_3C_f^3 + e_4C_f^4$$

Coefficients,  $e_i$ , are empirically determined. Within the range of validity of the efficiency polynomial, fan power consumption,  $E_{fan}$ , is determined.

$$E_{fan} = \frac{\dot{m}\Delta p}{\rho\eta}$$

### 3.2.9 VAV Box (Type526)

A typical VAV box with a reheat coil is shown in Figure 5. This VAV box model represents a pressure-independent VAV terminal box. The reheat coil is excluded here, but the actuator is included. Only the zone supply airflow rate variation due to the VAV damper opening is considered. A VAV terminal box controller sends a signal of demand flow rate to a VAV box. In responding to the signal, the VAV damper opening varies.

For a given size of VAV box as nominal volumetric flow rate,  $V_{nom}$ , fractional demand speed of actuator motor,  $\omega_d$ , is determined.

$$\omega_d = K_p(V_d - V_m), \quad \omega_{d,\min} \leq \omega_d \leq 1.0$$

where

$K_p$  = proportional gain

$V_d$  = fractional demand volumetric flow rate

$\omega_{d,\min}$  = minimum fractional speed of motor

The measured fractional volumetric flow rate at the previous time step,  $V_m(t-1)$ , is

$$V_m(t-1) = \frac{\dot{m}(t-1)}{\rho V_{nom}}$$

Taking the average fractional demand speed during the time step,  $\bar{\omega}_d$ , new angular position of the actuator,  $\theta(t)$ , is

$$\theta(t) = \theta(t-1) + \bar{\omega}_d \frac{\Delta t}{T_{trav}}, \quad 0 \leq \theta(t) \leq 90^\circ$$

The travel time,  $T_{trav}$ , is the time required for the motor drive to travel from  $0^\circ$  to  $90^\circ$ . In turbulent flow, the mass flow rate through the VAV box is given in terms of the pressure drop,  $\Delta p$ , and the total flow resistance,  $r_{tot}$ .

$$\dot{m}(t) = \sqrt{\frac{\Delta p}{r_{tot}}}$$

The total resistance is a sum of fixed system resistance,  $r_{fix}$ , and damper position-dependent resistance,  $r_\theta$ .

$$r_{fix} = \frac{\Delta p_{open}}{\rho^2 V_{nom}^2} - \frac{0.001 k_{open}}{2 \rho A_f^2}$$

where

$\Delta p_{open}$  = pressure drop at normal flow with fully open damper

$k_{open}$  = loss coefficient of fully open damper

$A_f$  = face area of damper

Legg's correlation is used to calculate the damper position-dependent resistance.

$$\ln(k_\theta) = \alpha + \beta \theta(t), \quad 15^\circ < \theta < 55^\circ \text{ for opposed blade damper}$$

$$15^\circ < \theta < 65^\circ \text{ for parallel blade damper}$$

$\alpha$  and  $\beta$  are empirically determined constants. Using damper loss coefficient,  $k_\theta$ , the damper resistance is represented as

$$r_\theta = \frac{e^{k_\theta}}{C}$$



where C is the conversion factor.

### 3.2.10 Fluid Resistance (Type341)

The flow resistance model is based on a square law relationship at high flow rates and a linear relationship at low flow rates. This routine calculates the inlet pressure,  $p_i$ , for given outlet pressure,  $p_o$ , mass flow rate,  $\dot{m}$ , and flow resistance,  $r$ .

$$\begin{aligned} p_i &= p_o + r\dot{m}|\dot{m}| && \text{in turbulent flow} \\ p_i &= p_o + r\dot{m}_{crit}\dot{m} && \text{in laminar flow} \end{aligned}$$

where  $\dot{m}_{crit}$  is the critical mass flow rate, which is the lower limit of purely quadratic flow.

### 3.2.11 Add Heat (Type366)

The outlet temperature of a fan or a duct,  $T_o$ , is calculated by adding the temperature rise,  $\Delta T$ , due to added heat and the inlet temperature,  $T_i$ .  $\Delta T$  is obtained analytically from

$$\tau_h \frac{d\Delta T}{dt} + \Delta T = \frac{\dot{Q}_{add}}{c_p \dot{m}}$$

where

$$\begin{aligned} \dot{Q}_{add} &= \text{rate of heat addition} \\ \tau_h &= \text{time constant} \\ c_p &= \text{specific heat of dry air} \end{aligned}$$

### 3.2.12 Merge Flow (Type422)

The outlet mass flow rate is the sum of the two inlet mass flow rates.

$$\dot{m}_o = \dot{m}_{i,1} + \dot{m}_{i,2}$$

The outlet smoke concentration,  $C_o$ , is calculated in a simple way.

$$C_o = \frac{C_{i,1}\dot{m}_{i,1} + C_{i,2}\dot{m}_{i,2}}{\dot{m}_o}$$

### 3.2.13 Mix Flow (Type365)

When multiple moist air flow streams merge, the outlet mixed air temperature,  $T_{mix}$  and the humidity ratio,  $h_{mix}$ , are obtained from

$$h_{mix} = \frac{\sum h_i \dot{m}_i}{\sum \dot{m}_i}, \quad (i = 1, n)$$

$$T_{mix} = \frac{\sum \dot{m}_i T_i (c_{pa} + c_{pg} h_i)}{(\sum \dot{m}_i)(c_{pa} + c_{pg} h_{mix})}, \quad (i = 1, n)$$

where  $c_{pa}$  and  $c_{pg}$  are the specific heat of dry air and the specific heat of water vapor. Only two flow streams are used for ZFM-HVAC.

### 3.2.14 Mass Flow Balance (Type425)

An assumption is made in ZFM-HVAC that no air leaks to outside from a zone, and the outlet mass flow rate from a zone,  $\dot{m}_{outlet}$ , is the same as the inlet mass flow rate,  $\dot{m}_{inlet}$ .

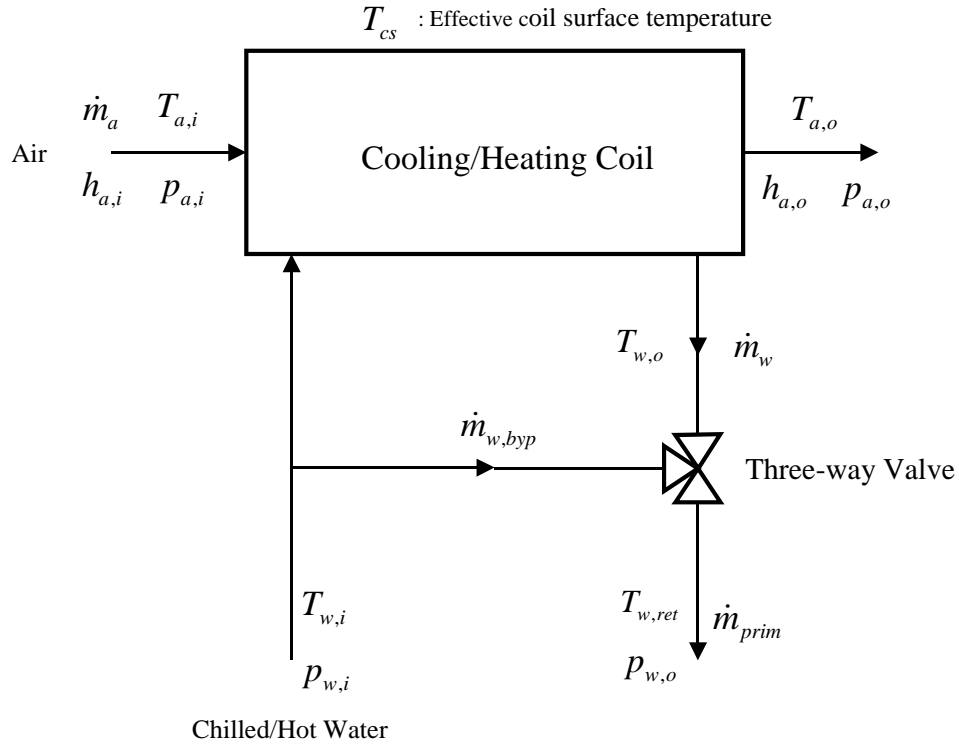
$$\dot{m}_{outlet} = \dot{m}_{inlet}$$

### 3.2.15 Coil & Valve (Type524)

The combined model of heating/cooling coil and its three-way control valve is the most complex routine among the component models used in HVACSIM<sup>+</sup>. The temperature and humidity of the airflow through heating or cooling coil are governed by the three-way coil valve, which is connected to a coil valve actuator. The actuator operates in responding to the control signal from the BMS.

The coil model used is a finned-tube cross-flow heat-exchanger with both fluids unmixed. When the working fluid is chilled water, the coil acts as a cooling coil, whereas when the working fluid is hot water, the coil is a heating coil. On the air-side of the heat-exchanger, the inlet air dry bulb temperature,  $T_{a,i}$ , inlet air humidity ratio,  $h_{a,i}$ , and dry air mass flow rate,  $\dot{m}_a$ , are given. On the water-side of the heat-exchanger, the inlet water Temperature,  $T_{w,i}$ , inlet water pressure,  $p_{w,i}$ , and outlet water pressure,  $p_{w,o}$ , are given. With these input conditions, the outlet air dry bulb temperature,  $T_{a,o}$ , outlet air humidity ratio,  $h_{a,o}$ , outlet water temperature,  $T_{w,o}$ , primary circuit water mass flow rate,  $\dot{m}_{w,prim}$ , water mass flow rate through the coil,  $\dot{m}_w$ , and mixed return water temperature,  $T_{w,ret}$ , are determined. Using the outlet air pressure,  $p_{a,o}$ , the inlet air pressure,  $p_{a,i}$ , is also calculated. Figure 13 is a schematic diagram of the coil with external water circuits.

The equations in a general case are presented, not exactly following the calculation logic flow of the routine.



**Figure 13.** The cooling/heating coil and three-way valve.

**Outlet air dry bulb temperature of a dry coil ( $T_{a,o}$ )**

$$T_{a,o} = T_{a,i} + \frac{\dot{Q}_{a,dry}}{c_{pa}\dot{m}_a}$$

where

$c_{pa}$  = specific heat of dry air

$\dot{Q}_{a,dry}$  = air-side heat transfer of a dry coil

$$\dot{Q}_{a,dry} = (T_{cs} - T_{a,i})C_a(1 - B_f)$$

$T_{c,s}$  = effective coil surface temperature

$C_a$  = air capacity rate =  $(c_{pa} + c_{pg} h_{a,i}) \dot{m}_a$

$c_{pg}$  = water vapor specific heat

$B_f$  = coil by-pass factor

### **Effective coil surface temperature ( $T_{cs}$ )**

The effective coil surface temperature is obtained by solving the first-order differential equation.

$$\frac{dT_{cs}}{dt} = \alpha T_{cs} + \beta$$

where

$$\alpha = \frac{r_1 + r_2}{r_1 r_2 HC_{coil}}$$

$$\beta = \frac{1}{HC_{coil}} \left( \frac{T_{a,i}}{r_1} + \frac{T_{w,i}}{r_2} \right)$$

$HC_{coil}$  = heat capacity of coil =  $HC_{fin} + HC_{tube} + HC_{water}$

$$r_1 = \frac{1}{C_a(1 - B_f)}$$

$$r_2 = \frac{1}{\varepsilon_{HX} C_{min}}$$

$C_{min}$  = minimum heat capacity rate

$\varepsilon_{HX}$  = heat-exchanger effectiveness

### **Coil by-pass factor ( $B_f$ )**

$$B_f = e^{-\frac{A_{ext}}{C_a r_a}}$$

where

$A_{ext}$  = heat-exchanger total heat transfer area on air-side

$r_a$  = air-side thermal resistance =  $\frac{1}{\tilde{h}_a \varepsilon_{fin}}$

$$\tilde{h}_a = \text{air-side heat transfer coefficient} = \frac{Nu_a k_a}{D_h}$$

$$Nu_a = \text{Nusselt number of air} = 3.66 + \frac{0.0668 Re_a Pr_a D_h}{L_{coil}} \frac{1}{1 + 0.04 \left( \frac{Re_a Pr_a D_h}{L_{coil}} \right)^{2/3}}$$

$$Re_a = \text{Reynolds number of air} = \frac{\dot{m}_a D_h}{A_{free} \nu_a}$$

$$Pr_a = \text{Prantl number of air} = \frac{c_{pa} \nu_a}{k_a}$$

$k_a$  = thermal conductivity of air

$D_h$  = hydraulic diameter

$L_{coil}$  = length of coil

$A_{free}$  = heat-exchanger minimum free-flow area on air side

$$\nu_a = \text{dynamic viscosity of air} = \frac{1.458 \times 10^{-6} (273.16 + T_{a,i})^{1.5}}{383.4 + T_{a,i}}$$

$\varepsilon_{fin}$  = fin effectiveness

$$\varepsilon_{fin} = 1 - \left( \frac{A_{fin,net}}{A_{fin,net} + A_{tube,net}} \right) \left( 1 - \frac{\tanh(\gamma)}{\gamma} \right)$$

$$\gamma = \sqrt{\frac{2\tilde{h}_a}{k_{fin} t_{fin}}} \left[ 1 + 0.35 \ln \left( \frac{R_{fin,o}}{R_{fin,i}} \right) \right] H_{fin}$$

$A_{fin,net}$  = net fin heat transfer area

$A_{tube,net}$  = net tube heat transfer area

$k_{fin}$  = thermal conductivity of fin material

$t_{fin}$  = fin thickness

$R_{fin,o}$  = effective fin radius

$R_{fin,i}$  = fin inside radius

### **Heat-exchanger effectiveness ( $\varepsilon_{HX}$ )**

The effectiveness of a compact cross-flow heat-exchanger with both fluids unmixed is calculated for a typical condition.

$$\varepsilon_{HX} = 1 - \exp\left[\frac{-NTU^{0.22}\left(1 - e^{-C_{rr}NTU^{0.78}}\right)}{C_{rr}}\right]$$

where

$$C_{rr} = \frac{C_w}{C_a} \text{ for water is minimum}$$

$$C_{rr} = \frac{C_a}{C_w} \text{ for air is minimum}$$

$$C_w = \text{water heat capacity rate} = c_{pw}\dot{m}_w$$

$$c_{pw} = \text{specific heat of water}$$

$$NTU = \text{number of transfer units} = \frac{A_{ext}}{C_{min}r_{tot}}$$

$$r_{tot} = \text{sum of resistances of air-side, water-side, and material}$$

### **Outlet air dry bulb temperature of a wet coil ( $T_{a,o}$ )**

$$T_{a,o} = T_{a,i} + \dot{Q}_{a,wet}SHR$$

where

$$SHR = \text{sensible heat ratio} = \frac{C_a(T_{a,o,est} - T_{a,i})}{\dot{Q}_{a,wet}}$$

$$T_{a,o,est} = \text{estimated outlet air dry bulb temperature}$$

$$T_{a,o,est} = B_f(T_{a,i} - T_{cs}) + T_{cs}$$

$$\dot{Q}_{a,wet} = \text{air-side heat transfer of a wet coil}$$

$$\dot{Q}_{a,wet} = (T_{cs} - T_{wb,i})C_{a,sat}(1 - B_f)$$

$$T_{wb,i} = \text{inlet air wet bulb temperature}$$

$C_{a,sat}$  = saturated air capacity rate =  $c_{p,sat}\dot{m}_a$

$c_{p,sat}$  = saturated air specific heat

**Outlet air humidity ratio ( $h_{a,o}$ )**

$$h_{a,o} = \frac{H_{a,o} - c_{pa}T_{a,o}}{c_{pg}T_{a,o} + HFG}$$

where

$HFG$  = latent heat of vaporization

$$H_{a,o} = \text{outlet air enthalpy} = H_{a,i} + \frac{\dot{Q}_{a,wet}}{\dot{m}_a}$$

**Coil outlet water temperature ( $T_{w,o}$ )**

$$T_{w,o} = T_{w,i} - \frac{\dot{Q}_w}{C_w}$$

where

$$\dot{Q}_w = \text{heat transfer on water-side} = \frac{T_{w,i} - T_{cs}}{r_2}$$

**Mixed return water temperature ( $T_{w,ret}$ )**

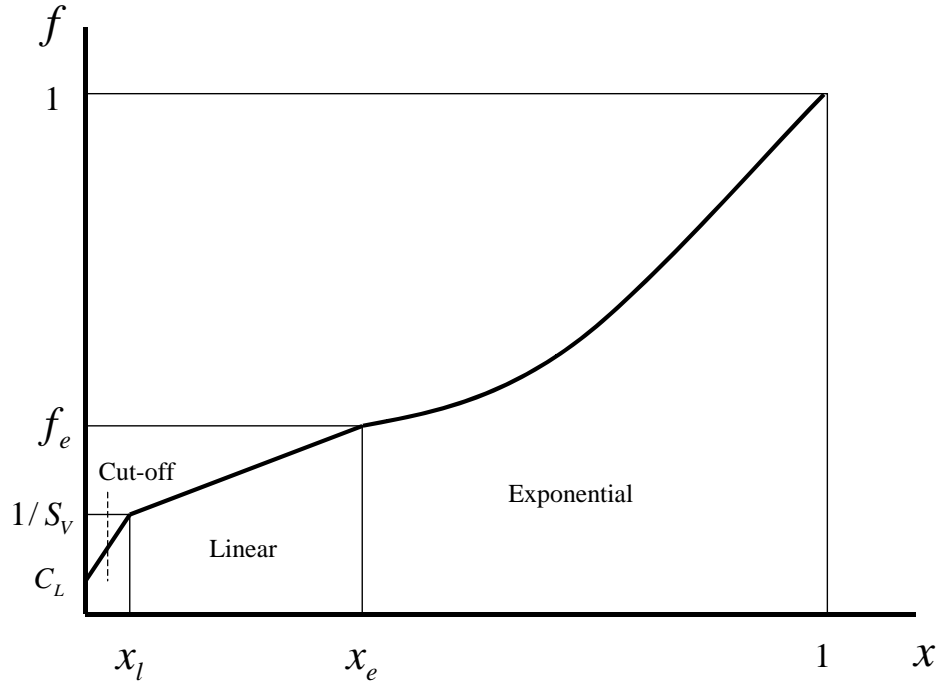
$$T_{w,ret} = \frac{T_{w,i}(\dot{m}_{w,prim} - \dot{m}_w) + T_{w,o}\dot{m}_w}{\dot{m}_{w,prim}}$$

where

$\dot{m}_{w,prim}$  = primary circuit water mass flow rate

$\dot{m}_w$  = water mass flow rate through the coil

$T_{w,i}$  = inlet water temperature



**Figure 14.** Water flow control valve characteristics

The water flow control valve characteristics used in the model in the general form is presented in Figure 14. The figure shows the relationship between the fractional flow rate through the control valve,  $f(x)$ , and the valve stem position,  $x$ . A constant pressure is applied. There are three regions – cut-off, linear, and exponential.

In the cut-off region,

$$f(x) = \left( \frac{1}{S_v} - C_L \right) \left( \frac{x}{x_l} \right) + C_L \quad 0 \leq x \leq x_l$$

In the linear region,

$$f(x) = \left( \frac{f_e - \frac{1}{S_v}}{x_e - x_l} \right) (x - x_l) + \frac{1}{S_v} \quad x_l < x \leq x_e$$

In the exponential region,

$$f(x) = a^{x-1} \quad x_e < x \leq 1$$



where

$S_V$  = rangeability – ratio of highest to lowest controllable flow

$C_L$  = fractional leakage flow when the valve is fully closed

$x_l$  = break point between the linear and cut-off regions

$x_e$  = break point between the exponential and linear regions

$a$  = curvature parameter for equal percentage characteristic

$f_e = f(x_e)$

The hydraulic resistance across the flow port of the control valve,  $r_{w,v,f}$ , is expressed in terms of the fractional flow rate and valve capacity,  $K_V$ .

$$r_{w,v,f} = \frac{1296}{K_V^2 f^2(x)}$$

The resistance across the bypass port of the valve,  $r_{w,v,byp}$ , is calculated from

$$r_{w,v,byp} = \frac{1296}{K_V^2 f^2(1-x)}$$

**Water flow rate through the coil ( $\dot{m}_w$ )**

$$\dot{m}_w = \sqrt{\frac{P_{w,i} - P_{w,o}}{r_{w,c} + r_{w,v,f}}}$$

where

$p_{w,i}$  = inlet water pressure

$p_{w,o}$  = outlet water pressure

$r_{w,c}$  = hydraulic resistance through the coil

**By-pass water flow rate ( $\dot{m}_{w,byp}$ )**

$$\dot{m}_{w,byp} = \sqrt{\frac{P_{w,i} - P_{w,o}}{r_{w,byp} + r_{w,v,byp}}}$$

where

$r_{w,byp}$  = hydraulic resistance through the by-pass water circuit

**Primary water flow rate ( $\dot{m}_{w,prim}$ )**

$$\dot{m}_{w,prim} = \dot{m}_w + \dot{m}_{w,byp}$$

**Return water temperature ( $T_{w,ret}$ )**

$$T_{w,ret} = \frac{T_{w,i}\dot{m}_{w,byp} + T_{w,o}\dot{m}_w}{\dot{m}_{w,prim}}$$

**Inlet air pressure of the coil ( $p_{a,i}$ )**

$$p_{a,i} = p_{a,o} + r_{a,c}\dot{m}_a \left| \dot{m}_a \right| \quad \text{above the critical bound}$$

$$p_{a,i} = p_{a,o} + r_{a,c}\dot{m}_{crit}\dot{m}_a \quad \text{below the critical bound}$$

where

$$\dot{m}_{crit} = \text{critical flow} - \text{lower limit of purely quadratic flow}$$

Figure 15 is a diagram showing the airflows through various building HVAC component models used here. The four big blocks are AHU, VAV, Flow merge, and Fire Model. Air pressure, air mass flow rate, air temperature, air humidity ratio, and smoke concentration are denoted by p, m, t, h, and o, respectively. The numbers following the characters are indices chosen for identification. A component model is identified by “Ty” plus the specific number for the TYPE routine in HVACSIM<sup>+</sup> as seen in Figure 10. No specific number is given to the new mixing box routine in ZFM-HVAC. The same configuration is applied to all the three AHUs. Some simplification was made to the models compared with the model using HVACSIM<sup>+</sup>. Particularly, a constant static pressure in the air supply duct is assumed during emulation.

As shown in the Figure 15, the fire model receives the supply air mass flow rate, supply temperature, supply pressure, and smoke concentration from HVAC duct as inputs to a zone. The fire model determines the zone outlet pressures, temperatures, and combustion product concentrations. No solar heat gain, nor internal heat gain in a zone is considered in normal status, which is no fire condition.

#### **4. ZFM-HVAC RUNS AND DISCUSSION**

Three scenarios were selected to demonstrate the use of ZFM-HVAC in the VCBT.

Case 1: A virtual three-story building with nine conditioned zones and an unconditioned stairwell. Three AHUs and nine VAV boxes are involved.

Case 2: A virtual single-story building with nine conditioned zones. Eight of nine zones are identically sized. Three AHUs and nine VAV boxes are used.

Case 3: A virtual single-story building with nine conditioned zones with different sizes. Three AHUs and nine VAV boxes are involved.

