NBSIR 88-3739

Comparison of Direct Digital Control and Pneumatic Control Systems in A Large Office Building

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U.S. DEPARTMENT OF COMMERCE, C. William Verity, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

ABSTRACT

A distributed, microprocessor-based direct digital control (DDC) energy management and control system was developed and installed in an eleven story office building in Gaithersburg, Maryland. Over a period of one year the performance of this system under various control strategies was investigated along with the performance of a conventional pneumatic control system. The quality of control and performance characteristics for the two control systems were compared.

Overall the DDC system was found to maintain better control of the supply air temperature and to follow planned reset schedules more closely than the pneumatic system. One particular air handling unit performed as well under pneumatic control as it did under DDC in maintaining a supply air setpoint, but it did not precisely follow the planned reset schedule. Each air handling unit had different performance characteristics while under pneumatic control, but all units behaved essentially the same under DDC.

The results indicate that a pneumatic system can perform as well as a DDC system but more effort is required to maintain system performance. The DDC system was found to be more flexible and it is easier to insure that multiple air handling units follow the same control strategy with the DDC system. The instrumentation associated with the DDC system proved to be very useful in troubleshooting problems with the pneumatic system because of the information readily available to the operators.

CONTENTS

ACKNOWLEDGEMENTS

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LIST OF FIGURES

1. INTRODUCTION

A nonproprietary microprocessor based energy management and control system (EMCS) was built and installed in a large office building to investigate the performance of previously developed direct digital control (DDC) algorithms in a typical office building. The microprocessor-based EMCS was constructed entirely from off the shelf, commercially available components and all communication and control software was written in house. Data were collected on the performance of the EMCS over one year using a variety of control strategies. The results of these tests were compared with each other and also with data collected while the building equipment was being controlled by a conventional pneumatic control system.

This paper presents performance characteristics and compares the quality of control for the DDC and pneumatic systems. Some of the data collected were also used to validate a computer model of this building which was used to investigate the effects of different control schemes on energy consumption. A description of the model and the simulation results are presented elsewhere [1].

The building used for this project, shown in figure 1.1, is an eleven story office building which serves as the Administration Building for the National Bureau of Standards in Gaithersburg, Maryland. The building is a reinforced concrete structure, 49.7m (163 ft) high (excluding the bulkhead on the roof), built in the late 1960's. The width of the building is 15m (49 ft) and it is 67m (220 ft) long. The structure is enclosed by gray face bricks, insulated porcelain steel panels, and glass windows. Extended aluminum enclosures, located on both the north and south walls, cover concrete columns and the supply air ducts which originate from the air handling units located on the mezzanine floor of the building.

Each floor area is 867 m^2 (9,330 ft^2)and the ceiling height is 3.1m (10.2 ft). Floors two through eleven are served by four air handling units. The four service zones are shown in figure 1.2. Two return air ducts serve floors two through six and two ducts serve floors seven through eleven. Thus only two return air ducts serve each floor. This creates a complicated air distribution pattern because each air handling unit supplies air to one zone on all floors, but the return air to any particular air handling unit is a mixture of air from all four zones in either the top half or bottom half of the building.

The four air handling units which serve these zones are all located on the mezzanine level of the building. Each unit provides approximately 32,400 m3/hr (19,500 cfm) of primary air to the zone. Two fluid to air heat exchange coils are located in each unit, one providing preheat with steam, and the other providing cooling to the air using chilled water. Air entering the units is a mixture of return and outdoor air controlled by dampers with pneumatic actuators. The flow of steam and chilled water through the coils is controlled by pneumatically actuated valves.

The offices in the building contain induction terminal reheat units with a hot water heating coil under the control of a local thermostat. Conditioned air from the air handling unit is supplied through the terminal reheat unit.