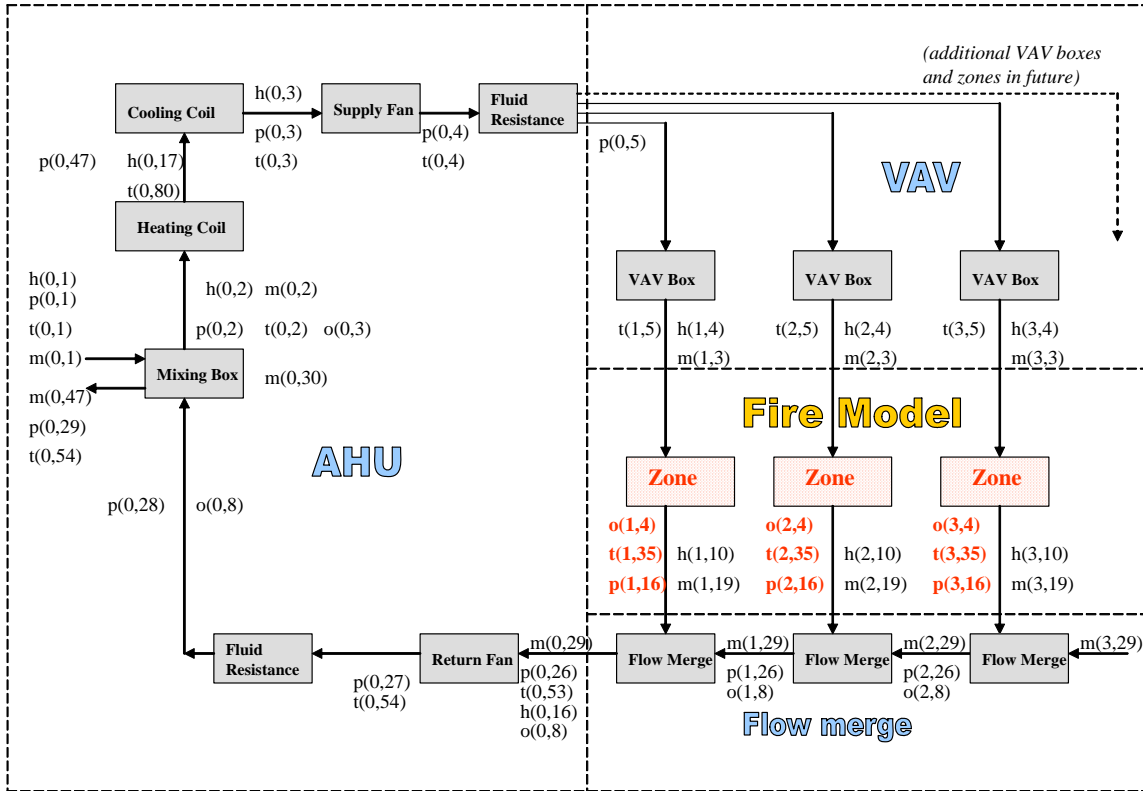
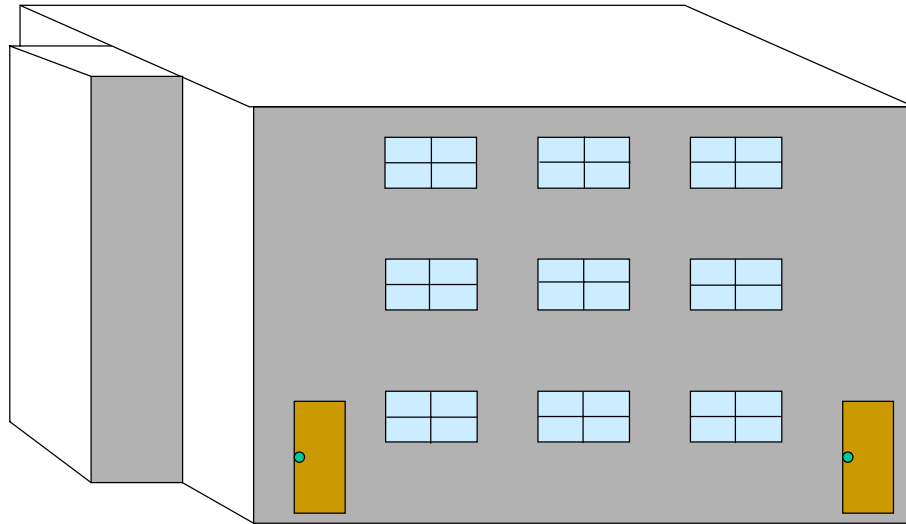


Figure 15. The airflow paths through various building HVAC components for all cases.

#### 4.1 Case 1 Scenario

As an example run, a virtual three-story building as shown in Figure 16 was modeled. This virtual building has three zones on each floor and a stairwell. Figures 17 to 19 show the layouts for all three floors. As shown in Figure 20, three air-handling units serve three zones each. AHU1 serves Zones 1, 2, and 3; AHU2 serves Zones 4, 5, and 6; and AHU3 serves Zones 7, 8, and 9, respectively. None of the AHUs serves the stairwell (Zone 10). Access doors to the stairwell are located at Zone 7, 8, and 9. Two access doors to outside are located in Zone 7. Airflow is allowed between zones. The AHUs supply and extract the airflows through ducts and VAV boxes. It should be emphasized that the ZFM-HVAC was primarily designed to observe the effects on the zone air temperature and smoke concentration in the zones as well as HVAC system responses due to fire.

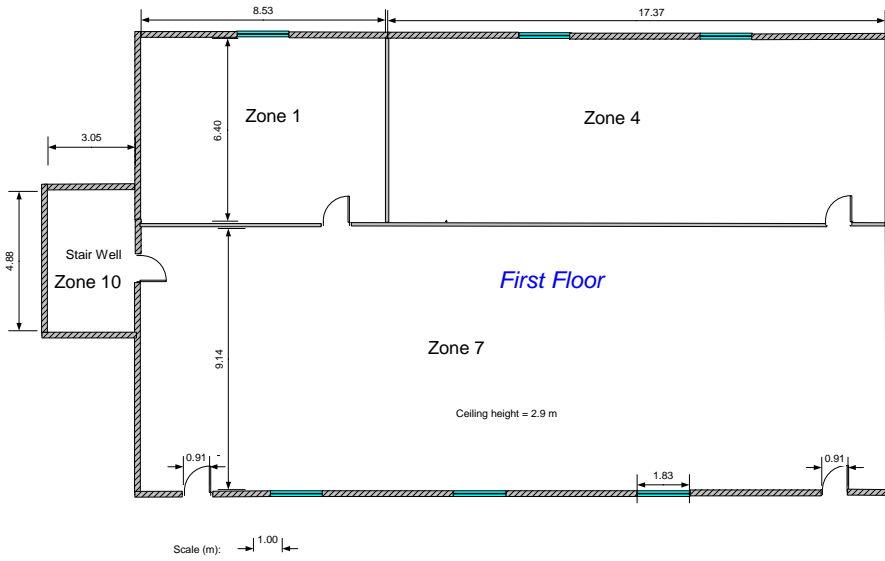


*Not To Scale*

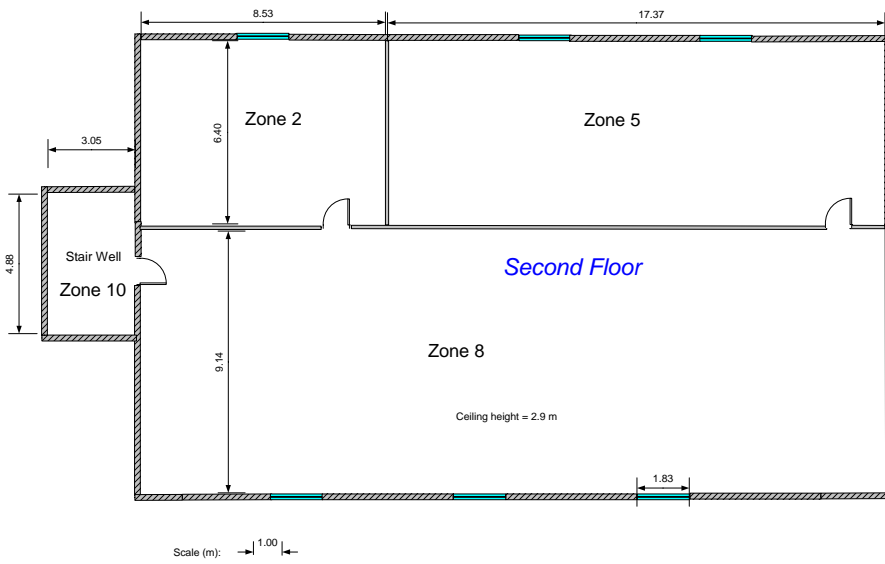
**Figure 16.** A virtual three-story building in Case 1.

No controller tuning, FDD, nor HVAC system energy consumption analysis is emphasized with ZFM-HVAC. In all the cases, the supply and return fans were set to run continuously at all times.

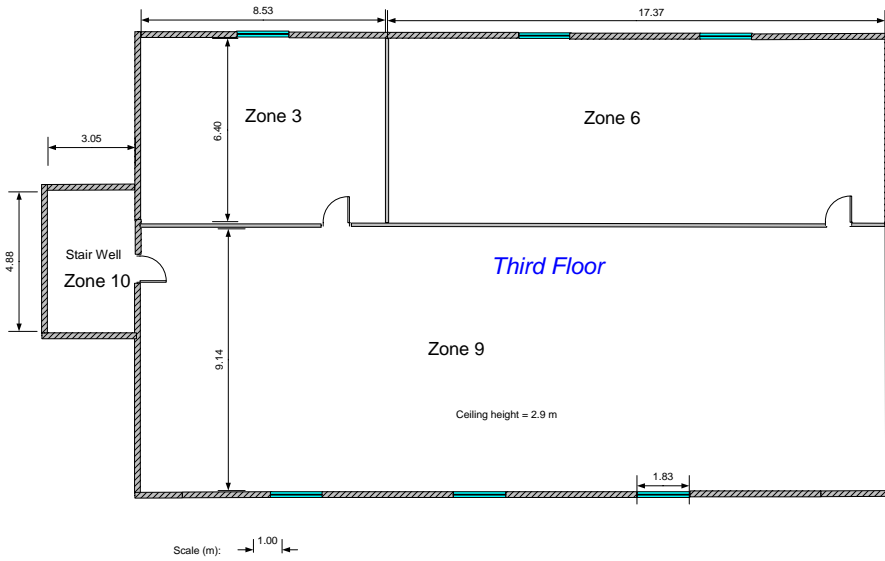
Initially AHUs and VAV boxes operated in a normal mode in conjunction with the real BACnet HVAC controllers. Two different sizes of fire were used. The heat release rate determines the size of a fire. Figure 21 shows heat release rates in terms of time. These heat release rates were artificially imposed as input conditions. Case 1\_1 and Case 1\_2 represent the small fire and the large fire respectively. Appendix C is the ZFM-side input data for Case 1\_1.



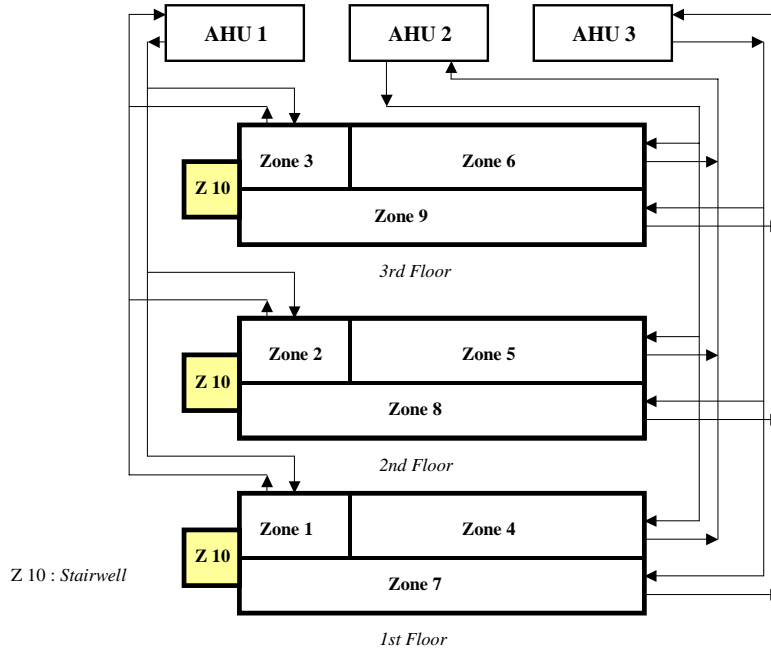
**Figure 17.** The first floor layout of the virtual three-story building in Case 1.



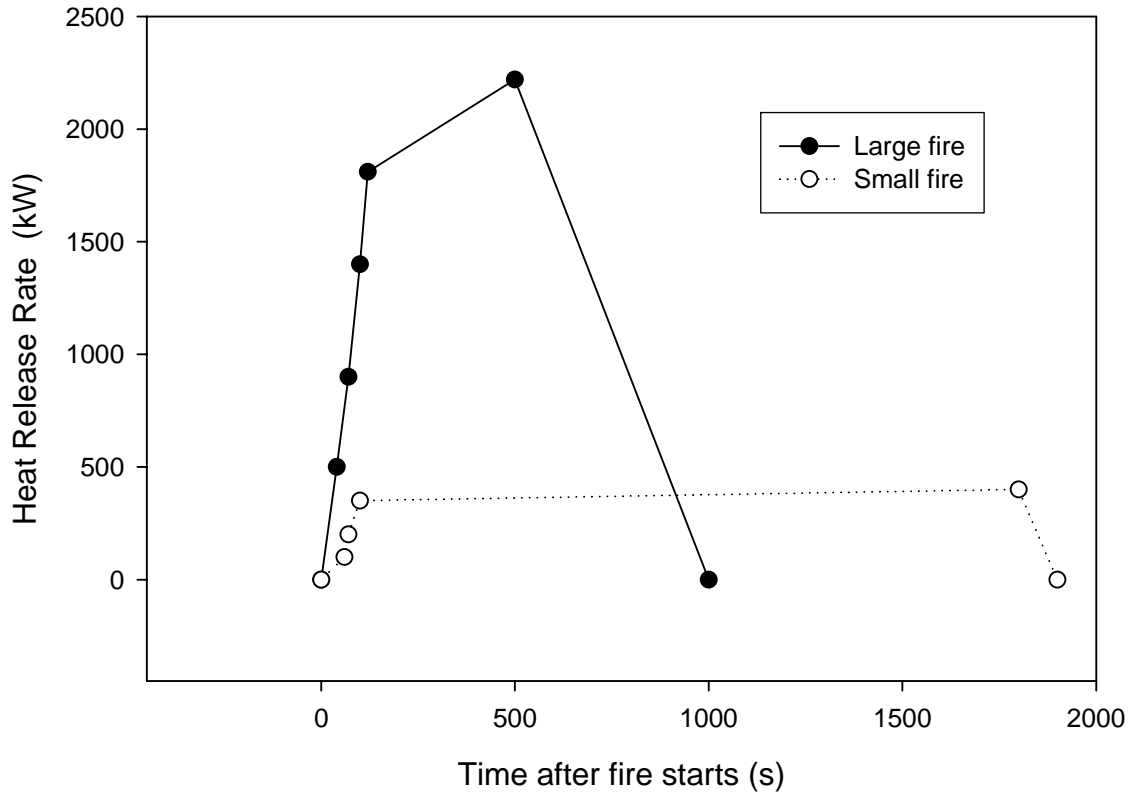
**Figure 18.** The second floor layout of the virtual three-story building in Case 1.



**Figure 19.** The third floor layouts of the virtual three-story building in Case 1.



**Figure 20.** Air distribution for nine conditioned zones of the virtual three-story building in Case 1.



**Figure 21.** Heat release rates for large and small fires.

Appendix D shows the HVAC-side configuration input data, where  $n_{ahu}$  is the number of air-handling units and  $nbr$  is the number of flow branches for VAVs served by each air-handling unit. The files with extension ‘inp’ are input data files and those with ‘out’ are output files. Sample input data for AHU and VAV are given in Appendices E and F. The parameter data are actually used in computation. Others are for information. Appendix G lists initial data of the HVAC-side of ZFM-HVAC.

First, the VCBT emulation results of Case 1\_1 for the small fire is examined. At 7200 s from the beginning of emulation, a fire was set in Zone 1. For the AHU1 branch, the BACnet controllers involved are the AHU controller (ID = 100), and the VAV controllers (ID = 101, 102, and 103). Refer to Figure 7. The control strategies actually implemented in these controllers are much complicated than the general strategies described previously (See Section 2.5). For example, the VAV controller sets an alarm condition and limits the supply flow rate at the minimum when the zone air temperature becomes above 50 °C, although generally we might expect the maximum rate instead. Note that emulation results of this report reflect the responses of controllers of different companies in different ways.

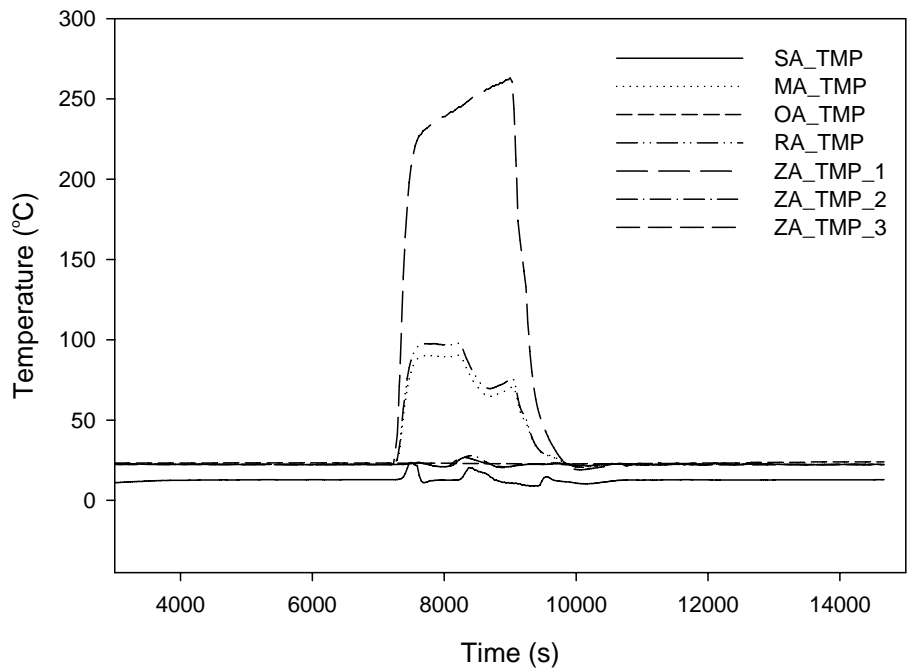
Figures 22 and 23 show the return air temperatures from zones, the air temperatures at AHU1, the flow rates of AHU1 branch, the damper opening demand by controllers of AHU1, the coil opening demand signals, and the reheat coil control signals. Referring to Figure 15, ZA\_TMP\_1 [t(1,35)], ZA\_TMP\_2 [t(2,35)], and ZA\_TMP\_3 [t(3,35)] represent the return air temperatures from Zone 1, 2, and 3, respectively. The bottom and top edges of rectangular return air ducts locate 1.5 m and 2.0 m from the floor respectively as shown in Appendix C. The fire side of the ZFM-HVAC program determines the return air temperatures. In this case, the changes in ZA\_TMP\_2 and ZA\_TMP\_3 are not noticeable, but ZA\_TMP\_1, which is the return air temperature from the fire zone, Zone 1, is very high as expected. The zone air temperatures on the 2<sup>nd</sup> and the 3<sup>rd</sup> floors are not much affected due to the small fire size.

The supply air temperature of AHU1, mixed air temperature, return air (extracted air) temperature, and outdoor air temperature are denoted as SA\_TMP [t(0,4)], MA\_TMP [t(t(0,2))], RA\_TMP [t(0,54)], and OA\_TMP [t(0,1)], respectively. Although SA\_TMP was maintained around the set point, MA\_TMP and RA\_TMP approached 100°C during the fire. OA\_TMP did not vary much in this emulation period. The flow rates in the flow branch served by AHU1 are plotted for SA\_FLOW [m(0,2)], RA\_FLOW [m(0,29)], ZFLOW\_1 [m(1,3)], ZFLOW\_2 [m(2,3)], and ZFLOW\_3 [m(3,3)], which represent the supply airflow rate, return airflow rate, and the zone airflow rates of Zone1, 2, and 3, respectively.

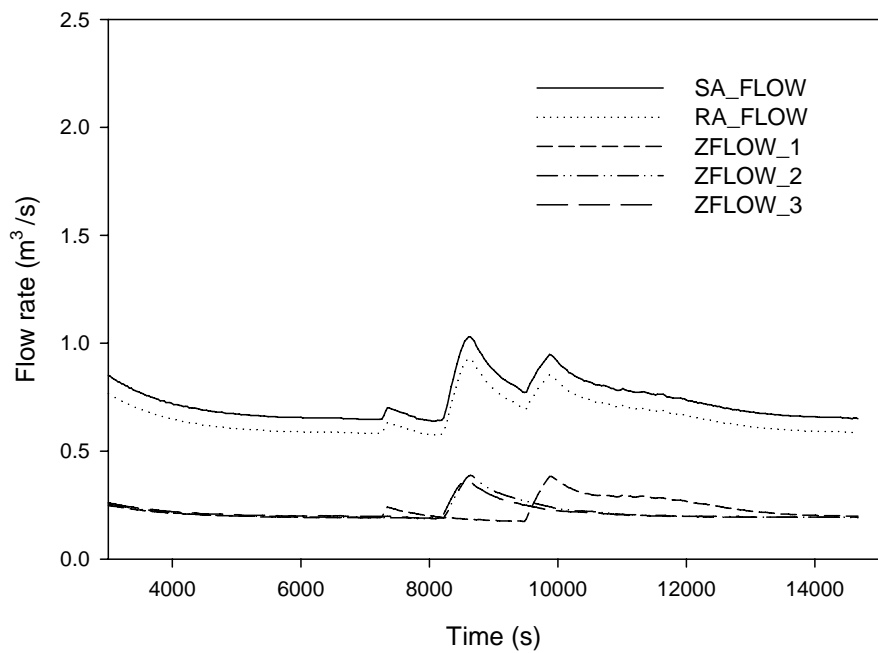
Demand control signals from BMS were observed. The AHU damper opening demand signal (DMP\_DEM), the cooling coil valve opening demand signal (CC\_DEM), and the heating coil valve opening demand signal (HC\_DEM) are shown in Figure 23a. The actual damper opening (DMP\_opening) is also shown on the same chart. It can be seen that DMP\_opening value remained the same value of 0.15, which means that approximately 15 % of the AHU fresh (outdoor) air damper, 15 % of the exhaust air damper, and 85 % of the AHU re-circulation damper were open. It is because the DMP\_opening was set to the constant value of 15 % in ZFM-HVAC overriding DMP\_DEM that varied between 0.15 and 1.0. The AHU1 controller operated with the enthalpy economizer logic enabled. The VAV box damper opening demand signals (ZDMP\_CTL\_1, ZDMP\_CTL\_2, ZDMP\_CTL\_3) and the reheat coil valve opening demand signals (RHC\_CTL\_1, RHC\_CTL\_2, RHC\_CTL\_3) are shown in Figure 23b.



(a) Temperatures at AHU1 and return air temperatures from zones 1, 2, and 3

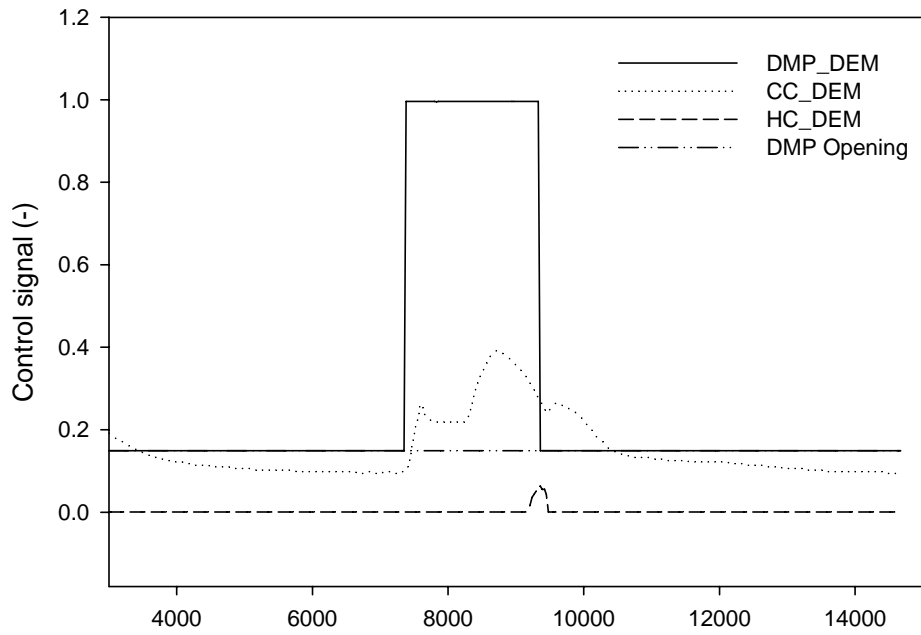


(b) Flow rates of AHU1 branch

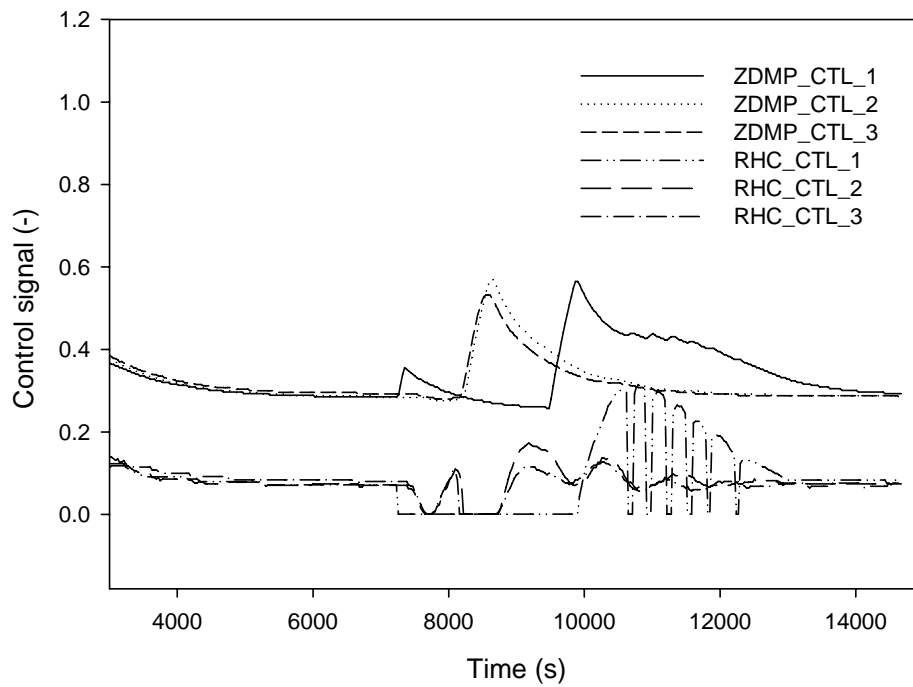


**Figure 22.** Temperatures, and flow rates of AHU1 in Case 1\_1.

(a) Damper and coil opening demands by AHU1 controller



(b) VAV damper and reheat coil signals by VAV controllers



**Figure 23.** Control signals of AHU1 in Case 1\_1. (-) means dimensionless.

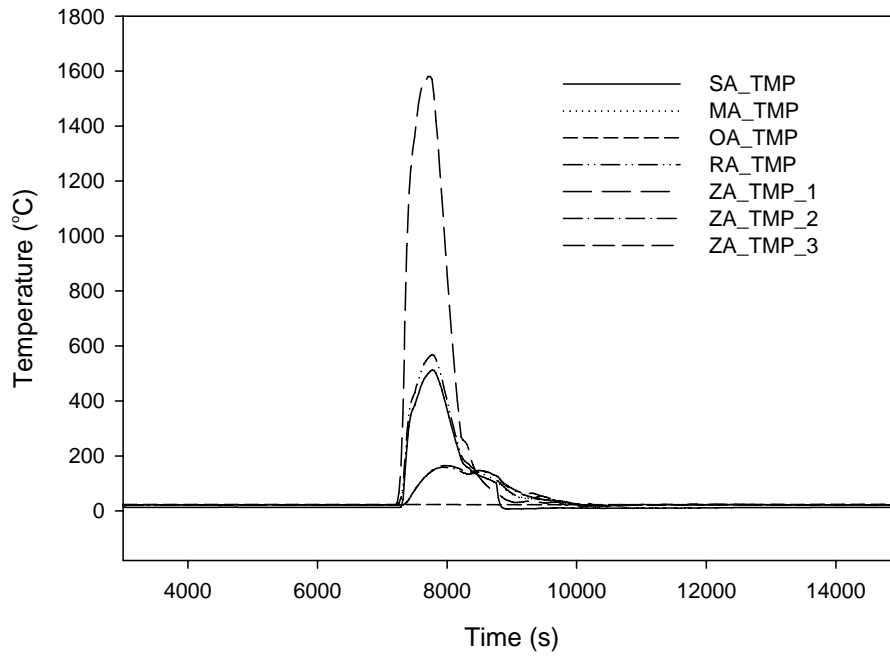
In Case 1\_2, the same building configuration as the previous case was applied, except that a large fire was set in the Zone 1 at 7,200 s after the start of emulation. Figure 24 shows the same kind of plots for AHU1 branch similar to Case 1\_1. Notice that ZA\_TMP\_1 went up to 1600 °C, and ZA\_TMP\_2 and ZA\_TMP\_3 approached 160 °C. The airflow through the stairwell and the AHU ducts could contribute to the temperature increases. Since DMP opening was set to the minimum value of 15 %, roughly 85 % of the extracted flow from zones (RA\_FLOW) returned to zones as the supply airflow after mixing with the fresh air. The supply air temperature became quite high during the period of fire. The cooling coil model in ZFM-HVAC was programmed up to 100 °C. Beyond the limit, the cooling coil discharge temperature was set to equal the return air temperature ensuring that no cooling would occur.

It is worthwhile to mention about why the reheat coils were activated by the VAV terminal box controller during the cooling season under no fire condition when the outdoor air temperature (OA\_TMP) of the select weather condition was at 23.5 °C to 24.0 °C. The set point of the supply air temperature of the AHU was set at 12.8 °C, while the set point of the zone VAV controllers was 23.4 °C. No heat source (e.g., generated heat by person, equipment, or lighting, and heat transfer from ceiling, floor, or wall) in a zone was enabled. The only way the zone temperature could reach the set point value was reheating by the reheat coils. As a result, active reheat coil valve control signals can be observed.

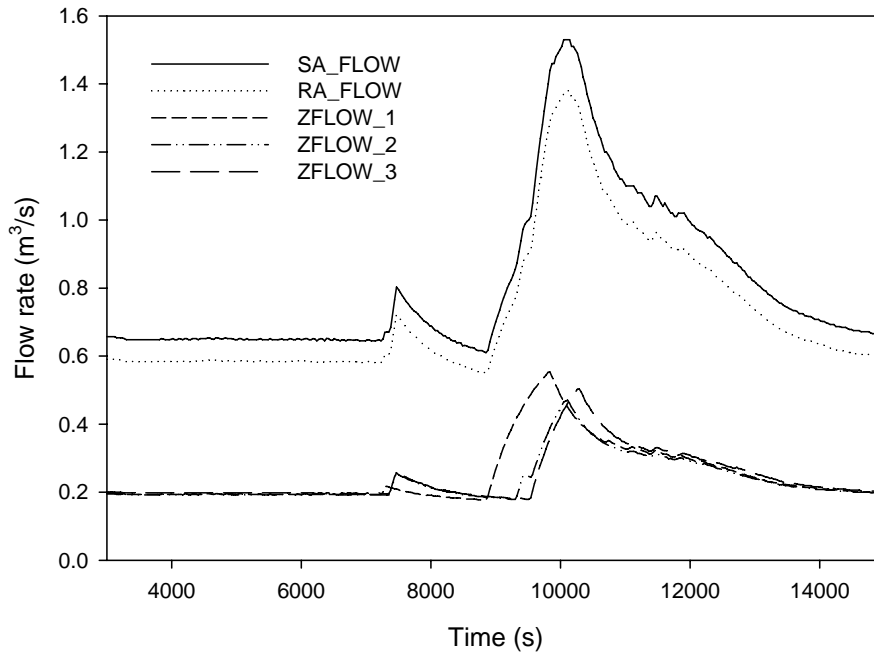
Figures 26 and 27 show temperatures, flow rates, and control signals of the air-handling unit AHU2 and the VAVs served by AHU2 in Case 1\_2. ZA\_TMP\_4, ZA\_TMP\_5, and ZA\_TMP\_6 represent the return air temperatures from Zone 4, 5, and 6, respectively. See Figures 17 through 20. For the AHU2 branch, the BACnet device instances of the AHU controller and the VAV controllers are 310, 304, 305 and 306 as shown in Figure 7. Compared with Figure 24, the return air temperatures from zones were much lower. The peak value was about 150 °C. The flow rates as well as control loops for the AHU2 branch quite fluctuated.

Figures 28 and 29 depict the similar plots as before for the AHU3 branch. Zones 7, 8, and 9 have openings to Zone 1, 2, and 3. This would bring the return air temperatures higher than those of AHU2. ZA\_TMP\_7 went up to 500 °C and ZA\_TMP\_8 and ZA\_TMP\_9 reach near 180 °C. Note that SA\_TMP followed a similar pattern as MA\_TMP or RA\_TMP, which was near 260 °C at its peak. Here again as seen in Figure 29a, DMP\_DEM was sometimes at 100 %, but the actual damper opening was set to 15 % at all times by ignoring the output signal, DMP\_DEM, from the AHU enthalpy control.

(a) Temperatures at AHU1 and return air temperatures from zones 1, 2, and 3

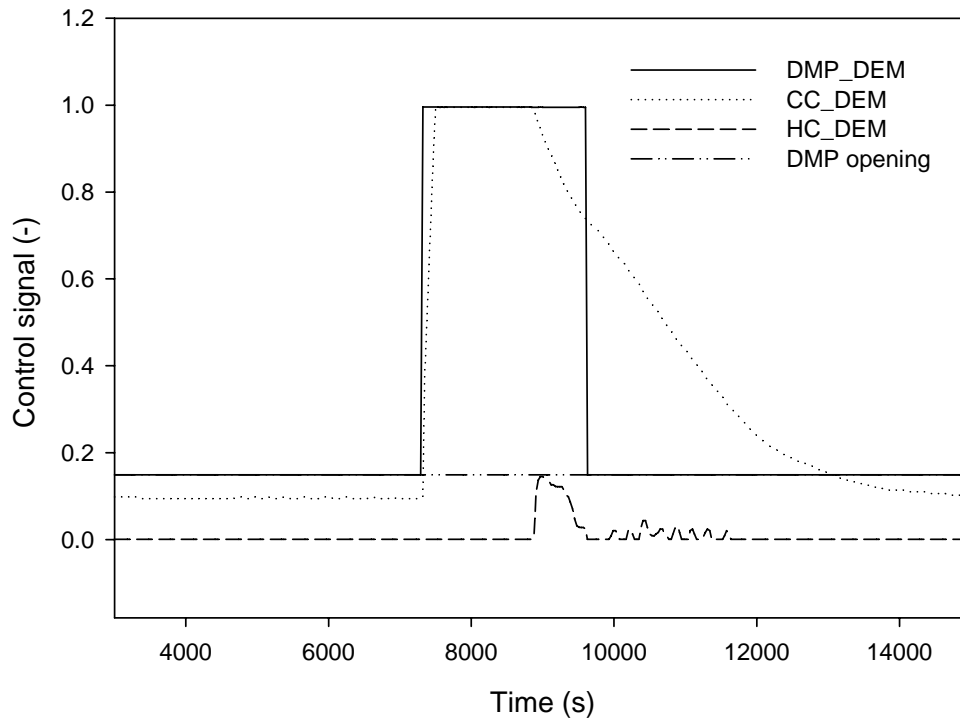


(b) Flow rates of AHU1 branch



**Figure 24.** Temperatures, and flow rates of AHU1 in Case 1\_2.

(a) Damper and coil opening demands by AHU1 controller



(b) VAV damper and reheat coil signals by VAV controllers

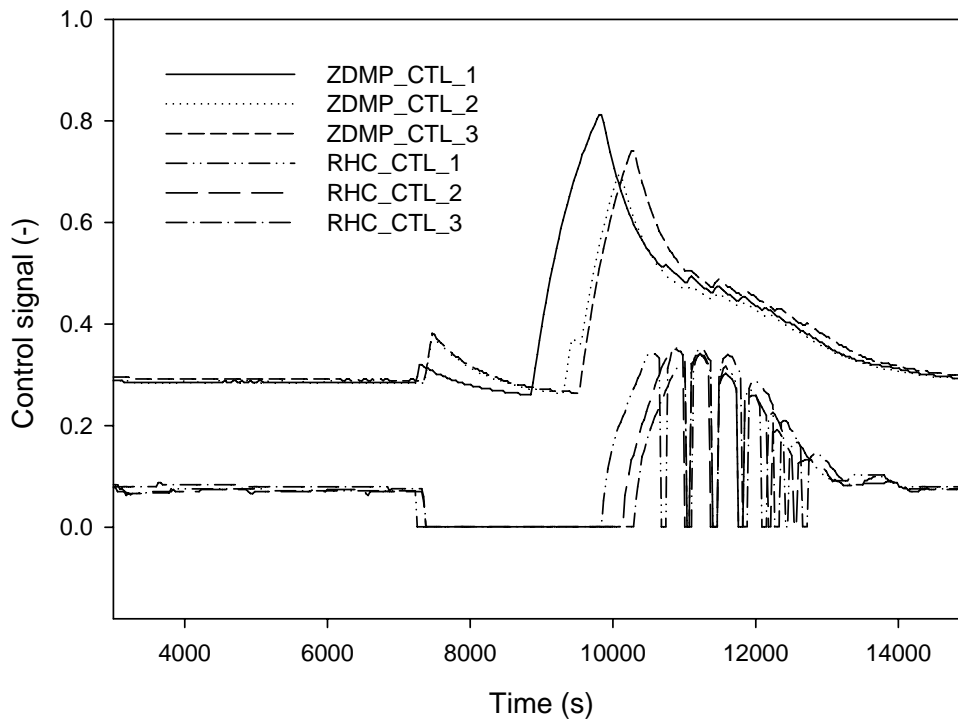
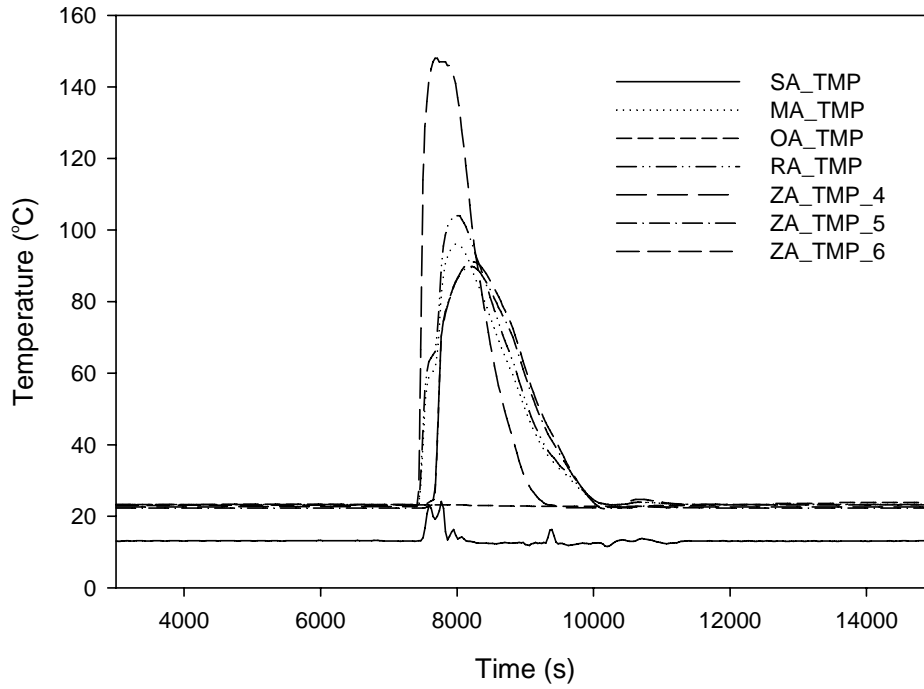
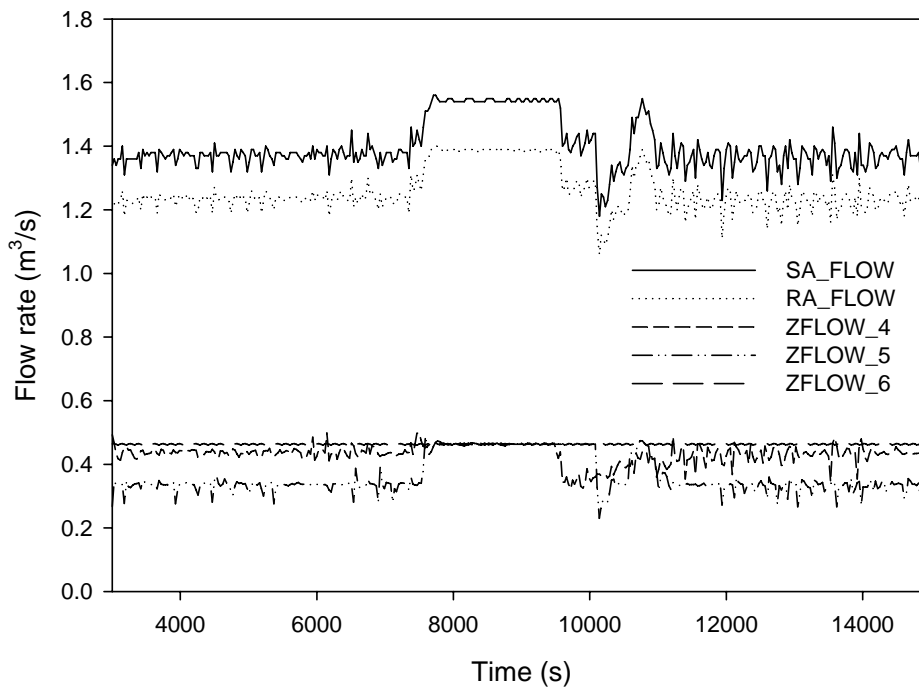


Figure 25. Control signals of AHU1 in Case 1\_2.