Figure 1.1. The NBS Administration Building

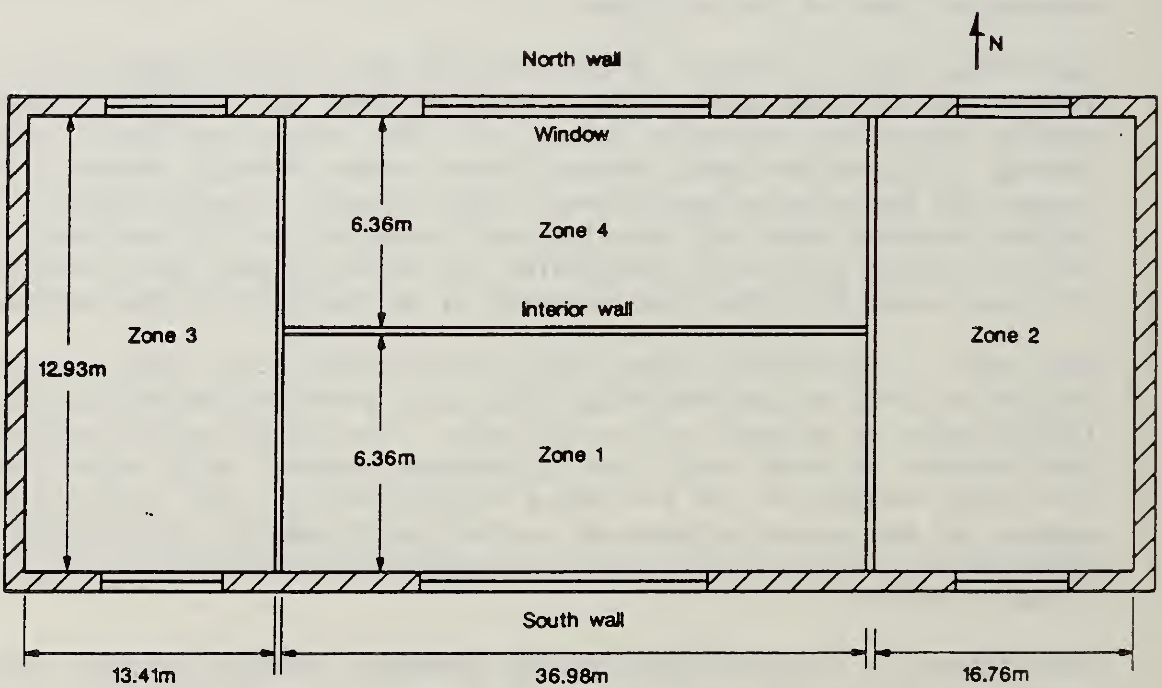


Figure 1.2. HVAC service zones in NBS Administration Building

Return air is brought to the air handling unit through ducts located in the ceiling of the halls in the building. Each office has grills over its door to allow air to flow from the room to the return air duct when the door is closed.

2. EMCS DESCRIPTION

The experimental EMCS used for this project was developed by NBS staff. The EMCS utilizes distributed computer processors arranged in a hierarchy as shown in figure 2.1. The highest level is the central control unit (CCU), the middle level is the field interface device (FID), and the lowest level is the multiplexer (MUX). There is no interaction between the nodes of the system at each level, that is one MUX cannot communicate with other MUXes and one FID cannot communicate with another FID.

The multiplexers shown in figure 2.1 are hardware oriented microcomputer signal conditioning units performing low level tasks, with software fixed in EPROMs (firmware). A MUX interrogates all of the sensors and controls all of the actuators tied to the system. Analog sensor inputs are converted into digitally coded numbers for transmission to higher levels of the EMCS.

The FIDs shown in figure 2.1 are also microcomputers. They represent more of a balance between hardware and software than the MUXes. FIDs contain a mixture of firmware and software and are intended to be flexible and easily reconfigured to a new application. They contain software to communicate with the multiplexers and make control decisions based on information from sensors connected to the multiplexers. The FID software contains implementations of EMCS algorithms and provides DDC of the valves and dampers on an air handling unit to maintain the supply air temperature at a setpoint. FID processors also contain software for communication with the CCU level. A FID is capable of controlling an air handling unit without interaction with the higher level CCU.