(a) Temperatures at AHU2 and return air temperatures from zones 4, 5, and 6

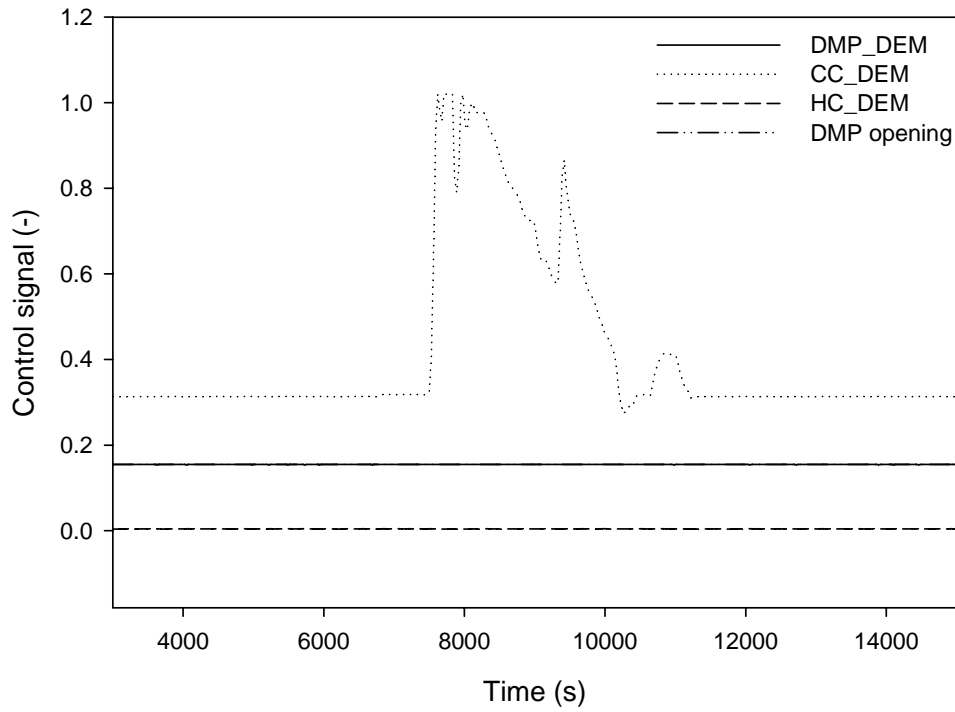


(b) Flow rates of AHU2 branch

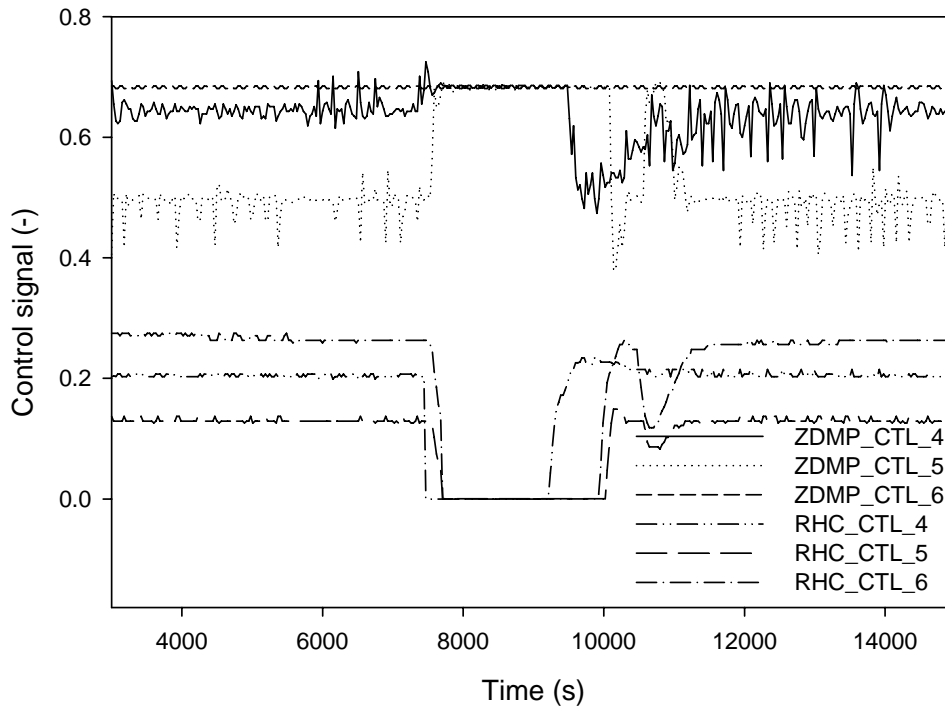


**Figure 26.** Temperatures, and flow rates of AHU2 in Case 1\_2.

(a) Damper and coil opening demands by AHU2 controller

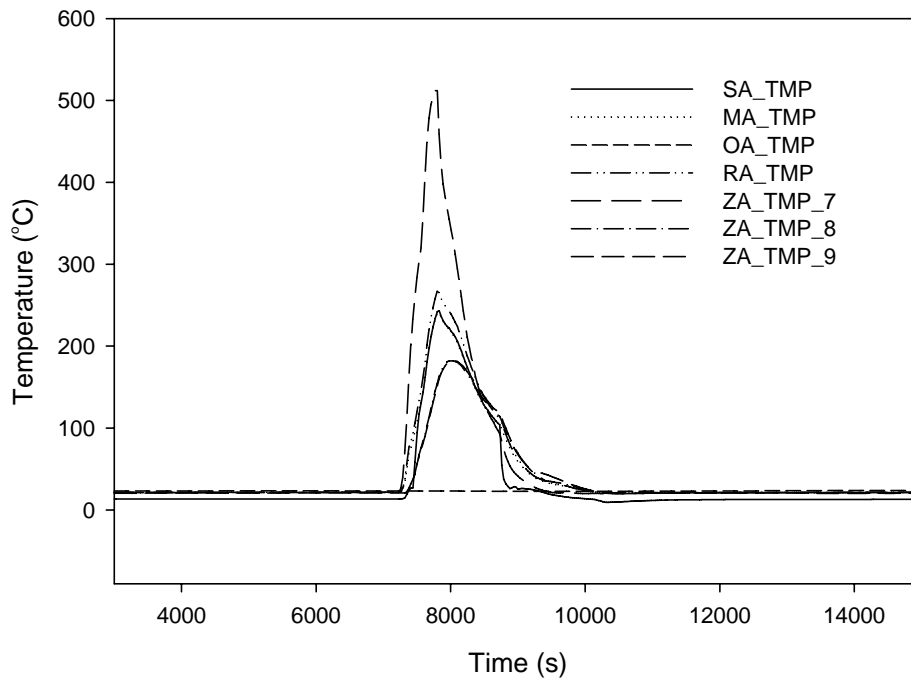


(b) VAV damper and reheat coil signals by VAV controllers

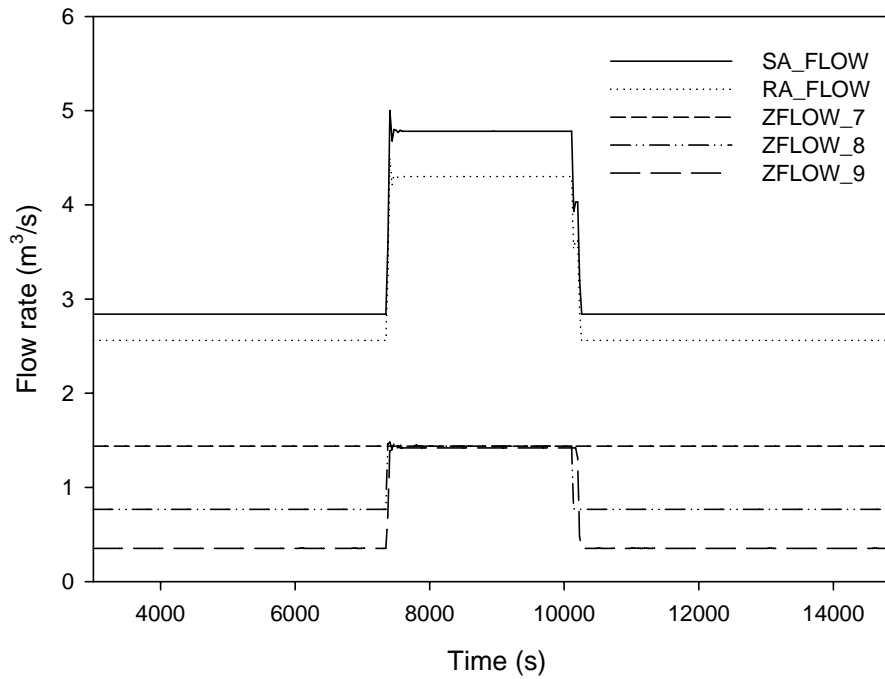


**Figure 27.** Control signals of AHU2 in Case 1\_2.

(a) Temperatures at AHU3 and return air temperatures from zones 7, 8, and 9



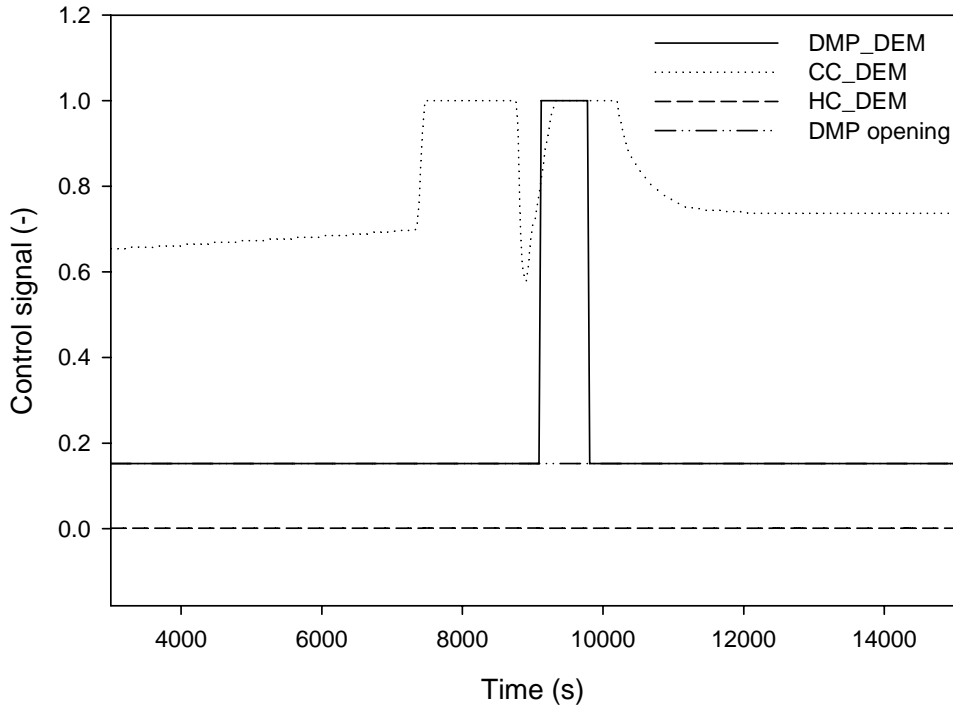
(b) Flow rates of AHU3 branch



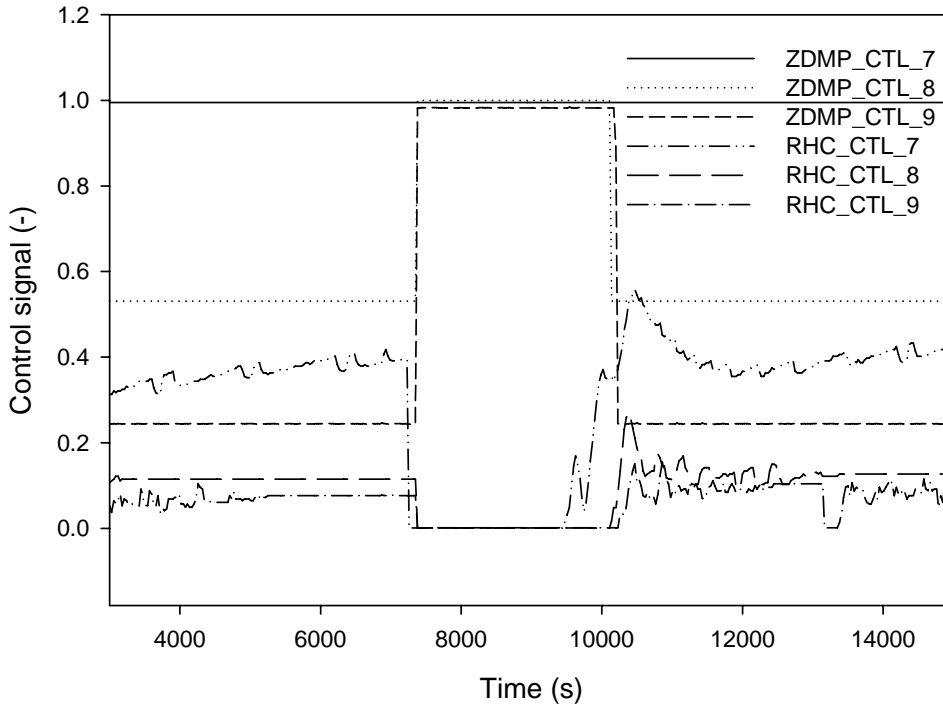
**Figure 28.** Temperatures, and flow rates of AHU3 in Case 1\_2.



(a) Damper and coil opening demands by AHU3 controller



(b) VAV damper and reheat coil signals by VAV controllers



**Figure 29.** Control signals of AHU3 in Case 1\_2.

The fire model, ZFM, was developed based on the modeling approach used in CFAST [25], which models the fire gases as homogeneous upper (hot) and lower (cool) layers. The temperatures and smoke concentrations (or mass fraction) of upper and lower layers are shown in Figure 30 for Case 1\_2. The labels Zone\_1L, Zone\_2L, and Zone\_3L represent the lower layer temperatures of Zone 1, 2, and 3, respectively. Likewise Zone\_1U, Zone\_2U, and Zone\_3U represent the upper layer temperatures. As expected, the upper layer temperature of Zone 1 was highest about 1580 °C, and the lower layer temperature of the same zone was 690 °C at its peak. The peak upper and lower layer temperatures of the other two zones were almost 160 °C. The peak values of other two zone's layer temperatures appeared in delay compared with the peak time in Zone 1. The smoke concentrations of Zone 1 apparently were high, while those in other zones, which were located in the second and third floor, were insignificant in this virtual three-story building.

Based upon Bouguer's law, the transmitted light intensity,  $I$ , through the smoke is given by:

$$I = I_o e^{-KcL}$$

where

$I_o$  = incident light intensity

$K$  = extinction coefficient

$c$  = smoke density

$L$  = path length

Thus, the path length is expressed as

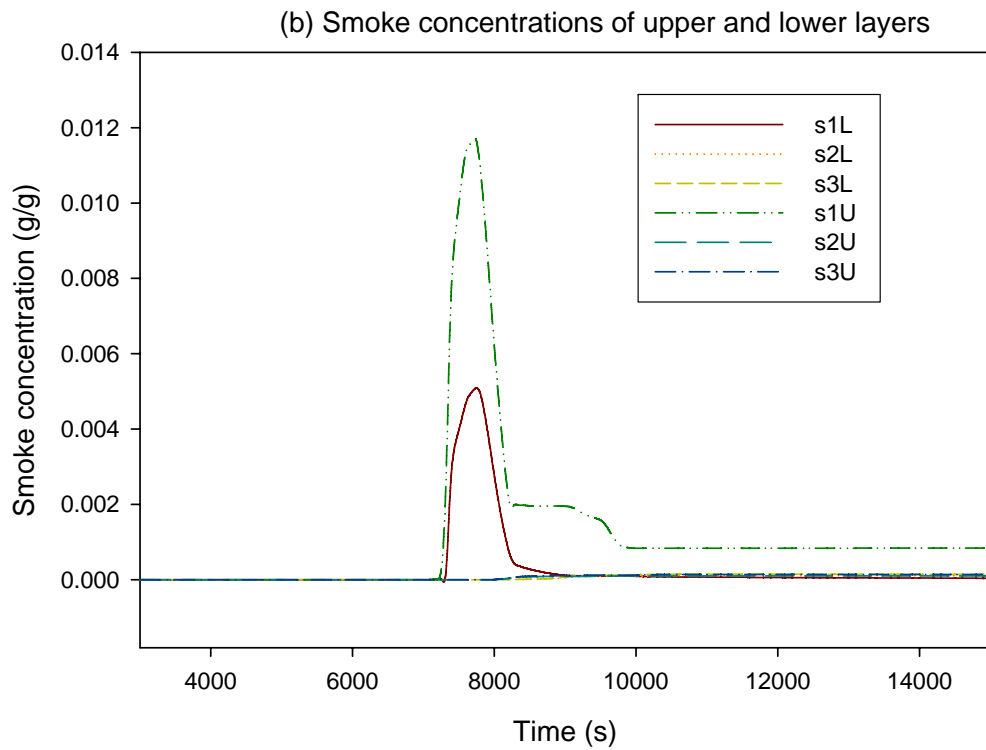
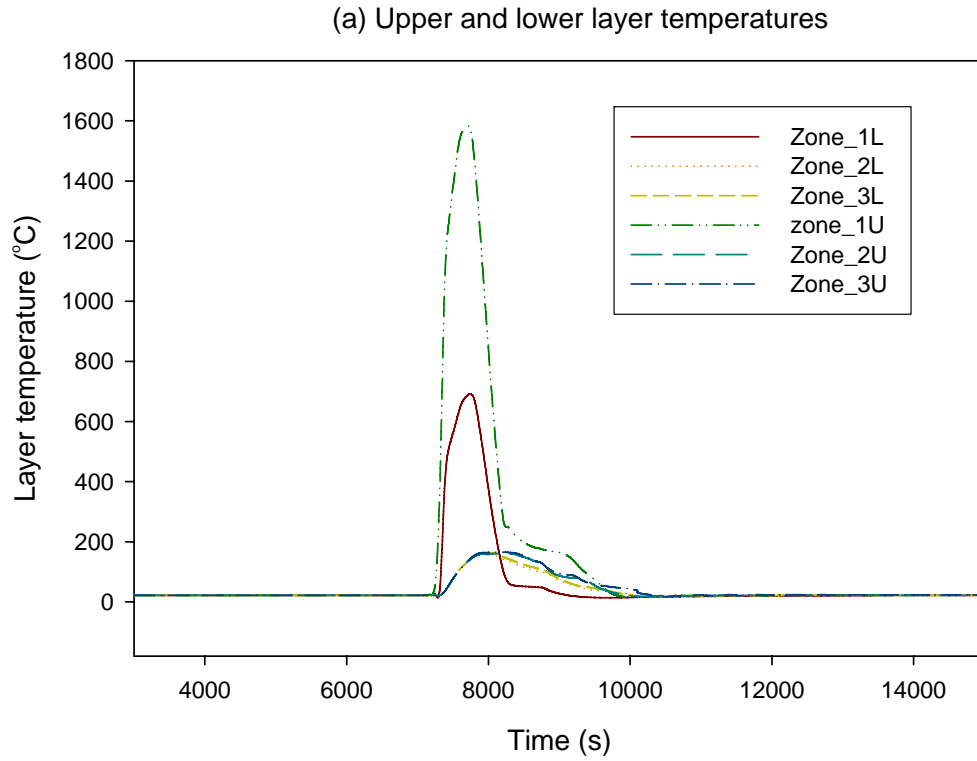
$$L = \frac{\ln\left(\frac{I}{I_o}\right)}{-Kc}$$

According to Mulholland and Johnson [20], the extinction coefficient for over-ventilated flaming combustion is  $8.7 \text{ m}^2 / \text{g}$ . Using the value of air density,  $1294.3 \text{ g} / \text{m}^3$ , the visibility limit or path length in meters that we see only 0.1 % of light is

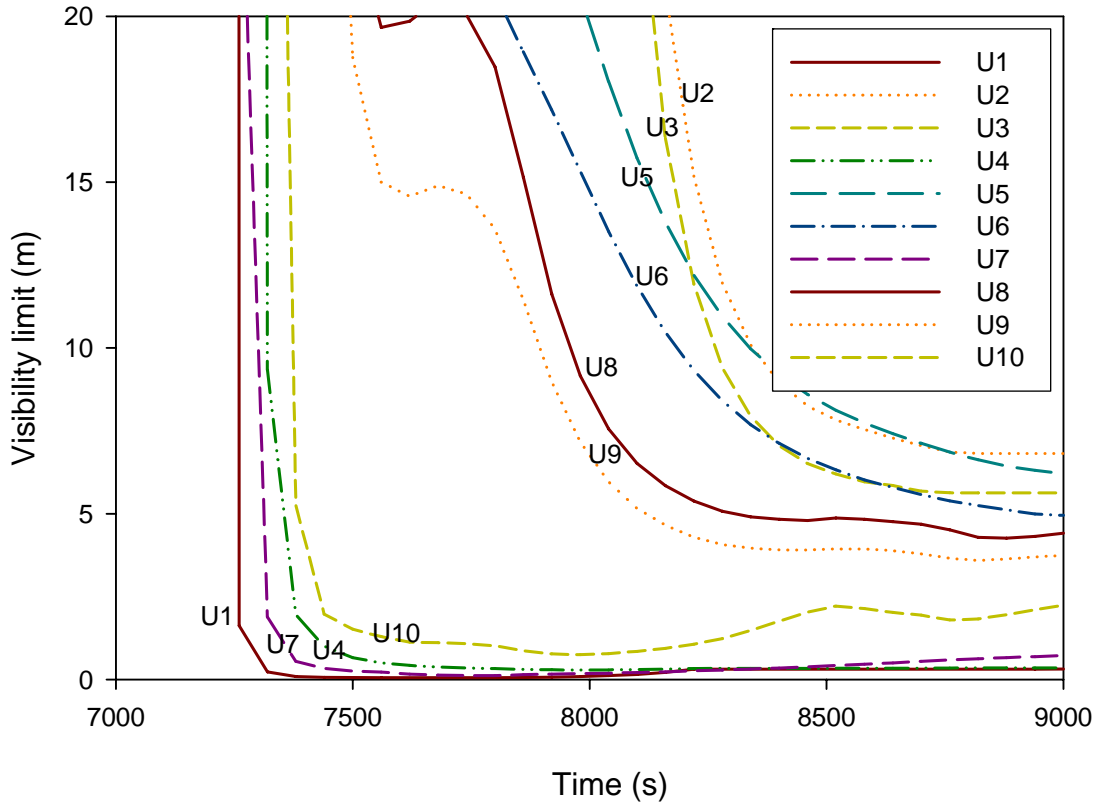
$$L = \frac{\ln(0.001)}{-8.7(1294.3st)}$$

where  $st$  is the dimensionless smoke concentration.

Figure 31 shows the visibility limits at the upper layers of the nine conditioned zones of the building and the unconditioned stairwell in Case 1\_2. As seen in Figure 31, the visibility was low in zones at the 1st floor (Zone 1, 4, and 7) and the stairwell. U\_1 in the figure represents the visibility limit of the upper layer in Zone 1.



**Figure 30.** Layer temperatures and smoke concentrations of zones served by AHU1 in Case 1\_2.

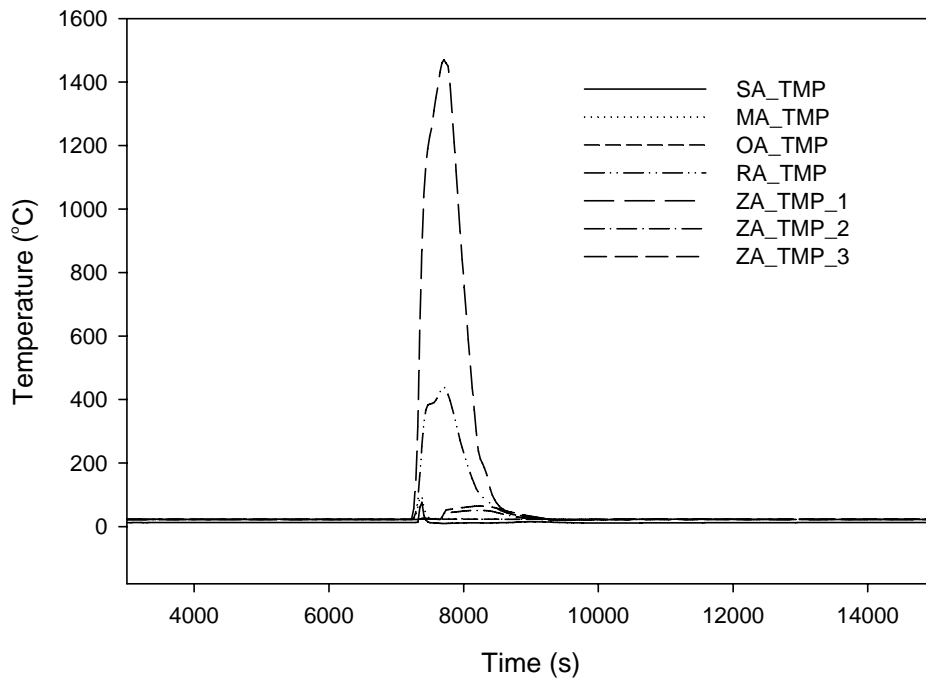


**Figure 31.** Visibility limits at the upper layers due to smoke in Case 1\_2.

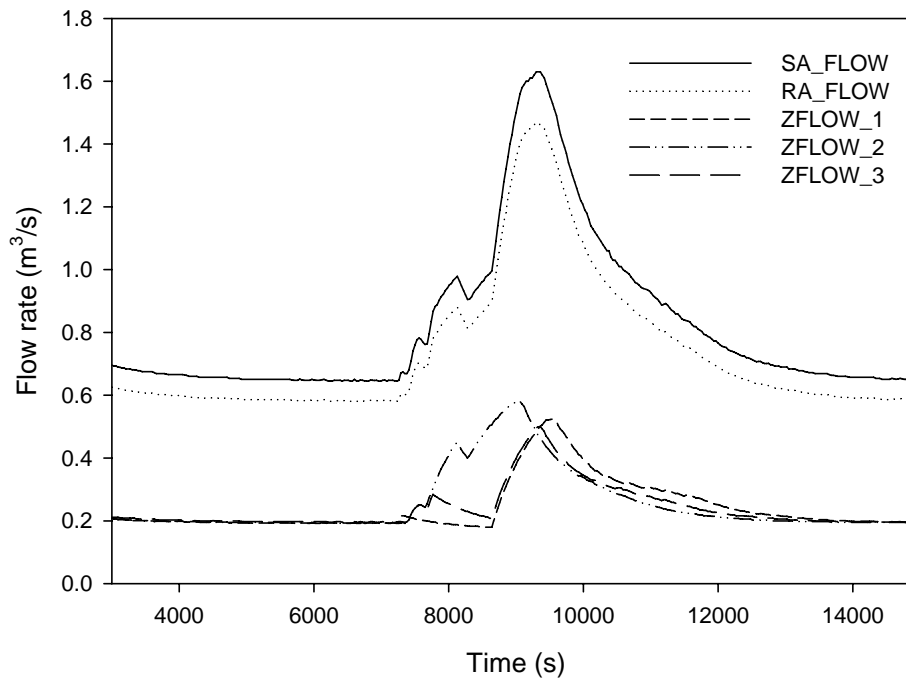
An emulation run (Case 1\_3) was performed with the same configuration as Case 1\_2 except that the AHU damper opening was allowed to obey the BMS enthalpy economizer command. Namely the restriction given to the damper opening to be 15 % at all times was removed. As a result, the AHU damper was opened fully whenever the return air enthalpy was greater than the outside air enthalpy. The temperatures, flow rates, and BMS control signals of AHU1 are shown in Figures 32 and 33. When ZA\_TMP\_2 and ZA\_TMP\_3 of Case 1\_3 are compared with those of Case 1\_2, quite different outcomes can be seen.

The zone air temperatures in Case 1\_3 other than in Zone 1 did not significantly increase. Since the most of the return air was exhausted and almost 100 % of fresh air entered into the mixing box when the AHU damper was fully open, the supply air temperature, SA\_TMP, and the mixed air temperature, MA\_TMP, were considerably lower despite the high temperature of the return air due to fire. Layer temperatures and smoke concentrations of the zones served by AHU1 in Case 1\_3 are shown in Figure 34. Compared with Figure 30a, it can be seen that the upper and lower temperatures of Zone 3 are much lower in this case. Those of Zone 1 also are slightly lower. Otherwise Figure 34 is very similar to Figure 30.

(a) Temperatures at AHU1 and return air temperatures from zones 1, 2, and 3

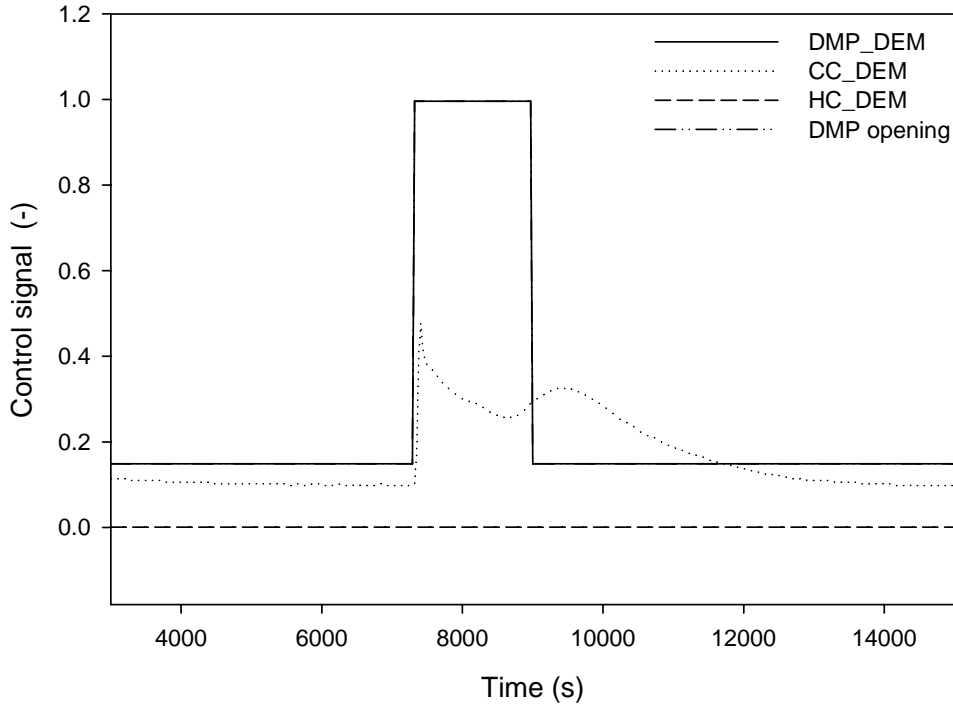


(b) Flow rates of AHU1 branch

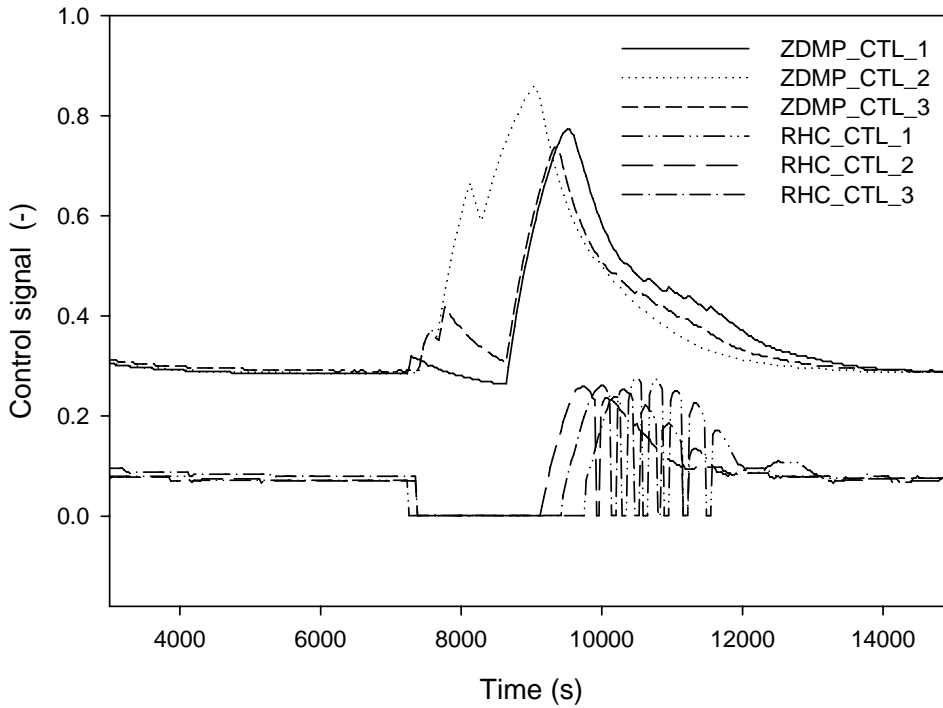


**Figure 32.** Temperatures, and flow rates of AHU1 in Case 1\_3.

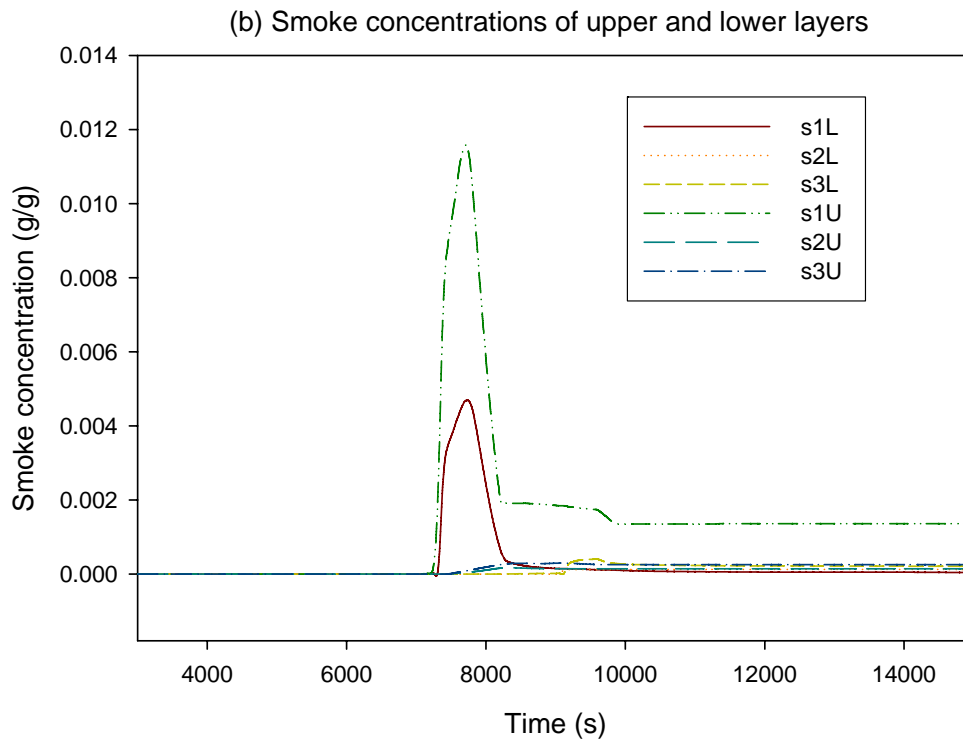
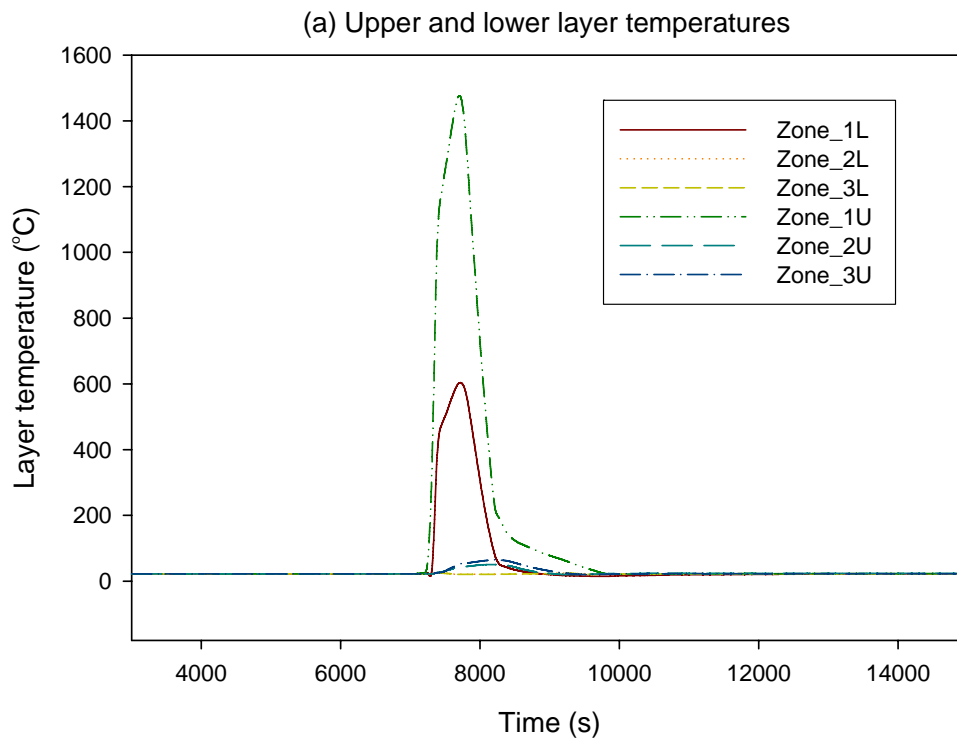
(a) Damper and coil opening demands by AHU1 controller



(b) VAV damper and reheat coil signals by VAV controllers



**Figure 33.** Control signals of AHU1 in Case 1\_3.



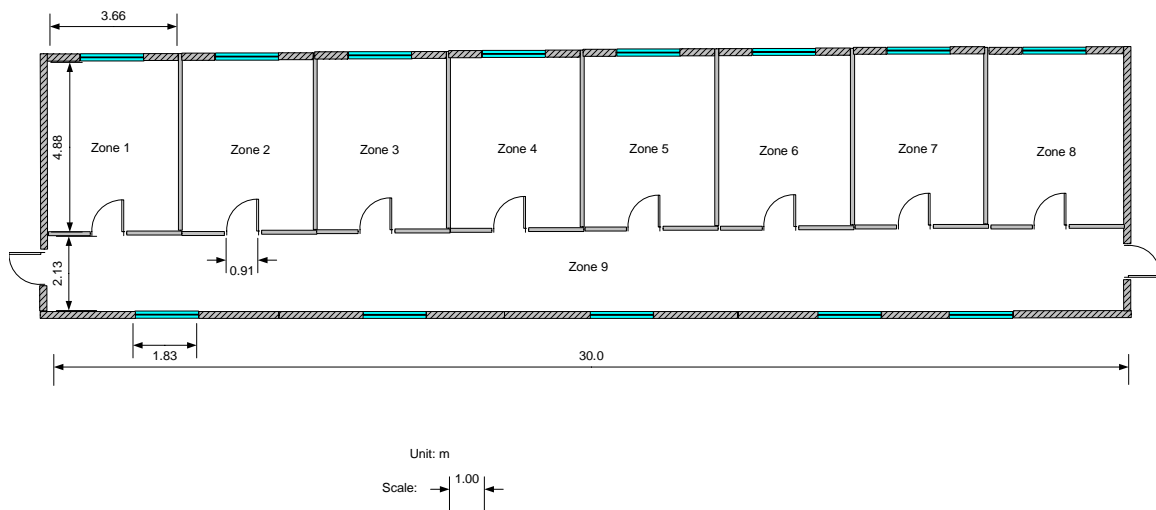
**Figure 34.** Layer temperatures and smoke concentrations of zones served by AHU1 in Case 1\_3.

## 4.2 Case 2 Scenario

Figure 35 shows a layout of a single-story virtual building. There are eight identically sized rooms (or zones) and a corridor. Each zone has a VAV box and each AHU serves 3 VAV boxes. AHU 1 serves for Zones 1, 2 and 3; AHU 2 for Zones 4, 5 and 6; and AHU 3 for Zones 7, 8 and 9, respectively as seen in Figure 36.

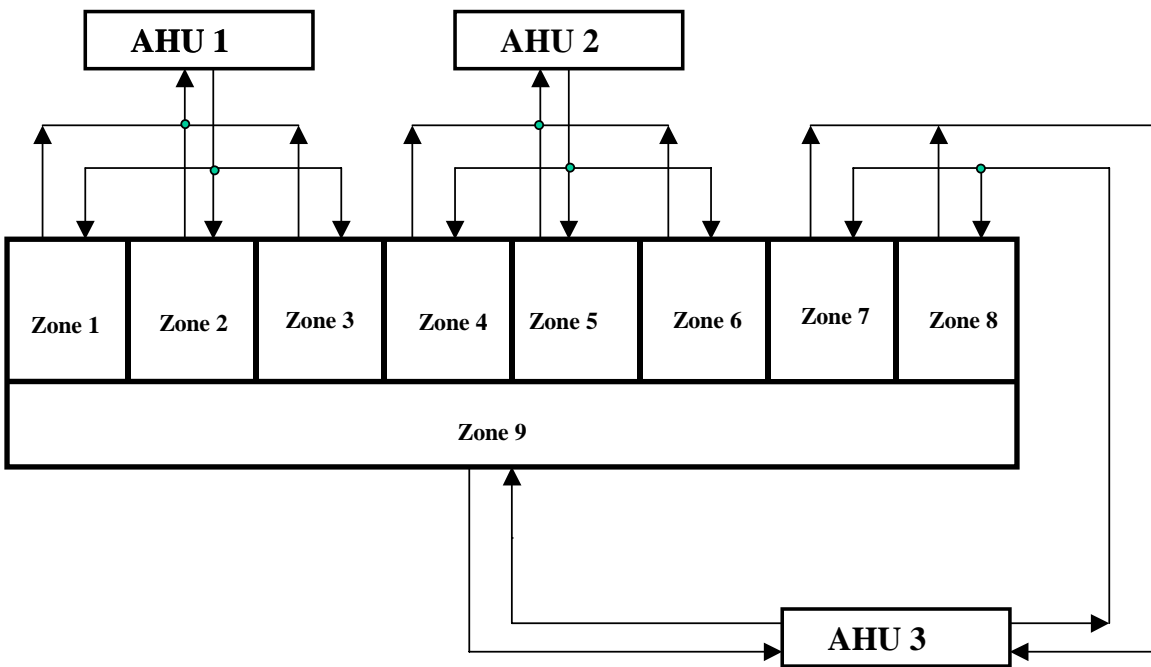
A fire was set in Zone 1 at 7200 s of emulation time. The enthalpy economizer cycle signal from BACnet AHU controller was ignored and set to the minimum damper position. Since all the zones are on the same floor, the fire-spreading pattern appeared quite different from the Case 1. Figures 37 and 38 shows temperatures, airflow rates, and BMS control signals of AHU1. SA\_TMP reached up to 960 °C, so did MA\_TMP. The return air temperature, RA\_TMP, went up to 1070 °C.

Layer temperatures and smoke concentrations of zones served by AHU1 are shown in Figure 39. Obviously the configuration makes quite different form of distribution of temperature as well as smoke compared with the previous scenario. As seen in Figure 40, visibility limits were very low in all the zones. No data of AHU2 and AHU3 are presented here.



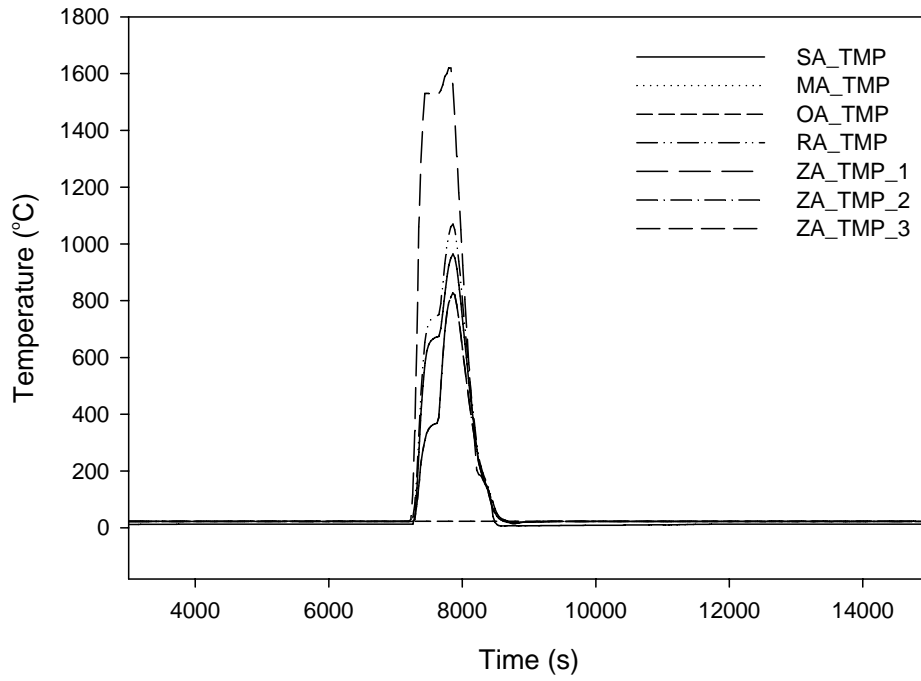
**Figure 35.** Floor layout of the virtual single-story building with eight identically sized zones in Case 2.



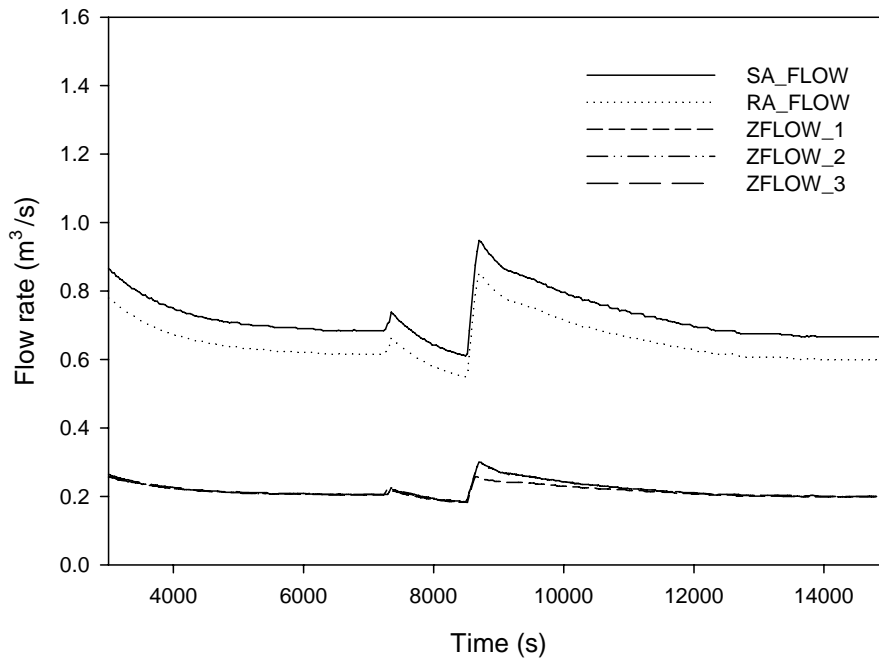


**Figure 36.** Air distribution for the single-floor building with eight same-size zones in Case 2.

(a) Temperatures at AHU1 and return air temperatures from zones 1, 2, and 3

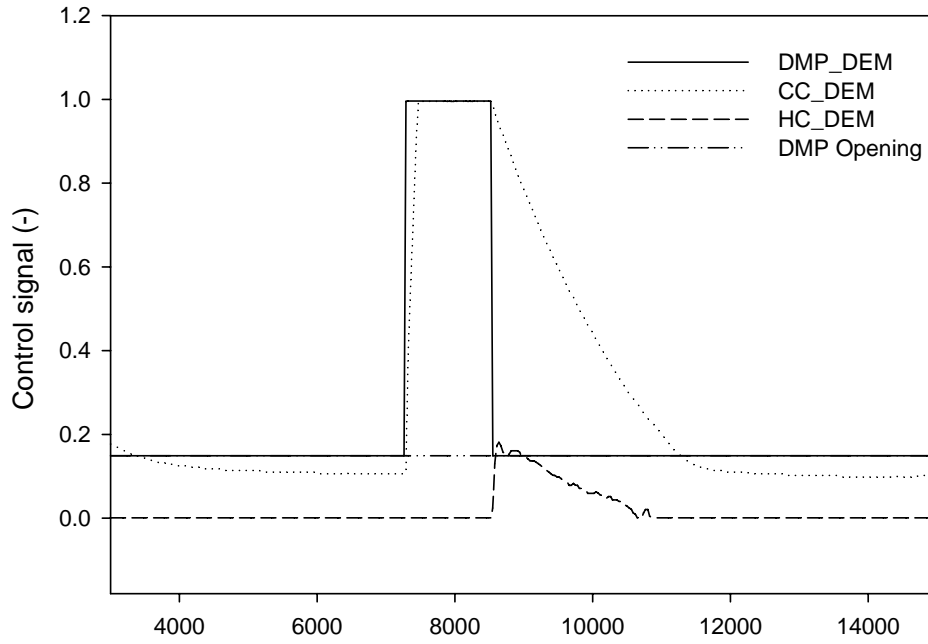


(b) Flow rates of AHU1 branch

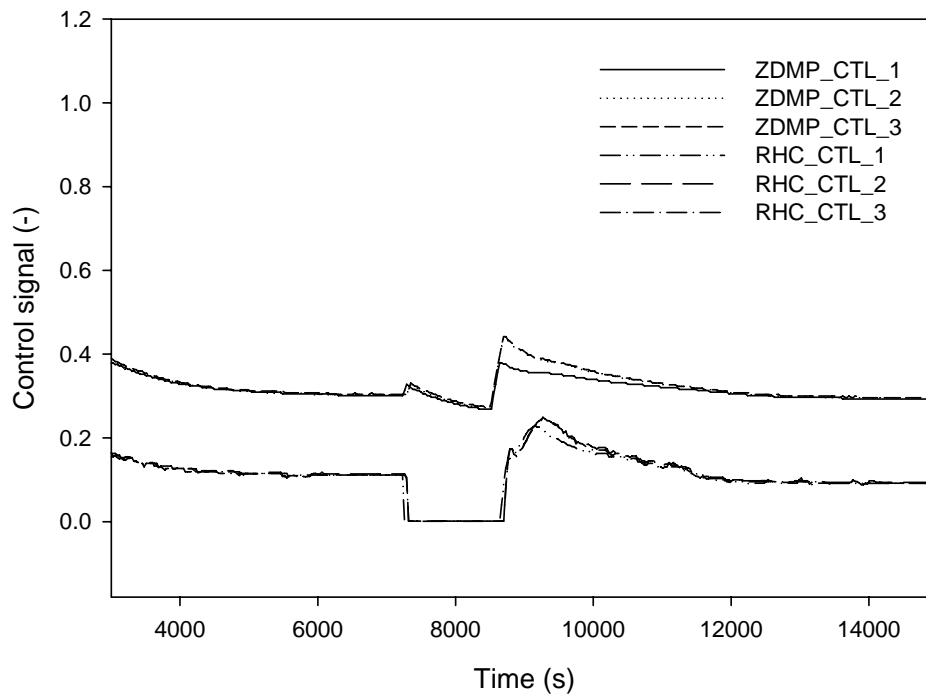


**Figure 37.** Temperatures, and flow rates of AHU1 in Case 2.

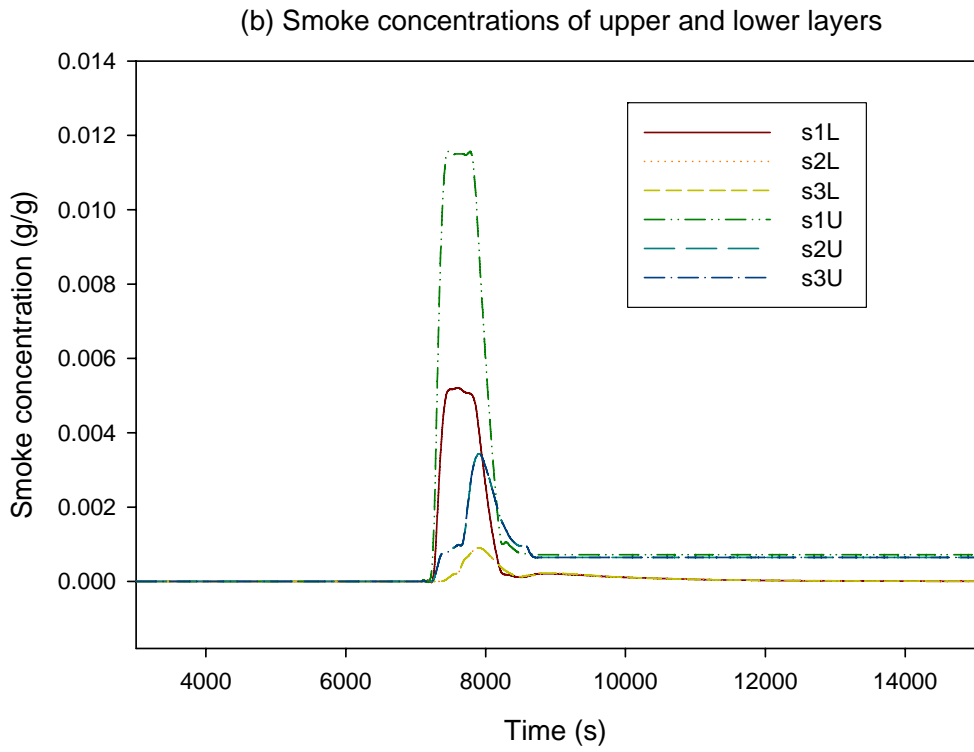
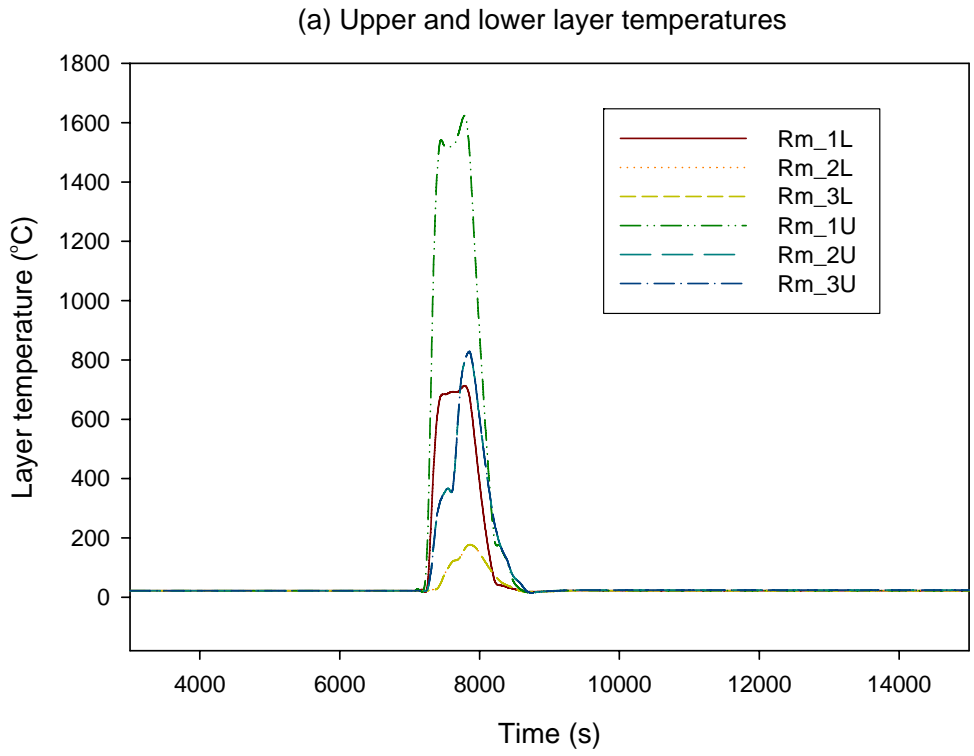
(a) Damper and coil opening demands by AHU1 controller