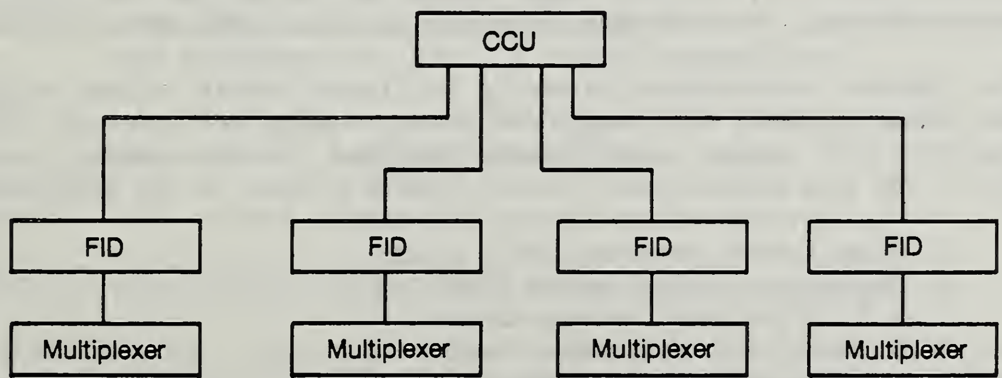


Figure 2.1. Schematic diagram of NBS laboratory EMCS processors

The central control unit, shown in figure 2.1, provides supervisory control functions and is connected by serial communication lines to each of the FIDs. The CCU is used to collect and store historical data from EMCS sensors, detect and display alarm conditions, and allow EMCS algorithm parameters used by field processors to be changed. The CCU provides the operator interface with the EMCS.

In the event of a power failure, the FID and MUX are designed to restart automatically. The FID loads a new copy of the software into RAM from the onboard bubble memory and commences execution. Manual restart of the CCU is required.

The experimental EMCS was installed in a manner which permits the continued operation of the pneumatic control system which previously controlled the air handling units in this building. Control of the air handling units can easily be switched back and forth between the two systems. This provides a complete and independent backup to the experimental EMCS.

2.1 Multiplexer Hardware

Each multiplexer in the building EMCS has the following capabilities:

- 32 Analog input channels
- 4 Analog output channels
- 8 pulse accumulator or counter channels
- 8 relay-isolated binary input channels
- 16 optically isolated binary input channels
- 16 optically isolated binary output channels

The MUX hardware consists of six specialized circuit boards linked together by a parallel communication bus and provided with appropriate power supply and connectors for the serial communication to higher levels of the distributed system. The bus used in the MUX is the IEEE-696 (S-100) bus designed for microprocessor based systems. This bus has a 16 bit, bidirectional data bus and a 24 bit, unidirectional address bus. The bus is based on a 100-line parallel bus with 100-pin edge connectors along the bus for the insertion of circuit cards. The bus-edge connector is often referred to as the "motherboard".

The IEEE-696 motherboard assembly is placed within a card cage which supports the cards. This card cage and power supply are mounted in a NEMA cabinet together with signal conditioning hardware for the analog inputs and cooling fans. The six specialized circuit boards placed in the motherboard are:

1. Single card computer (SCC) board.
2. Analog-to-digital board (two).
3. 4 Parallel input/output board.
4. 8 Parallel input/output board.
5. Digital-to-analog board.

The SCC board contains the master microprocessor for the MUX and is the IEEE-696 bus master. This card uses the Z-80A microprocessor which runs at a speed of 4 MHz. Also on the board are 1 K byte of 4045 static RAM, sockets for 8 K bytes of 2716 EPROMs, three 8-bit parallel I/O ports, and an asynchronous

RS-232 serial port for communication with the field processor. Four EPROMS are installed to provide firmware for the MUX. These will be discussed in the MUX firmware section.

Two analog-to-digital converter boards are installed to take readings from 32 analog sensors. The sensor outputs first pass through signal conditioning cards which convert the various sensor outputs into 0-5 volt DC signals. The sensors used and the signal conditioning circuits are discussed in the instrumentation section.