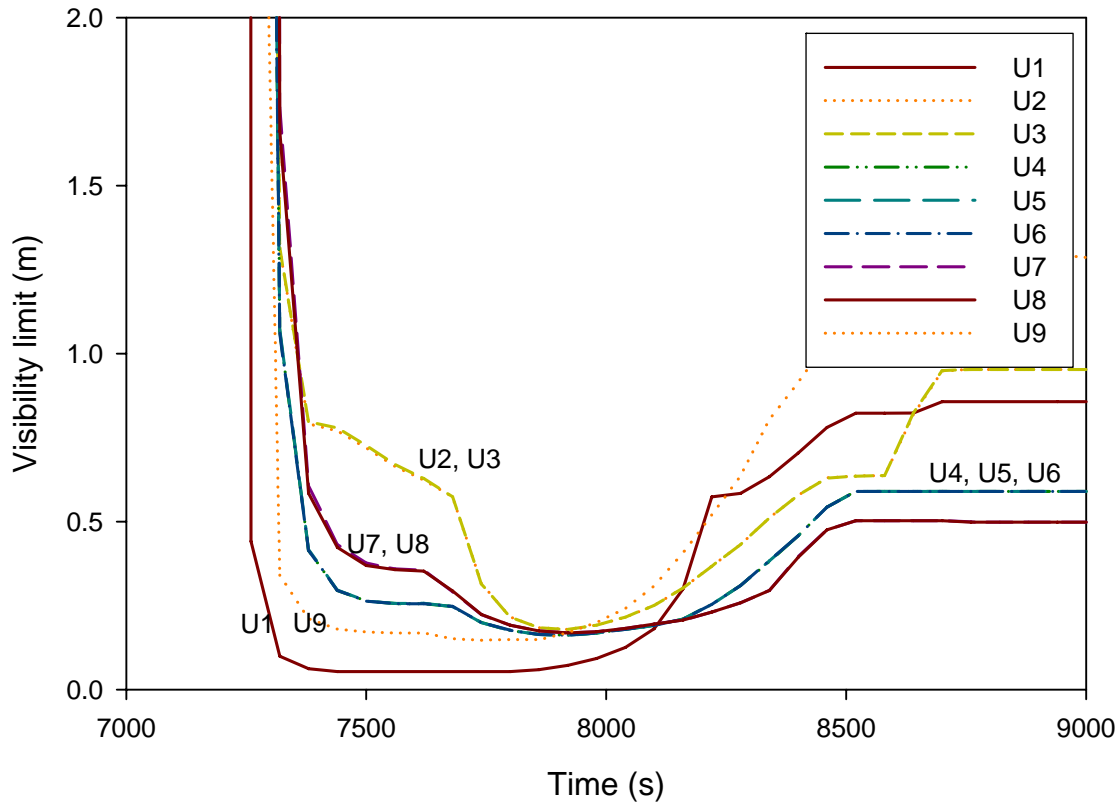
(b) VAV damper and reheat coil signals by VAV controllers



**Figure 38.** Control signals of AHU1 in Case 2.



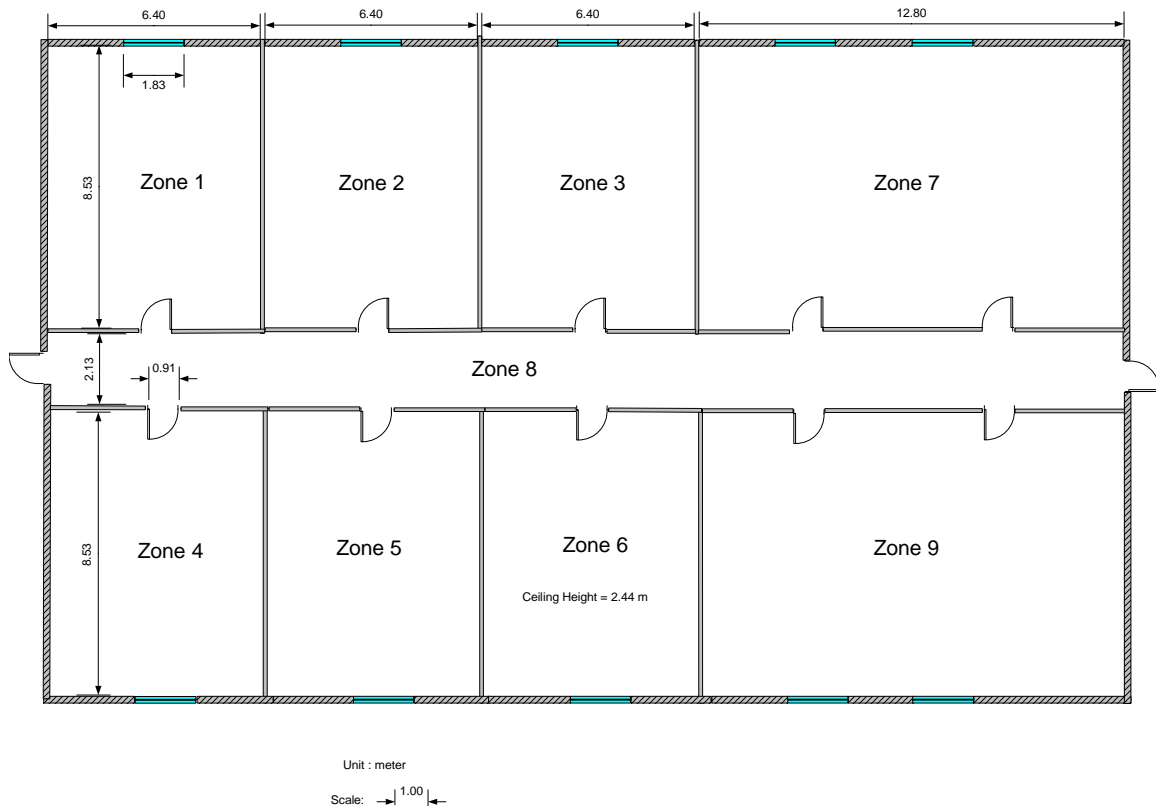
**Figure 39.** Layer temperatures and smoke concentrations of zones served by AHU1 in Case 2.



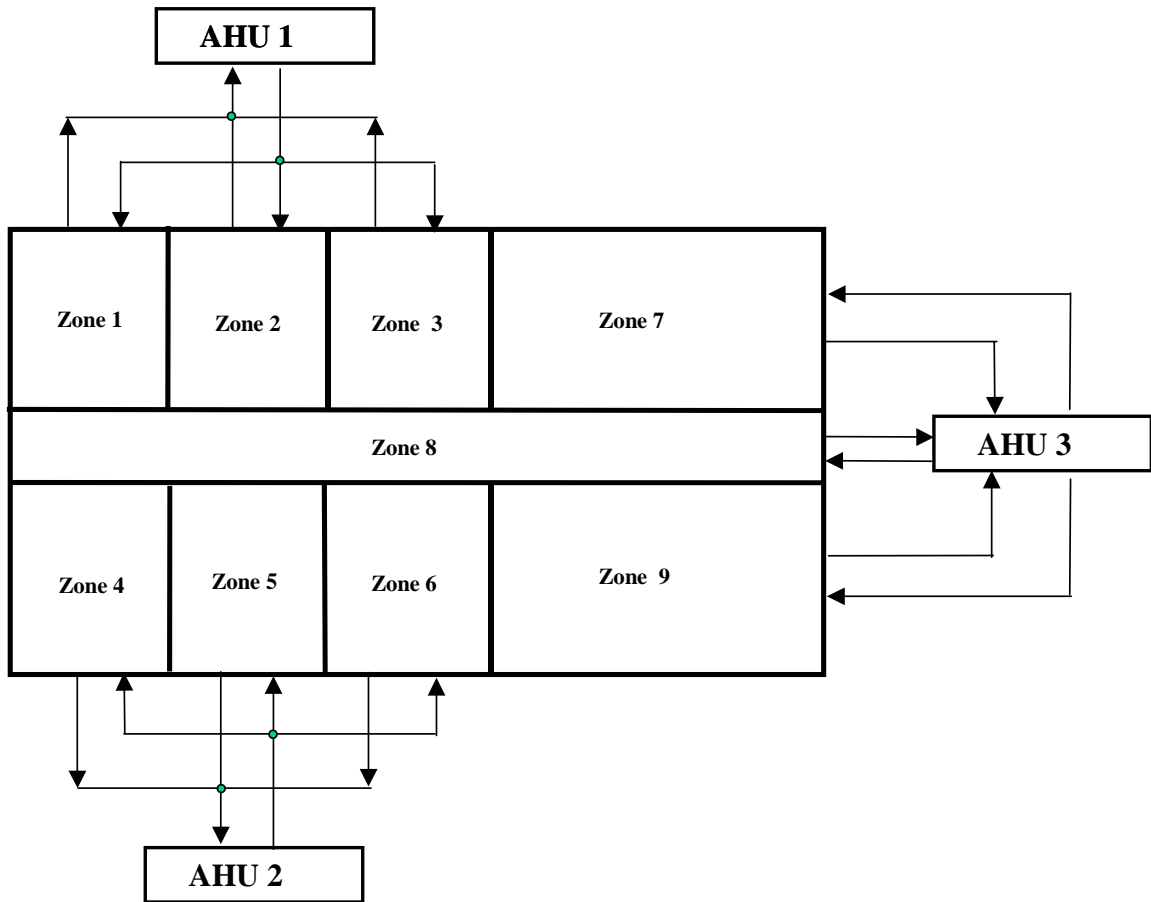
**Figure 40.** Visibility limits at the upper layers due to smoke in Case 2.

### 4.3 Case 3 Scenario

A virtual single-story building with nine zones with different sizes was considered. Figure 41 shows the floor layout and Figure 42 shows the air distribution by three air handling units. Each zone has a VAV box and each AHU serves three VAV boxes. AHU1 serves for Zone 1, 2, and 3; AHU2 for Zone 4, 5, and 6; AHU3 for Zone 7, 8, 9, respectively. Zone 8 is a corridor. As was done in Cases 1 and 2, fire was set in Zone 1, and the start time of fire was 7200 s of emulation time. The behavior of AHU1 is close to that in Case 2 as seen in Figures 43 and 44. Due to the different configuration, the time history of upper and lower layer temperature and smoke concentrations as shown in Figure 45 has some differences as expected. Quite low visibility in all zones can be seen in Figure 46.

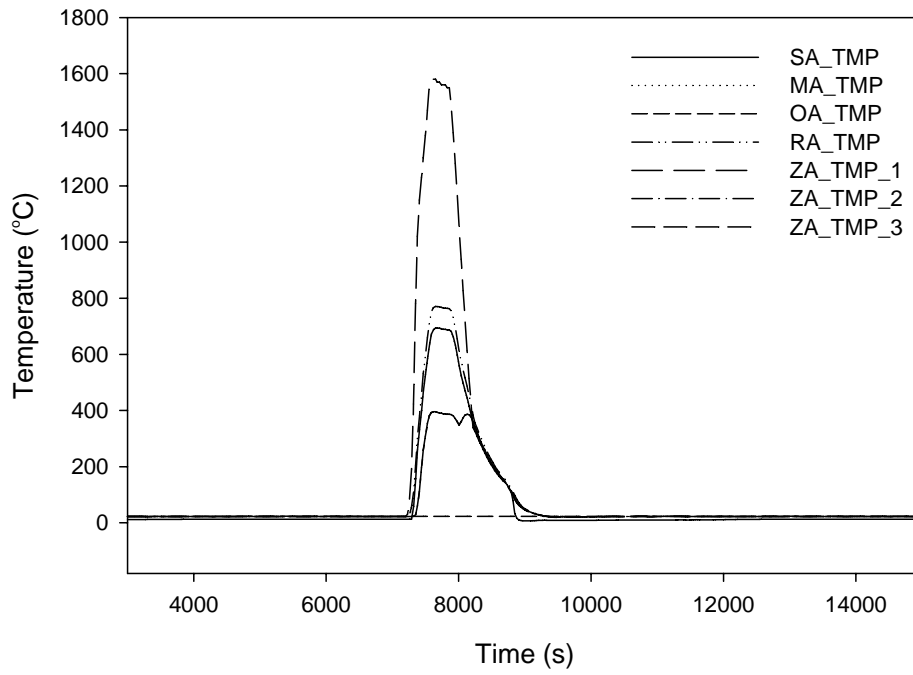


**Figure 41.** Floor layout of the single-story building with different size zones in Case 3.

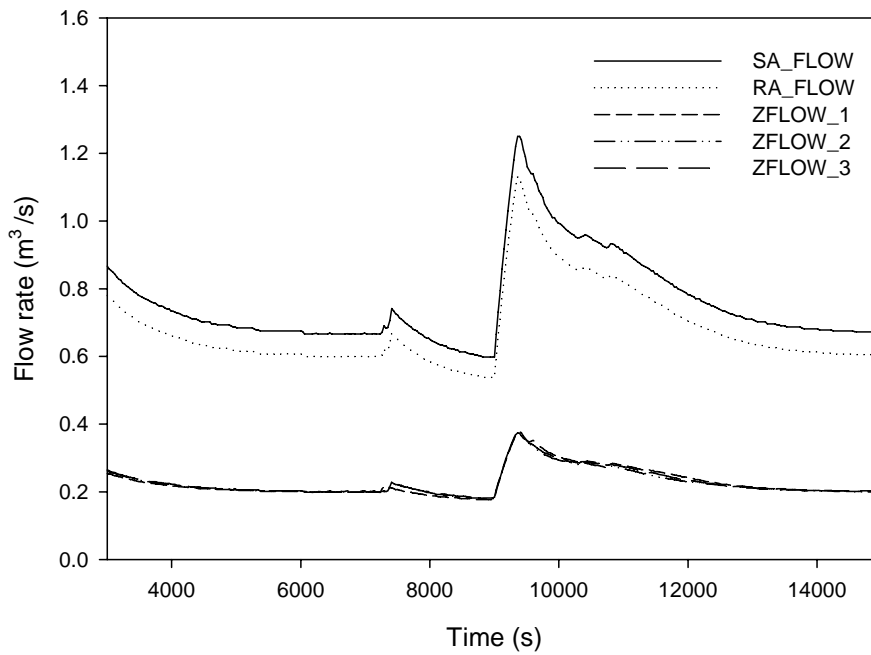


**Figure 42.** Air distribution for the virtual single-floor building with different size zones in Case 3.

(a) Temperatures at AHU1 and return air temperatures from zones 1, 2, and 3



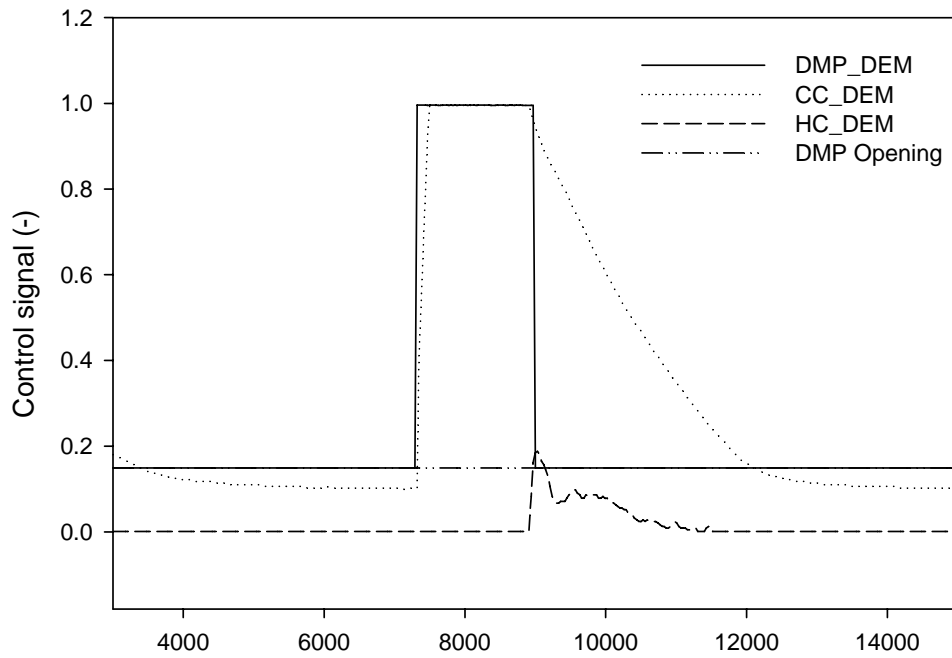
(b) Flow rates of AHU1 branch



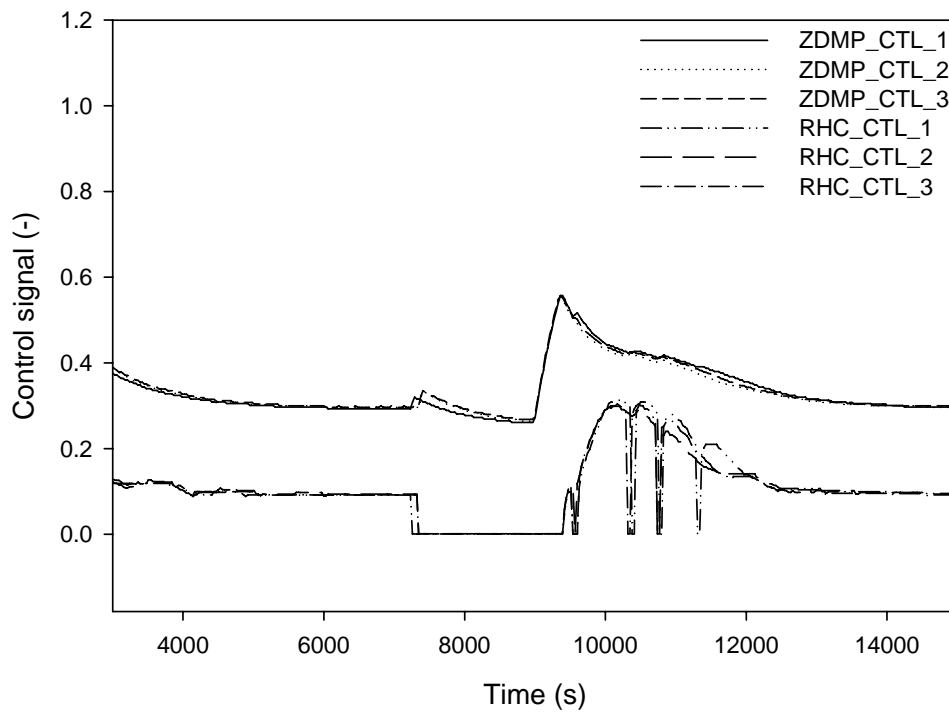
**Figure 43.** Temperatures, and flow rates of AHU1 in Case 3.



(a) Damper and coil opening demands by AHU1 controller

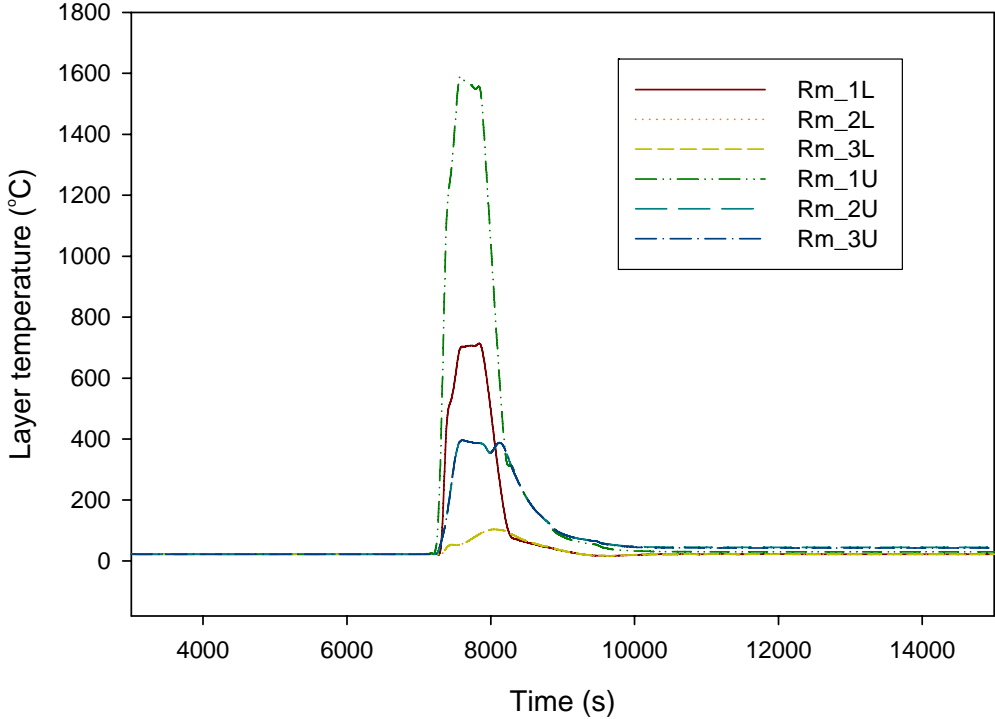


(b) VAV damper and reheat coil signals by VAV controllers



**Figure 44.** Control signals of AHU1 in Case 3.

(a) Upper and lower layer temperatures



(b) Smoke concentrations of upper and lower layers

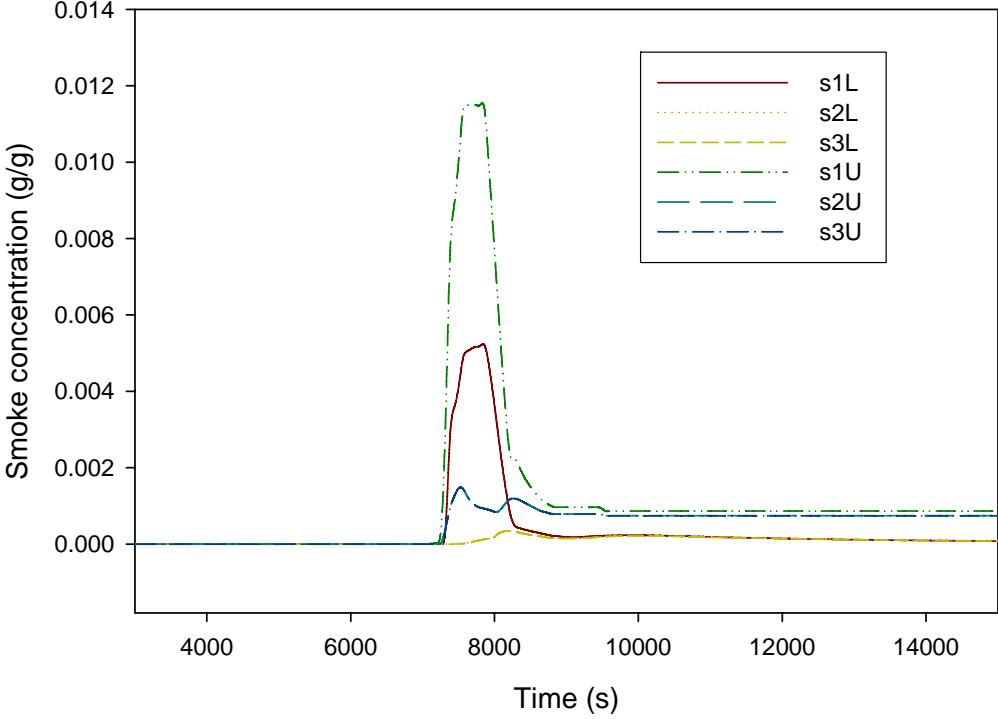
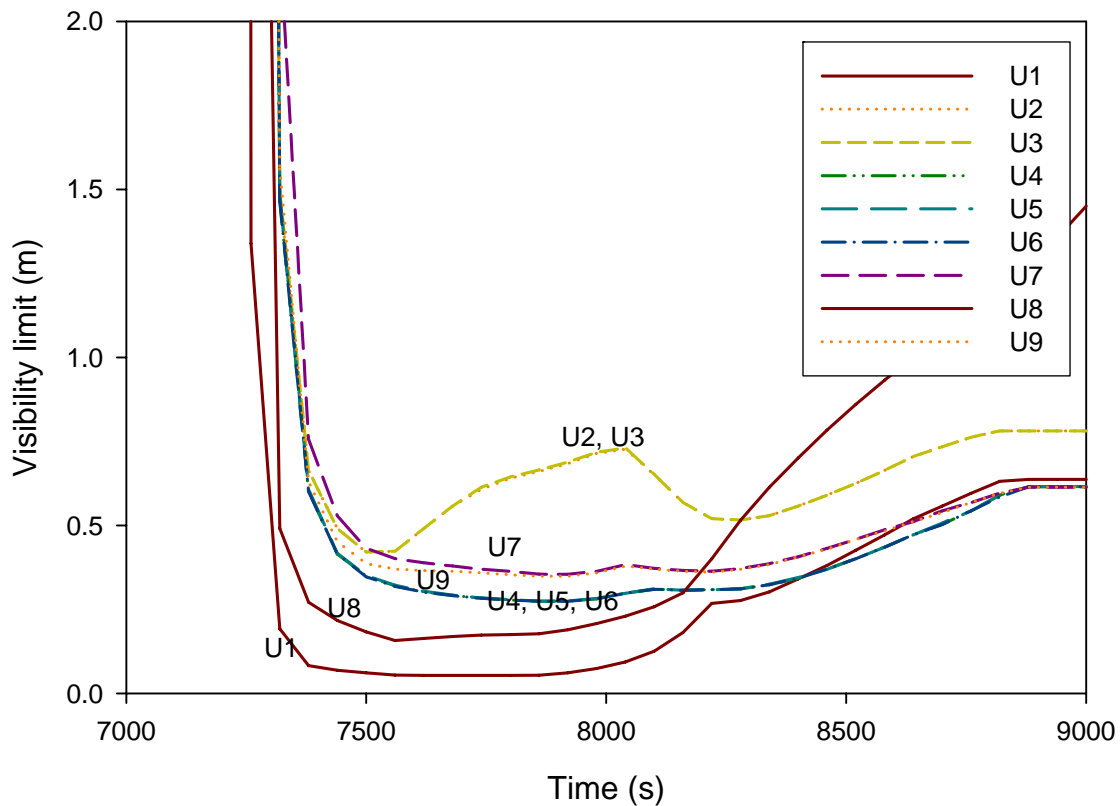


Figure 45. Layer temperatures and smoke concentrations in Case 3.