The 4 parallel input/output board provides the capability for the MUX to actuate digital outputs and determine digital input states. This board has 24 optically isolated binary inputs, 16 optically isolated binary outputs, and 8 magnet relay isolated binary outputs rated at 1 amp @ 32 volts DC.

The 8 port input/output board is used in the MUX primarily to allow a simple switch register input to the MUX and a set of output LEDs. The input switches are used to permit simple reconfiguration of the MUX without firmware changes and the output LEDs are used to display MUX operational status. This board actually has 8 parallel bidirectional I/O ports, but these are not used in the present MUX configuration except to read 11 bits of switch register input and set 8 bits of LED output.

The digital-to-analog board provides a means for the MUX to send analog voltage signals to analog type controllers. This board has four independent digital-to-analog converters , each of which can be driven with a resolution of 12 bits. The board makes use of eight I/O ports, two for each digital-to-analog converter. The range of each analog output can be selected independently of the other outputs.

2.2 Multiplexer Firmware

All multiplexer firmware is contained in four EPROMs. The four EPROMs and their functions are:

MONITOR - used for start-up, diagnostic operations, and downloading new software (not used in normal operations).

COMM - used for communication with the field processor, handles all protocol and error checking.

ANALOG - sets analog outputs and reads analog inputs.

DIGITAL - sets digital outputs and reads digital inputs.

The activities of the MUX can be divided into two broad categories, communication with the FID and scanning of the sensors attached to the MUX. Most of the time the MUX will be scanning sensors, repeating the scan of all points over and over without regard to any time schedule.

Execution of the point scanning software begins at the start of the ANALOG module. The first instruction in the ANALOG module is a subroutine call to the

DIGITAL module, and, in fact, the entire DIGITAL module is written as a single large subroutine to the ANALOG module. The DIGITAL module sets digital outputs according to the values stored in the internal data base, reads digital inputs and stores the values in the internal data base, and then checks the digital inputs associated with pulse counters, incrementing counters in the data base if the counter inputs have changed. When the execution of the DIGITAL module is complete, a return to the ANALOG module occurs.

The ANALOG module begins with setting analog outputs in accordance with the analog output data base. Next, the analog input channels are read in sequence and stored in the data base. Finally, a jump is made back to the start of the ANALOG module.

If the FID sends a communication to the MUX, an interrupt causes an immediate jump to the COMM module. This module accepts the FID message (or rejects it if there is an error) and determines what the FID is commanding the MUX to do. A return is then made to the point scanning routine, which is allowed to complete one full scan. Following this scan, a jump is made back to the appropriate place in the COMM module, depending on what function the FID has commanded. The command function will either be a transmission of requested data to the FID or a reception of data from the FID to set analog or digital outputs. After the command function is complete, a return is made to continuous scanning.

2.2.1. Reporting by exception

One of the most important functions of the MUX is to transmit to the FID data for only those points which have changed by a certain amount since the last transmission of data to the FID. This is termed reporting by exception. This function is accomplished most efficiently by having the MUX check for data change since last transmission as it scans the data points. If a point has changed, the program will write the encoded point into a special message buffer which will be ready for transmission when the FID requests it (thus speeding up response to the command).

The three critical elements of the exception reporting are the filter increment or differential, the structure of the exception message buffer, and the baseline for comparison with the current analog value to see if a change has occurred. The filter increment is the amount that a data point must change from the baseline before it is registered as a change. A filter increment of zero means that any change is registered. However, if there is noise in the readings, excessive exception reports will occur even when the actual physical quantity measured may not be changing.

The exception buffer must always be current in the intervals between data transmission. Since the data values will change at different times and rates, the buffer must have a random access character. In the NBS MUX, the following approach is used: every time the exception buffer is transmitted to the FID, the buffer is subsequently filled with ASCII nulls. The buffer is sliced up into sections, one for each data point. A data point is always associated with the same buffer section. If a data point changes value, the point update routine will also write the value of the point into the proper buffer section. If the point changes again before buffer transmission, the buffer section is overwritten with the new value. If a point never changes between transmission times, the buffer section will contain nulls. When the buffer is transmitted to the FID, if a null character is encountered, it is not transmitted. Thus the message contains only exceptions, and the values are always current and transmitted in the same order.