**Figure 46.** Visibility limits at the upper layers due to smoke in Case 3.

## 5. CONCLUSION

The VCBT has been enhanced and the overall structure of the current VCBT is reviewed in this preliminary report. ZFM-HVAC was added to the VCBT, the component models used in the HVAC-side of ZFM-HVAC were described and three scenarios were emulated. Some of the emulation results are presented graphically along with brief discussion. Interaction between building HVAC system and fire was demonstrated. In this study, nine conditioned space cases were utilized, because of availability of real BACnet controllers.

Recently, capability to dynamically configure the capacities of AHUs and VAVs based on the zone floor areas was added to ZFM-HVAC. Also simplification of input data to ZFM-HVAC was made. Additionally virtual AHU and VAV box controllers were added to the VCBT in order to emulate buildings with a large number of zones, not limited to nine zones as done this report.

## **6. REFERENCES**

1. May, W.B. & C. Park, Building Emulation Computer Program for Testing of Energy Management and Control System Algorithms, NBSIR 85-3291, NIST, 1985.
2. Kelly, G.E., C. Park, and J.P. Barnett, Using Emulators/Tester for Commissioning EMCS Software, Operator Training, Algorithm Development, and Tuning Local Control Loops, ASHRAE Trans., V. 97, Pt. 1, 1991.
3. Kohonen, R., et al., Development of Emulation Methods, IEA Annex 17 Report, August 1993.
4. Benninn, H., BACnet Virtual Building, Practical Training Report, University of Maryland, 1997.
5. Decious, G.M., C. Park, & G.E. Kelly, A Low-Cost Building/HVAC Emulator, Heating/Piping/AirConditioning, HPAC, Jan. 1997.
6. Fuhrmann, F., Integrating Multiple Programs over the Internet using CORBA, Practical Training Report, University of Maryland, 1999.
7. Bushby, S.T., N.S. Castro, M. Galler, C. Park, and J.M. House, Using the Virtual Cybernetic Building Testbed and FDD Test Shell for FDD Tool Development, NISTIR 6818, NIST, 2002.
8. Park, C., D.R. Clark, and G.E. Kelly, An Overview of HVACSIM<sup>+</sup>, A Dynamic Building/HVAC/Control Systems Simulation Program, Proceedings of the 1st Annual Building Energy Simulation Conf., Seattle, WA, August 21-22, 1985.
9. Castro, N.S., J. Schein, C. Park, M.A. Galler, S.T. Bushby, & J.M. House, Results from Simulation and Laboratory Testing of Air Handling Unit and variable Air Volume Box Diagnostic Tools, NISTIR 6964, NIST, 2003.
10. Bushby, S.T., Application Layer Communication Protocols for Building Energy management and Control Systems, ASHRAE Transactions 1988, V. 94, Pt. 2, ASHRAE, 1988.
11. Bushby, S.T., BACnet: A Standard communication Infrastructure for Intelligent Buildings, Automation in Construction, V. 6, No. 5-6, 1997.
12. Reneke, P.A., R.D. Peacock, G.P. Forney, and W.D. Davis, ZFM Zone Fire Model (Version 1) Reference Guide, (to be published in NIST publication).
13. Siegel, J., CORBA Fundamentals and Programming, John Wiley & Sons, 1996.

14. Norford, L.K. and P. Haves, A Standard Simulation Testbed for the Evaluation of Control algorithms and Strategies, ASHRAE Report 825-RP, ASHRAE, 1997.
15. Kusuda, T., Thermal Response Factors for Multilayer Structures of Various Heat Conduction Systems, ASHRAE Trans. V. 75, 1969, pp. 246-270.
16. WYEC2 User's Manual and Toolkit, ASHRAE contract 728-TRP, Augustyn+ Company, 1997.
17. Seborg, D.E., T.F. Edgar, and D.A. Mellichamp, Process Dynamic and Control, John Wiley & Sons, 1989.
18. Treado, S., S.C. Cook, & M. Galler, Distributed Biometric Access Control Testbed, NISTIR 7190, NIST, 2004.
19. Peacock, R.D., G.P. Forney, P. Reneke, R. Portier, and W.W. Jones, CFAST, the Consolidated Model of Fire Growth and Smoke Transport, NIST Tech. Note 1299, NIST, 1993.
20. Mulholland, G.W., and E.L. Johnson, A New Smoke Concentration Meter, 3<sup>rd</sup> International Conf. on Fire Research and Engineering, Chicago, IL, Oct. 4-8, 1999.

Appendix A. Sample BACnet Air-handling Unit Controller Object Database.

BACnet Objects of a VAV Air-handling Unit Controller				
Object	Description	Default	Remarks	
AI-0	Supply Air Temperature	n/a	0 to 5 volts = 0 °F to 200 °F	
AI-1	Supply Air Pressure	n/a	0 to 5 volts = 0" to 5"	
AI-2	Return Air Temperature	n/a	0 to 5 volts = 0 °F to 100 °F	
AI-3	Return Air Humidity	n/a	0 to 5 volts = 0 % to 100 %	
AI-4	Outside Air Temperature	n/a	0 to 5 volts = -50 °F to 150 °F	
AI-5	Outside Air Humidity	n/a	0 to 5 volts = 0 % to 100 %	
AI-6	Supply Flow Rate	n/a	0 to 5 volts = 0 to 8000 CFM	
AI-7	Return Flow Rate	n/a	0 to 5 volts = 0 to 8000 CFM	
AI-8	Mixed Air Temperature	n/a	0 to 5 volts = -50 °F to 150 °F	
BI-9	Supply Flow Proof	n/a	0 volts = Fan ON, 5 volts = Fan OFF	
BI-10	Return Flow Proof	n/a	0 volts = Fan ON, 5 volts = Fan OFF	
BO-0	Supply Fan	n/a		
BO-1	Return Fan	n/a		
AO-0	Supply Fan Speed		0 to 10 volts = 0 % to 100 %	
AO-1	Cooling Coil		0 to 10 volts = 0 % to 100 %	
AO-2	Heating Coil		0 to 10 volts = 0 % to 100 %	
AO-3	Economizer		0 to 10 volts = 0 % to 100 %	
AO-4	Return Fan Speed		0 to 10 volts = 0 % to 100 %	
AV-0	Temperture Ctrl Signal	0		
AV-28	OSA Enthalpy	0		
AV-29	Return Enthalpy	0		
AV-40	Min. Return Fan Speed	20		
AV-41	Min. Supply Fan Speed	20		
AV-42	Supply/Return CFM Differential	1000		
AV-43	Dehumidifying Supply Temp. Setpoint	50		
AV-44	Current Supply Temp. Setpoint	0		
AV-45	Supply Temp. SP Reset Loop	0		
AV-46	Highest Cooling Signal (from VAV's)	0		
AV-47	Supply Pressure SP Reset Loop	0		
AV-48	Current Supply Pressure Setpoint	0		
AV-49	Highest Need More Air Signal (from VAV's)	0		
AV-50	Supply Pressure Setpoint - Warmup	1.4		
AV-51	Supply Pressure Setpoint - Hi Limit	2		
AV-52	Supply Pressure Setpoint - Lo Limit	0.2		
AV-53	Supply Pressure Setpoint - Manual/Startup	1		
AV-55	Supply Temp. Setpoint - Hi Limit	65		
AV-56	Supply Temp. Setpoint - Lo Limit	50		
AV-57	Supply Temp. Setpoint - Manual/Startup	60		
AV-58	Supply Temp. Setpoint - Warmup	160		
AV-60	Supply Temp. Low Limit	50		
AV-66	Econ Min. Position %	15		
AV-80	Humidity Hi Limit	60		
BV-20	Alarm Reset	OFF		
BV-26	Supply Fan Alarm	OFF		
BV-28	Return Fan Alarm	OFF		
BV-32	Economizer Lockout Status	OFF	ON = Econ. locked out	
BV-40	Occupied Command	OFF	Starts AHU, Econ. to Min. Position	
BV-41	WarmupCommand	OFF	Starts AHU, Econ. stays closed	
BV-43	Return Fan Proof	OFF	Transferred from BI-9	
BV-46	Supply Fan Proof	OFF	Transferred from BI-10	
BV-47	Supply Pressure Setpoint Reset Switch	OFF	ON = Autoreset, OFF = Manual	
BV-48	Supply Temp. Setpoint Reset Switch	OFF	ON = Autoreset, OFF = Manual	
BV-49	Dehumidifying	OFF	Indicates system is dehumidifying	

*Appendix B. Sample BACnet VAV Box Controller Object Database.*

BACnet Objects of a VAV Box Controller						
Object	Description	Default	Remarks			
AI-0		n/a	not used			
AI-1	Room Temp.	n/a	0 to 5 volts = 30 °F to 130 °F			
AI-2	Discharge Air Temp.	n/a	0 to 5 volts = 40 °F to 190 °F			
AI-3	Airflow Rate	n/a	0 to 5 volts = 0 to 4000 CFM			
AO-0	Damper Command	OFF	0 to 10 volts = Full closed to full open			
AO-1	Heating Valve Command	OFF	0 to 10 volts = Full closed to full open			
AO-2		OFF	not used			
AV-0	Heating Signal	0				
AV-1	Cooling Signal	0				
AV-4	Desired Airflow - Cold	0	CFM			
AV-6	Occupied Heating Setpoint	0				
AV-7	Occupied Cooling Setpoint	0				
AV-9	Cooling Damper Position %	0				
AV-10	Need More Air - Clg	0				
AV-14	Heating Valve Position %	0				
AV-20	Windsock - Cold ( 0 to 1)	0				
AV-64	Cooling Damper Time	60	seconds			
AV-65	Heating Valve Time	60	seconds			
AV-66	Reheat Air - CFM	300	Desired airflow when htg valve full open			
AV-67	Max Airflow - CFM	1000				
AV-68	Min. Airflow - CFM	100	Min. air applies only when occupied			
AV-90	Occupied Setpoint	72	Limited by AV-91 and AV-92			
AV-91	Occupied Setpoint - Hi Limit	80	Limit for AV-90			
AV-92	Occupied Setpoint - Lo Limit	65	Limit for AV-90			
AV-93	Cooling Offset	1				
AV-94	Heating Offset	1				
AV-95	Unoccupied Cooling Setpoint	85				
AV-96	Unoccupied Heating Setpoint	55				
AV-97	Afterhours Timer Limit	0	Duration for Microtouch			
AV-98	Afterhours Timer (hr)	0	Automatically counts down to 0			
AV-99	Current Cooling Setpoint	0	Calculated			
AV-100	Current Heating Setpoint	0	Calculated			
AV-101	Microset Room Temp.	0	Use DDC to transfer AI to this AV			
AV-102	Humidity from Microset	0				
AV-103	Outside Air Temp.	0	Transfer from Lsi			
AV-104	Mictouch Lever Offset	0	Calculated from current lever position			
AV-105	Mictouch Bias Limit	0	Assigned Offset for full stroke			
AV-106	Demand Offset	0	Transfer from Lsi			
BV-0	Bad Sensor Alarm	OFF				
BV-1	Heating/Cooling Mode: On= Heating	OFF				
BV-2	Persistent Communication Fail	OFF				
BV-7	Main Air Status - Cold	OFF				
BV-8	Warm Air in Duct	OFF				
BV-9	Force Min. Air - Cold	OFF				
BV-10	Force Reheat Air	OFF				
BV-11	Force Max. Air - Cold	OFF				
BV-12	Force Open - Cold	OFF				
BV-13	Force Closed - Cold	OFF				
BV-19	Day Mode 2 hour Delay	OFF				
BV-24	Space Too Warm	OFF				
BV-25	Space Too Cold	OFF				
BV-38	Heating Lockout	OFF	Used for demand control			
BV-39	Cooling Lockout	OFF	Used for demand control			
BV-40	Occupied Command	OFF	Typically sent from Lsi			
BV-41	Optimum Start Heating	OFF				
BV-42	Optimum Start Cooling	OFF				
BV-64	Occupied SP's Command	OFF	Turns ON Micset and BV-67			
BV-65	OFF Mode Enable	OFF	OFF button ends daymode			
BV-66	Afterhour Timer Status	OFF	ON when AV-98 > 0, otherwise OFF			
BV-67	Occupied Status	OFF	Determined by BV-64 to BV-66			
BV-68	Field Service Lockout	OFF	ON = Field Service Locked out			
BV-69	English/Metric display Swap	OFF	OFF = Use VLC Mode, ON = Swap			
BV-70	Microset Present Flag	OFF	ON = Microset Present			
BV-71	English/Metric VLC Mode	OFF	OFF = English, Read Only			

Appendix C. Fire-related Input Data for Case 1\_1.

File name: zfm-hvac.inp

```
ROOMS      ! Case 1_1: Three-story building with a small fire 08/05/05
10
0.0  8.53  6.40  2.9      ! elevation, length, width, height
2.9  8.53  6.40  2.9
5.8  8.53  6.40  2.9
0.0 17.37  6.40  2.9
2.9 17.37  6.40  2.9
5.8 17.37  6.40  2.9
0.0 25.91  9.14  2.9
2.9 25.91  9.14  2.9
5.8 25.91  9.14  2.9
0.0  3.05  4.88  8.7

VENTS      ! number of vents
11         ! from room#, to room#, bottom, top, width
          ! from room 7 to outside (door)
7  0  0.  2.  0.91
7  0  0.  2.  0.91
7 10  0.  2.  0.91
7  1  0.  2.  0.91
7  4  0.  2.  0.91
8 10  0.  2.  0.91
8  2  0.  2.  0.91
8  5  0.  2.  0.91
9 10  0.  2.  0.91
9  3  0.  2.  0.91
9  6  0.  2.  0.91

SOLVEPRODS
FIRES
1         ! nfires
1  3  0.1  1  5.0e+7  0.002  0.5  0.2 ! room#, type, elevation, flag, heat_c,
species(i=2,3,4)
6         ! number of points
          ! time, heat release rate(kW)
          0.         0.
          60.        100.
          70.        200.
          100.       350.
          1800.      400.
          1900.      000.

HSIM
9         ! number of HVAC paths
1 1.5 2.0 1 1.5 2.0 ! supply room#, duct bottom, top, return room#,
duct bottom, top
1 1 1         ! AHU#, return path#, supply path#
2 1.5 2.0 2 1.5 2.0
1 2 2
3 1.5 2.0 3 1.5 2.0
1 3 3
4 1.5 2.0 4 1.5 2.0
2 1 1
5 1.5 2.0 5 1.5 2.0
2 2 2
6 1.5 2.0 6 1.5 2.0
2 3 3
7 1.5 2.0 7 1.5 2.0
3 1 1
8 1.5 2.0 8 1.5 2.0
```



```

3 2 2
9 1.5 2.0 9 1.5 2.0
3 3 3
PLOT
zfm-hvac
TIME
    0.0      50000.0      ! start time, end time
    0.0      2.897 300. 300. ! pressure, layer height, lower layer temp,
upper layer temp
    0.0      2.897 300. 300.
    0.0      2.897 300. 300.
    0.0      2.897 300. 300.
    0.0      2.897 300. 300.
    0.0      2.897 300. 300.
    0.0      2.897 300. 300.
    0.0      2.897 300. 300.
    0.0      2.897 300. 300.
    0.0      8.697 300. 300.

```

### Appendix D. HVAC-side Configuration Input Data

File name: run\_hvac.inp

```

3                                ! n_ahu
3, 3, 3                          ! nbr
AHU1.inp                        ! (1) AHU 1
AHU2.inp                        ! (2) AHU 2
AHU3.inp                        ! (3) AHU 3
VAV1.inp                        ! (4) AHU 1 (Zone 3, 2, 1)
VAV2.inp                        ! (5) AHU 2 (Zone 6, 5, 4)
VAV3.inp                        ! (6) AHU 3 (Zone 9, 8, 7)
AHU1init.inp                    ! (7) AHU 1 Initial data
AHU2init.inp                    ! (8) AHU 2 Initial data
AHU3init.inp                    ! (9) AHU 3 Initial data
AHUout1.out                      ! (10) AHU 1, 2, & 3 Output data
AHUout2.out                      ! (11) AHU 1, 2, & 3 Output data

```

## Appendix E. Sample AHU Input Data

### File name: AHU1.inp

! AHU1.inp Changed for ZFM-HVAC model  
! Base data file: emuex29i.mod

UNIT 17 TYPE 321 ----- OA damper  
Motor-driven actuator

- 1 INPUTS:  
CONTROL 149 - demanded position
- 2 OUTPUTS:  
CONTROL 38 - position of final control element  
CONTROL 0 - motor position  
CONTROL 133 - number of stops/starts/reversals  
CONTROL 0 - total distance traveled by final control element
- 3 PARAMETERS:  
1.00000 direction: 1=forward, -1=reverse, 0=stuck  
0.00000 starting position (0-1)  
125.000 travel time (lim-lim) (s)  
0.00000 minimum change in demanded position for movement (-)  
0.00000 hysteresis (-)  
0.00000 crank travel angle (0 for linear) (deg)  
1.00000 Upper limit of control element range on actuator scale  
0.00000 Lower limit of control element range on actuator scale

UNIT TYPE ----- AHU  
Mixing box (simplified)

- 1 INPUTS:  
TEMPERATURE 1 - Outside air dry bulb temperature  
HUMIDITY 1 - Outside air humidity ratio  
TEMPERATURE 54 - Extract air dry bulb temperature  
HUMIDITY 16 - Extract air humidity ratio  
FLOW 29 - Extract air mass flow rate  
CONTROL 38 - Outside air damper position (0=closed, 1=open)  
OTHER 8 - incoming smoke concentration
- 2 OUTPUTS:  
TEMPERATURE 2 - Mixed air dry bulb temperature  
HUMIDITY 2 - Mixed air humidity ratio  
FLOW 2 - Mixed air mass flow rate  
FLOW 1 - Total outside dry air mass flow rate  
FLOW 30 - Recirc air mass flow rate  
FLOW 47 - Exhaust air mass flow rate  
OTHER 3 - outgoing smoke concentration
- 3 PARAMETERS:  
0.100000 leakage factor of zones (-)  
0.000000 Economizer on = 1, off = 0 (-)  
0.100000 Minimum damper opening (-)

UNIT 67 TYPE 321 ----- Heating coil valve  
Motor-driven actuator

- 1 INPUTS:  
CONTROL 159 - demanded position
- 2 OUTPUTS:  
CONTROL 85 - position of final control element  
CONTROL 0 - motor position  
CONTROL 83 - number of stops/starts/reversals  
CONTROL 0 - total distance traveled by final control element

- 3 PARAMETERS:
- 1.00000 direction: 1=forward, -1=reverse, 0=stuck
  - 0.00000 starting position (0-1)
  - 125.000 travel time (lim-lim) (s)
  - 0.00000 minimum change in demanded position for movement (-)
  - 0.00000 hysteresis (-)
  - 0.00000 crank travel angle (0 for linear) (deg)
  - 1.00000 Upper limit of control element range on actuator scale
  - 0.00000 Lower limit of control element range on actuator scale

UNIT 68 TYPE 524 ----- Heating coil and valve  
Coil + three port valve, calculates flow

- 1 INPUTS:
- TEMPERATURE 2 - Inlet air dry bulb temperature
  - HUMIDITY 2 - Inlet air humidity ratio
  - PRESSURE 47 - Outlet air pressure
  - FLOW 2 - Dry air mass flow rate
  - TEMPERATURE 78 - Inlet water temperature
  - PRESSURE 48 - Inlet water pressure
  - PRESSURE 49 - Outlet water pressure
  - CONTROL 85 - Valve stem position
  - TEMPERATURE 79 - Effective coil surface temperature

- 2 OUTPUTS:
- TEMPERATURE 79 - Effective coil surface temperature
  - TEMPERATURE 80 - Outlet dry bulb air temperature
  - HUMIDITY 17 - Outlet air humidity ratio
  - PRESSURE 0 - Inlet air pressure
  - TEMPERATURE 81 - Outlet water temperature
  - FLOW 0 - Primary circuit water mass flow rate
  - FLOW 48 - Water mass flow rate through coil
  - TEMPERATURE 0 - Mixed return water temperature
  - POWER 10 - Total heat transfer to the air
  - CONTROL 0 - Sensible heat ratio
  - CONTROL 0 - Coil effectiveness
  - CONTROL 0 - Coil by-pass factor
  - ENERGY 0 - Outlet air specific enthalpy
  - CONTROL 0 - Outlet air relative humidity
  - TEMPERATURE 0 - Outlet air wet-bulb temperature

- 3 PARAMETERS:
- 1.00000 Method : 0 = steady state, 1 = dynamic
  - 0.00000 Fault : 0 for no faults, 1 = parallel flow (cooling co
  - 0.00000 Psycho : 0 = no psychrometric output calcs, 1 = calcs
  - 1.00000 Number of rows of tubes
  - 18.0000 Number of tubes per row
  - 18.0000 Number of parallel water circuits
  - 0.60000E-01 Length of finned section in direction of flow (m)
  - 1.37000 Height of finned section (m)
  - 2.77000 Width of finned section (m)
  - 0.159000E-01 Tube outside diameter (m)
  - 0.787400E-03 Tube wall thickness (m)
  - 2.00000 Tube material (Al=1,Cu=2,Fe=3,CaCO3=4)
  - 0.212000E-02 Fin spacing (pitch) (m)
  - 0.216000E-03 Fin thickness (m)
  - 1.00000 Fin material (Al=1,Cu=2,Fe=3)
  - 0.802500E-03 Flow resistance on air side (1000/kg.m)
  - 0.600000 Coil water flow resistance (1000/kg.m)
  - 0.100000E+07 By-pass water flow resistance (1000/kg.m)
  - 1.00000 Valve type: 0=lin/lin, 1=eq%(flow)/lin(byp), 2=lin/eq%
  - 5.43600 Valve capacity (Kv) (m3/hr @ 1 bar)
  - 3.54000 Valve curvature parameter (0=linear) (-)
  - 24.5100 Valve rangability (-)
  - 0.100000E-03 Valve leakage (fractional flow) (-)

UNIT 20 TYPE 321 ----- Cooling coil valve  
Motor-driven actuator

- 1 INPUTS:

- CONTROL 150 - demanded position
- 2 OUTPUTS:  
CONTROL 41 - position of final control element  
CONTROL 0 - motor position  
CONTROL 136 - number of stops/starts/reversals  
CONTROL 0 - total distance traveled by final control element
- 3 PARAMETERS:  
1.00000 direction: 1=forward, -1=reverse, 0=stuck  
0.00000 starting position (0-1)  
125.000 travel time (lim-lim) (s)  
0.00000 minimum change in demanded position for movement (-)  
0.00000 hysteresis (-)  
0.00000 crank travel angle (0 for linear) (deg)  
1.00000 Upper limit of control element range on actuator scale  
0.00000 Lower limit of control element range on actuator scale

UNIT 41 TYPE 524 ----- Cooling coil  
Coil + three port valve, calculates flow

- 1 INPUTS:  
TEMPERATURE 80 - Inlet air dry bulb temperature  
HUMIDITY 17 - Inlet air humidity ratio  
PRESSURE 3 - Outlet air pressure  
FLOW 2 - Dry air mass flow rate  
TEMPERATURE 55 - Inlet water temperature  
PRESSURE 32 - Inlet water pressure  
PRESSURE 33 - Outlet water pressure  
CONTROL 41 - Valve stem position  
TEMPERATURE 57 - Effective coil surface temperature (same as 1st o/
- 2 OUTPUTS:  
TEMPERATURE 57 - Effective coil surface temperature  
TEMPERATURE 3 - Outlet dry bulb air temperature  
HUMIDITY 3 - Outlet air humidity ratio  
PRESSURE 0 - Inlet air pressure  
TEMPERATURE 56 - Outlet water temperature  
FLOW 0 - Primary circuit water mass flow rate  
FLOW 40 - Water mass flow rate through coil  
TEMPERATURE 0 - Mixed return water temperature  
POWER 3 - Total heat transfer to the air  
CONTROL 0 - Sensible heat ratio  
CONTROL 0 - Coil effectiveness  
CONTROL 0 - Coil by-pass factor  
ENERGY 0 - Outlet air specific enthalpy  
CONTROL 0 - Outlet air relative humidity  
TEMPERATURE 0 - Outlet air wet-bulb temperature
- 3 PARAMETERS:  
1.00000 Method : 0 = steady state, 1 = dynamic  
0.00000 Fault : 0 for no faults, 1 = parallel flow (cooling co  
0.00000 Psycho : 0 = no psychrometric output calcs, 1 = calcs  
3.00000 Number of rows of tubes  
36.0000 Number of tubes per row  
36.0000 Number of parallel water circuits  
0.180750 Length of finned section in direction of flow (m)  
1.37000 Height of finned section (m)  
2.77000 Width of finned section (m)  
0.159000E-01 Tube outside diameter (m)  
0.787400E-03 Tube wall thickness (m)  
2.00000 Tube material (Al=1,Cu=2,Fe=3,CaCO3=4)  
0.212000E-02 Fin spacing (pitch) (m)  
0.216000E-03 Fin thickness (m)  
1.00000 Fin material (Al=1,Cu=2,Fe=3)  
0.802500E-03 Flow resistance on air side (1000/kg.m)  
0.600000 Coil water flow resistance (1000/kg.m)  
0.100000E+07 By-pass water flow resistance (1000/kg.m)  
1.00000 Valve type: 0=lin/lin, 1=eq%(flow)/lin(byp), 2=lin/eq%  
16.3100 Valve capacity (Kv) (m3/hr @ 1 bar)

3.54000 Valve curvature parameter (0=linear) (-)  
24.5100 Valve rangability (-)  
0.100000E-03 Valve leakage (fractional flow) (-)

UNIT 14 TYPE 333 ----- Supply fan  
Variable speed drive

1 INPUTS:  
CONTROL 157 - demanded fractional speed

2 OUTPUTS:  
OTHER 1 - actual rotation speed

3 PARAMETERS:  
22.3330 maximum rotation speed (rev/s)  
120.000 travel time (lim-lim) (s)

UNIT 26 TYPE 350 ----- Supply fan  
Fan or pump

1 INPUTS:  
FLOW 2 - mass flow rate of fluid  
PRESSURE 4 - outlet pressure  
OTHER 1 - fan or pump rotational speed

2 OUTPUTS:  
PRESSURE 3 - inlet pressure  
POWER 1 - fluid stream heat addition rate  
POWER 29 - power consumption

3 PARAMETERS:  
4.29040 1st pressure coefficient  
-1.38700 2nd pressure coefficient  
4.22930 3rd pressure coefficient  
-3.92920 4th pressure coefficient  
0.853400 5th pressure coefficient  
0.116200 1st efficiency coefficient  
1.54040 2nd efficiency coefficient  
-1.48250 3rd efficiency coefficient  
0.766400 4th efficiency coefficient  
-0.197100 5th efficiency coefficient  
0.685800 diameter (m)  
1.00000 mode: air=1, water=2  
1.00000 lowest valid normalized flow (-)  
2.00000 highest valid normalized flow (-)

UNIT 15 TYPE 333 ----- Return fan  
Variable speed drive

1 INPUTS:  
CONTROL 158 - demanded fractional speed

2 OUTPUTS:  
OTHER 2 - actual rotation speed

3 PARAMETERS:  
8.00000 maximum rotation speed (rev/s)  
120.000 travel time (lim-lim) (s)

UNIT 38 TYPE 350 ----- Return fan  
Fan or pump

1 INPUTS:  
FLOW 29 - mass flow rate of fluid  
PRESSURE 27 - outlet pressure  
OTHER 2 - fan or pump rotational speed

2 OUTPUTS:  
PRESSURE 26 - inlet pressure

POWER 2 - fluid stream heat addition rate  
POWER 30 - power consumption

- 3 PARAMETERS:  
4.19370 1st pressure coefficient  
-1.63370 2nd pressure coefficient  
12.2110 3rd pressure coefficient  
-23.9619 4th pressure coefficient  
9.81620 5th pressure coefficient  
0.619000E-01 1st efficiency coefficient  
3.14170 2nd efficiency coefficient  
-5.75510 3rd efficiency coefficient  
6.16760 4th efficiency coefficient  
-3.37480 5th efficiency coefficient  
1.13000 diameter (m)  
1.00000 mode: air=1, water=2  
0.700000 lowest valid normalized flow (-)  
1.00000 highest valid normalized flow (-)

UNIT 69 TYPE 341 ----- AHU HC  
Fluid resistance

- 1 INPUTS:  
FLOW 2 - Mass flow rate  
PRESSURE 47 - Outlet pressure
- 2 OUTPUTS:  
PRESSURE 2 - Inlet pressure
- 3 PARAMETERS:  
0.200000E-03 flow resistance (0.001/kg.m)

UNIT 25 TYPE 341 ----- AHU duct and CC  
Fluid resistance

- 1 INPUTS:  
FLOW 2 - Mass flow rate  
PRESSURE 3 - Outlet pressure
- 2 OUTPUTS:  
PRESSURE 47 - Inlet pressure
- 3 PARAMETERS:  
0.546000E-03 flow resistance (1000/kg.m)

UNIT 27 TYPE 341 ----- Supply duct  
Fluid resistance

- 1 INPUTS:  
FLOW 2 - Mass flow rate  
PRESSURE 5 - Outlet pressure
- 2 OUTPUTS:  
PRESSURE 4 - Inlet pressure
- 3 PARAMETERS:  
0.164000E-03 flow resistance (1000/kg.m)

UNIT 39 TYPE 341 ----- Return duct  
Fluid resistance

- 1 INPUTS:  
FLOW 29 - Mass flow rate  
PRESSURE 28 - Outlet pressure
- 2 OUTPUTS:  
PRESSURE 27 - Inlet pressure

- 3 PARAMETERS:  
0.118000E-03 flow resistance (1000/kg.m)

UNIT 42 TYPE 366 ----- AHU  
Ideal heating of fluid stream

- 1 INPUTS:  
FLOW 2 - mass flow rate  
TEMPERATURE 3 - inlet temperature  
POWER 1 - rate of heat addition
- 2 OUTPUTS:  
TEMPERATURE 4 - outlet temperature
- 3 PARAMETERS:  
1.00000 fluid: 1 = air, any other value + water (-)  
30.0000 time constant (s)

UNIT 47 TYPE 366 ----- AHU return stream  
Ideal heating of fluid stream

- 1 INPUTS:  
FLOW 29 - mass flow rate  
TEMPERATURE 53 - inlet temperature  
POWER 2 - rate of heat addition
- 2 OUTPUTS:  
TEMPERATURE 54 - outlet temperature
- 3 PARAMETERS:  
1.00000 fluid: 1 = air, any other value + water (-)  
30.0000 time constant (s)

UNIT 62 TYPE 305 ----- Supply air  
Static pressure sensor

- 1 INPUTS:  
PRESSURE 5 - pressure  
FLOW 2 - mass flow rate
- 2 OUTPUTS:  
CONTROL 65 - sensor output
- 3 PARAMETERS:  
1.00000 air = 1, water = 2 (-)  
1.00000 cross-sectional area of duct or pipe (m2)  
0.00000 offset: input for zero output (kPA)  
1.00000 gain: change in input for 0->1 output (kPA)  
1.00000 time constant (s)  
5.00000 upper limit of output range (-)  
-5.00000 lower limit of output range (-)

UNIT 60 TYPE 303 ----- Supply air  
Flow rate sensor

- 1 INPUTS:  
FLOW 2 - mass flow rate
- 2 OUTPUTS:  
CONTROL 63 - sensor output
- 3 PARAMETERS:  
2.00000 mass flow=1, vol flow=2, vel=3, vel pres=4 (-)  
1.00000 air = 1, water = 2 (-)  
1.00000 cross-sectional area of duct or pipe (m2)  
0.00000 offset: input for zero output (sensed quantity)

1.00000 gain: change in input for 0->1 output (sensed quantity)  
1.00000 time constant (s)  
20.00000 upper limit of output range (-)  
-10.00000 lower limit of output range (-)

UNIT 61 TYPE 303 ----- Return air  
Flow rate sensor

1 INPUTS:  
FLOW 29 - mass flow rate

2 OUTPUTS:  
CONTROL 64 - sensor output

3 PARAMETERS:  
2.00000 mass flow=1, vol flow=2, vel=3, vel pres=4 (-)  
1.00000 air = 1, water = 2 (-)  
1.00000 cross-sectional area of duct or pipe (m2)  
0.00000 offset: input for zero output (sensed quantity)  
1.00000 gain: change in input for 0->1 output (sensed quantity)  
1.00000 time constant (s)  
20.00000 upper limit of output range (-)  
-10.00000 lower limit of output range (-)

UNIT 54 TYPE 301 ----- SA  
Temperature sensor

1 INPUTS:  
TEMPERATURE 4 - temperature

2 OUTPUTS:  
CONTROL 61 - sensor output

3 PARAMETERS:  
0.00000 offset: input for zero output (C)  
1.00000 gain: change in input for 0->1 output (K)  
30.00000 time constant (s)  
2000.00000 upper limit of output range (-)  
0.00000 lower limit of output range (-)

UNIT 56 TYPE 301 ----- MA  
Temperature sensor

1 INPUTS:  
TEMPERATURE 2 - temperature

2 OUTPUTS:  
CONTROL 68 - sensor output

3 PARAMETERS:  
0.00000 offset: input for zero output (C)  
1.00000 gain: change in input for 0->1 output (K)  
30.00000 time constant (s)  
2000.00000 upper limit of output range (-)  
0.00000 lower limit of output range (-)

UNIT 53 TYPE 301 ----- OA  
Temperature sensor

1 INPUTS:  
TEMPERATURE 1 - temperature

2 OUTPUTS:  
CONTROL 60 - sensor output

3 PARAMETERS:  
0.00000 offset: input for zero output (C)  
1.00000 gain: change in input for 0->1 output (K)



30.0000 time constant (s)  
51.6700 upper limit of output range (-)  
-40.0000 lower limit of output range (-)

UNIT 55 TYPE 301 ----- RA  
Temperature sensor

1 INPUTS:  
TEMPERATURE 54 - temperature

2 OUTPUTS:  
CONTROL 62 - sensor output

3 PARAMETERS:  
0.00000 offset: input for zero output (C)  
1.00000 gain: change in input for 0->1 output (K)  
30.0000 time constant (s)  
2000.0000 upper limit of output range (-)  
0.00000 lower limit of output range (-)

UNIT 63 TYPE 302 ----- Outside air  
Humidity sensor

1 INPUTS:  
HUMIDITY 1 - humidity ratio  
TEMPERATURE 1 - temperature

2 OUTPUTS:  
CONTROL 66 - sensor output

3 PARAMETERS:  
1.00000 HR=1, RH=2, DP=3, WB=4, deg sat=5, spec enthalpy=6 (-)  
0.00000 offset: input for zero output (sensed quantity)  
1.00000 gain: change in input for 0->1 output (sensed quantity)  
30.0000 time constant (s)  
1.00000 upper limit of output range (-)  
0.00000 lower limit of output range (-)

UNIT 64 TYPE 302 ----- Return air  
Humidity sensor

1 INPUTS:  
HUMIDITY 16 - humidity ratio  
TEMPERATURE 54 - temperature

2 OUTPUTS:  
CONTROL 67 - sensor output

3 PARAMETERS:  
1.00000 HR=1, RH=2, DP=3, WB=4, deg sat=5, spec enthalpy=6 (-)  
0.00000 offset: input for zero output (sensed quantity)  
1.00000 gain: change in input for 0->1 output (sensed quantity)  
30.0000 time constant (s)  
1.00000 upper limit of output range (-)  
0.00000 lower limit of output range (-)

## Appendix F. Sample VAV Input Data

### File name: VAV1.inp

! VAV1.inp Changed for ZFM-HVAC model  
! Base data file: emuex29i.mod

UNIT 30 TYPE 526 ----- zone 1  
Motorized pressure-independent VAV box

1 INPUTS:  
PRESSURE 5 - inlet pressure  
PRESSURE 16 - outlet pressure  
CONTROL 151 - demanded flow rate (normalized to nominal)  
FLOW 3 - air mass flow rate

2 OUTPUTS:  
FLOW 3 - air mass flow rate  
CONTROL 77 - damper position (0=closed, 1=open)  
CONTROL 0 - fractional motor velocity  
CONTROL 143 - number of stops/starts/reversals  
CONTROL 0 - total distance traveled by valve/damper

3 PARAMETERS:  
0.565000 nominal volumetric flow rate (m3/s)  
0.250000 face area of damper(s) (m2)  
0.999000E-01 additional pressure drop at nominal flow (kPa)  
100.0000 actuator travel time (0-90 deg) (s)  
0.000000 minimum fractional motor speed (-)  
0.000000 hysteresis (-)  
9.990000 controller gain (frac speed/frac error)

UNIT 21 TYPE 321 ----- RHC valve zone 1  
Motor-driven actuator

1 INPUTS:  
CONTROL 154 - demanded position

2 OUTPUTS:  
CONTROL 42 - position of final control element  
CONTROL 0 - motor position  
CONTROL 137 - number of stops/starts/reversals  
CONTROL 0 - total distance traveled by final control element

3 PARAMETERS:  
1.000000 direction: 1=forward, -1=reverse, 0=stuck  
0.000000 starting position (0-1)  
125.0000 travel time (lim-lim) (s)  
0.000000 minimum change in demanded position for movement (-)  
0.000000 hysteresis (-)  
0.000000 crank travel angle (0 for linear) (deg)  
1.000000 Upper limit of control element range on actuator scale  
0.000000 Lower limit of control element range on actuator scale

UNIT 43 TYPE 524 ----- zone 1  
Coil + three port valve, calculates flow

1 INPUTS:  
TEMPERATURE 4 - Inlet air dry bulb temperature  
HUMIDITY 3 - Inlet air humidity ratio  
PRESSURE 16 - Outlet air pressure  
FLOW 3 - Dry air mass flow rate  
TEMPERATURE 58 - Inlet water temperature  
PRESSURE 34 - Inlet water pressure  
PRESSURE 35 - Outlet water pressure  
CONTROL 42 - Valve stem position  
TEMPERATURE 70 - Effective coil surface temperature (same as 1st o/

- 2 OUTPUTS:  
 TEMPERATURE 70 - Effective coil surface temperature  
 TEMPERATURE 5 - Outlet dry bulb air temperature  
 HUMIDITY 4 - Outlet air humidity ratio  
 PRESSURE 0 - Inlet air pressure  
 TEMPERATURE 64 - Outlet water temperature  
 FLOW 0 - Primary circuit water mass flow rate  
 FLOW 41 - Water mass flow rate through coil  
 TEMPERATURE 0 - Mixed return water temperature  
 POWER 4 - Total heat transfer to the air  
 CONTROL 0 - Sensible heat ratio  
 CONTROL 0 - Coil effectiveness  
 CONTROL 0 - Coil by-pass factor  
 ENERGY 0 - Outlet air specific enthalpy  
 CONTROL 0 - Outlet air relative humidity  
 TEMPERATURE 0 - Outlet air wet-bulb temperature
- 3 PARAMETERS:  
 1.00000 Method : 0 = steady state, 1 = dynamic  
 0.00000 Fault : 0 for no faults, 1 = parallel flow (cooling co  
 0.00000 Psycho : 0 = no psychrometric output calcs, 1 = calcs  
 1.00000 Number of rows of tubes  
 16.0000 Number of tubes per row  
 1.00000 Number of parallel water circuits  
 0.275000E-01 Length of finned section in direction of flow (m)  
 0.457000 Height of finned section (m)  
 0.305000 Width of finned section (m)  
 0.127000E-01 Tube outside diameter (m)  
 0.406000E-03 Tube wall thickness (m)  
 2.00000 Tube material (Al=1,Cu=2,Fe=3,CaCO3=4)  
 0.254000E-02 Fin spacing (pitch) (m)  
 0.152000E-03 Fin thickness (m)  
 1.00000 Fin material (Al=1,Cu=2,Fe=3)  
 0.150000 Flow resistance on air side (0.001 kg.m)  
 25.0000 Coil water flow resistance (0.001 kg.m)  
 0.100000E+07 By-pass water flow resistance (0.001 kg.m)  
 1.00000 Valve type: 0=lin/lin, 1=eq%(flow)/lin(byp), 2=lin/eq%  
 0.500000 Valve capacity (Kv) (m3/hr @ 1 bar)  
 3.22000 Valve curvature parameter (0=linear) (-)  
 50.0000 Valve rangability (-)  
 0.200000E-03 Valve leakage (fractional flow) (-)

UNIT 33 TYPE 425 ----- zone 1  
 Room air mass balance

- 1 INPUTS:  
 FLOW 3 - supply air mass flow rate (positive in)  
 PRESSURE 16 - room pressure  
 PRESSURE 30 - ambient pressure  
 TEMPERATURE 35 - room temperature
- 2 OUTPUTS:  
 FLOW 19 - return air mass flow rate (positive out)  
 FLOW 31 - leakage mass flow rate to ambient (positive out)
- 3 PARAMETERS:  
 1.00000 leakage resistance [0.001/(kg m)]  
 0.00000 local extract fan mass flow rate [kg/s]

UNIT 57 TYPE 301 ----- zone 1 air temperature  
 Temperature sensor

- 1 INPUTS:  
 TEMPERATURE 35 - temperature
- 2 OUTPUTS:  
 CONTROL 70 - sensor output
- 3 PARAMETERS:  
 0.00000 offset: input for zero output (C)

1.00000 gain: change in input for 0->1 output (K)  
10.0000 time constant (s)  
2000.00 upper limit of output range (-)  
0.00000 lower limit of output range (-)

UNIT 37 TYPE 422 ----- From Zone 1  
Flow merge with smoke

3 PARAMETERS:  
0.263200E-03 Inlet resistance 1 (0.001/k.m)  
0.263200E-03 Inlet resistance 2 (0.001/k.m)  
0.263200E-02 Resistance of outlet (0.001/k.m)

UNIT 46 TYPE 365 ----- AHU  
Mixing of two moist air streams

3 PARAMETERS:  
0.00000 (dummy)

Appendix G. Sample AHU Initial Data

File name: AHU1init.inp

PRESSURE	1 ->	0.00000	(kPa)
PRESSURE	2 ->	-0.09278	(kPa)
PRESSURE	3 ->	-0.09375	(kPa)
PRESSURE	4 ->	0.25100	(kPa)
PRESSURE	5 ->	0.25000	(kPa)
PRESSURE	16 ->	0.01000	(kPa)
PRESSURE	26 ->	-0.46000	(kPa)
PRESSURE	27 ->	0.06465	(kPa)
PRESSURE	28 ->	0.06465	(kPa)
PRESSURE	29 ->	0.06465	(kPa)
PRESSURE	30 ->	0.00000	(kPa)
PRESSURE	32 ->	39.0300	(kPa)
PRESSURE	33 ->	0.00000	(kPa)
PRESSURE	34 ->	38.1000	(kPa)
PRESSURE	35 ->	0.00000	(kPa)
PRESSURE	47 ->	0.00000	(kPa)
PRESSURE	48 ->	20.0000	(kPa)
PRESSURE	49 ->	0.00000	(kPa)
FLOW	1 ->	0.66100	(kg/s)
FLOW	2 ->	1.33000	(kg/s)
FLOW	3 ->	0.28300	(kg/s)
FLOW	19 ->	0.31200	(kg/s)
FLOW	28 ->	0.00000	(kg/s)
FLOW	29 ->	1.10000	(kg/s)
FLOW	30 ->	0.67300	(kg/s)
FLOW	31 ->	0.00000	(kg/s)
FLOW	40 ->	0.00000	(kg/s)
FLOW	41 ->	0.00000	(kg/s)
FLOW	47 ->	0.00000	(kg/s)
FLOW	48 ->	0.00000	(kg/s)
TEMPERATURE	1 ->	30.0000	(C)
TEMPERATURE	2 ->	20.0000	(C)
TEMPERATURE	3 ->	20.0000	(C)
TEMPERATURE	4 ->	20.0000	(C)
TEMPERATURE	5 ->	20.0000	(C)
TEMPERATURE	35 ->	25.0000	(C)
TEMPERATURE	53 ->	20.0000	(C)
TEMPERATURE	54 ->	20.0000	(C)
TEMPERATURE	55 ->	6.00000	(C)
TEMPERATURE	56 ->	6.00000	(C)
TEMPERATURE	57 ->	20.0000	(C)
TEMPERATURE	58 ->	80.0000	(C)
TEMPERATURE	64 ->	20.0000	(C)
TEMPERATURE	70 ->	20.0000	(C)
TEMPERATURE	78 ->	80.0000	(C)
TEMPERATURE	79 ->	20.0000	(C)
TEMPERATURE	80 ->	20.0000	(C)
TEMPERATURE	81 ->	20.0000	(C)
CONTROL	1 ->	1.0000	(-)
CONTROL	2 ->	1.0000	(-)
CONTROL	38 ->	0.0000	(-)
CONTROL	41 ->	0.0000	(-)
CONTROL	42 ->	0.0000	(-)
CONTROL	60 ->	30.0000	(-)
CONTROL	61 ->	20.0000	(-)
CONTROL	62 ->	20.0000	(-)
CONTROL	63 ->	6.17300	(-)
CONTROL	64 ->	5.25600	(-)
CONTROL	65 ->	0.223000	(-)
CONTROL	66 ->	0.153000E-01	(-)
CONTROL	67 ->	0.750000E-02	(-)
CONTROL	68 ->	20.0000	(-)
CONTROL	70 ->	22.2200	(-)
CONTROL	77 ->	0.00000	(-)

CONTROL	85 ->	0.00000	(-)
CONTROL	143 ->	0.00000	(-)
CONTROL	149 ->	0.10000	(-)
CONTROL	150 ->	0.26000	(-)
CONTROL	151 ->	0.70000	(-)
CONTROL	154 ->	0.00000	(-)
CONTROL	157 ->	0.50000	(-)
CONTROL	158 ->	0.20000	(-)
CONTROL	159 ->	0.00000	(-)
OTHER	3 ->	0.00000	(-)
OTHER	4 ->	0.00000	(-)
OTHER	8 ->	0.00000	(-)
POWER	1 ->	0.00000	(kW)
POWER	2 ->	0.00000	(kW)
POWER	3 ->	0.00000	(kW)
POWER	4 ->	0.00000	(kW)
POWER	10 ->	0.00000	(kW)
POWER	29 ->	0.00000	(kW)
POWER	30 ->	0.00000	(kW)
HUMIDITY	1 ->	0.162000E-01	(kg/kg)
HUMIDITY	2 ->	0.162000E-01	(kg/kg)
HUMIDITY	3 ->	0.162000E-01	(kg/kg)
HUMIDITY	4 ->	0.162000E-01	(kg/kg)
HUMIDITY	10 ->	0.162000E-01	(kg/kg)
HUMIDITY	16 ->	0.162000E-01	(kg/kg)
HUMIDITY	17 ->	0.162000E-01	(kg/kg)