The most simple baseline that can be used to compare the current data value with previous readings is the value in the RAM data storage area before it is updated with newly acquired information. If this baseline is used, the system will work but some changes will not be reported. If a change occurs at a rate such that the change between scans is smaller than the filter increment used for comparison, then since the scan rate is high frequency (0.1 kHz) the change will never be reported by exception.

A second baseline possibility is to set aside RAM for a copy of all the analog values. When an exception transmission is made, the copy is made. Thus the baseline is the set of analog values at the time the last exception report transmission was made. Still this is not perfect. If a slow change occurs, with a change in an analog value less than the differential between exception reports, the change will not be reported. The solution to this problem is to use as a baseline the analog value that was most recently transmitted in the exception buffer for that particular point. This is implemented by examining the exception buffer after transmission and if a particular slot of the buffer is not nulls, then the data value associated with that slot is transferred to the storage for data values at last transmission.

2.2.2. Custom Safety Interlocks

In order to provide special reliability to a research system such as the NBS controls laboratory monitoring and control system, it is necessary to be able to build in custom code to provide immediate actions if a measurement indicates an undesirable situation has been reached. A typical action would be to deactivate digital outputs which switch control from the digital control system to a backup system. Thus if a temperature climbed out of a desirable range, the digital control system would go off line, allowing a backup, which in this case is the original, pneumatic control system to take control. The custom code is executed at the end of the DIGITAL module.

2.3 FID Hardware

The FID hardware consists of seven specialized circuit boards linked together by an IEEE-696 (S-100) parallel bus, described in the multiplexer hardware section. The seven circuit boards used are:

1. CPU card
2. Real-time clock
3. EPROM memory board
4. RAM memory board
5. Bubble memory board
6. Bubble memory controller
7. Serial/Parallel interface card

The Central Processing Unit (CPU) card contains the master processor and is the IEEE-696 bus master. The card used in the NBS FID is a Z-80A microprocessor running at a clock speed of 4MHz and capable of performing dynamic memory refresh.

The real time clock card allows the FID to know the absolute time and thus keep in synchronization with the rest of the system and the real world. A clock also allows the FID to time software tasks that must be performed at regular intervals and permit the use of time of day control actions such as night setback without interaction from the CCU. The clock used in this system has a battery backup to allow the clock to keep time during short power outages.

The EPROM memory board contains firmware to hold monitor/diagnostic routines and software to "boot" the system from a cold start. Bubble memory utility routines are included to load a new copy of software into RAM when power is restored after a failure or after a reset.

The RAM board provides 64K bytes of dynamic memory for FID software and scratch space for program execution. The board used has a memory access time of 240 nanoseconds and on board memory refresh when the CPU does not refresh the memory.

A bubble memory card was included in the NBS field processor hardware to provide a means to recover from power failures. A copy of the processor software is loaded into the nonvolatile bubble memory and stored for later use. When power is restored after a failure, the booting procedure loads a new copy of software from the bubble memory into RAM. The bubble memory also allows reloading of clean software if the software in RAM fails, gets hung,or picks up an error. The bubble memory is theoretically insensitive to problems which might inflict a floppy disc drive used for the same purpose.

The bubble memory controller card reads and writes to the bubble memory and checks for errors in loading and saving data. It contains a separate Z-80 microprocessor chip which manages all bubble memory operations.

The serial/parallel interface card provides two serial communications ports to allow the FID to communicate with the other levels in the EMCS. Asynchronous RS-232 communication is used at both levels.

2.4 FID Software

The FID contains software for communication with both the MUX level and the CCU level of the EMCS. It also contains the software implementations of the EMCS control algorithms. The control algorithms used in this project were public domain algorithms developed at NBS. A brief description of the algorithms used is presented below.

ECONOMIZER algorithms are used to reduce the need for mechanical cooling in a building when the outside conditions permit cooling by bringing in outside air. Two general types are used, dry bulb economizers, which control air handler damper positions based on the difference between return air and outdoor air dry bulb temperatures, and enthalpy economizers, which control dampers based on the enthalpy difference between return air and outside air. Both types were implemented in this project. The details of the algorithms used and their verification have been discussed in previous reports [2,3].

TIME OF DAY control is used to schedule tasks to be executed at particular times on particular days. Examples of these tasks include morning start up, nighttime shutdown, weekend scheduling, and holiday scheduling. The details of the time of day algorithm used in this project may be found in reference [4].

RESET SCHEDULES are used to vary the supply air setpoint temperature as a function of some measure of the load. In this project supply air setpoint temperature was reset based on outdoor air temperature during the heating season and zone air temperature during the cooling season. Details of the algorithm used have been previously reported [3,5].

2.5 Central Control Unit

A minicomputer was used for the CCU in this project. Each FID was connected to the CCU by a dedicated line connected to a logical port on the minicomputer. The minicomputer disk drives were used to log data and alarms from the field units.

The CCU software contains communication routines to continuously monitor and log incoming alarms, collect data from field units, and provide the operator interface. The operator can check the status and sensor outputs from any FID, change parameters for control algorithms, manually start and stop tasks, change time of day control parameters, and download new software to the FID.

The CCU software actually consists of up to thirteen tasks running simultaneously on the CCU computer. Four FID I/O tasks are used to handle communication with the FIDs, one task for each FID. All of the other CCU tasks interact with these FID I/O tasks to send information to or obtain information from a FID. Four CCU tasks handle data acquisition, again one for each FID. These data acquisition tasks operate independently permitting customized data logging for each FID. If data are not being collected from a particular FID then its associated data collection task is not running. An alarm task periodically polls each FID I/O task requesting an alarm report. Appropriate action is taken to log any alarms which are found to a disk file and to send the information to the alarm console task which handles output to a dedicated alarm console. There is one task which serves as a watchdog to insure that communications are maintained between the CCU tasks and takes appropriate action if a problem develops. One task is used to provide the operator interface to the distributed control system and lastly, one task serves as the master CCU task. The role of the master task is to activate and deactivate the other tasks and serve as a controller of CCU intertask communication.

2.6 Pneumatic Control System

The pneumatic control system in this building was upgraded several years ago to interface with an energy management system which can perform some supervisory functions. It is primarily used to control nighttime shutdown and morning start up times. The controller on each air handling unit is also capable of implementing an economizer scheme, outdoor air reset, and zone air reset.

3. INSTRUMENTATION

Each of the four air handling units in the NBS Administration Building were instrumented in a virtually identical manner. A schematic diagram of the instrumentation used is shown in figure 3.1. Precision thermistors were used for all temperature measurements. An array of six thermistors was used to determine an average mixed air temperature. Single thermistors were used to measure supply air, return air, outdoor air, chilled water inlet, and chilled water outlet temperatures.

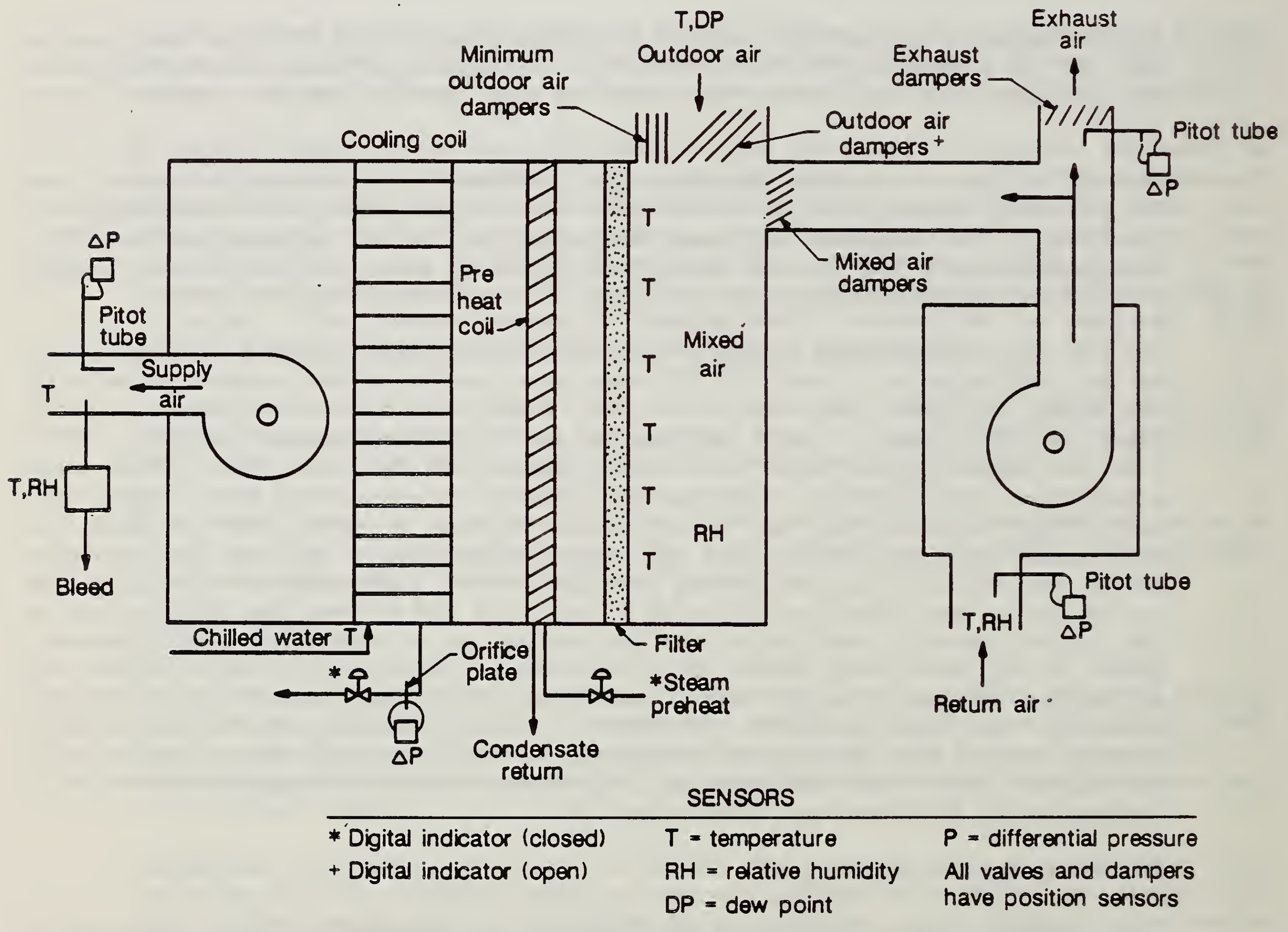


Figure 3.1. Schematic of AHU instrumentation

In order to implement the enthalpy economizer it was necessary to measure the humidity (or dew point) of the air streams. Outdoor air dew point was measured using chilled mirror devices. Supply air, return air, and mixed air humidities were measured with thin film polymer capacitance type sensors. Special arrangements, described below, had to be made in the case of supply air RH measurement because near saturated conditions are common during the cooling season in this humid climate. The thin film polymer sensors are not satisfactory when exposed for long periods to relative humidities above about 90%.

A heat exchanger box was built to raise the temperature of the supply air, thus lowering the relative humidity before measurement. This was done by using a standard electrical box with holes drilled into it to accommodate a thermistor, RH sensor, and air inlet and outlet. This box was placed several feet away from the supply air duct and connected to the duct by a small copper tube. The high pressure in the duct relative to the surround-ing room forces air through the copper tube into the box, and eventually out the bleed hole into the room. The residence time in the feed line and box was long enough to raise the temperature of the air to a point where reliable humidity measurements could be made. This RH was then corrected for the temperature change assuming constant moisture content heating. Details of the construction of these heat exchanger boxes are shown in figure 3.2.

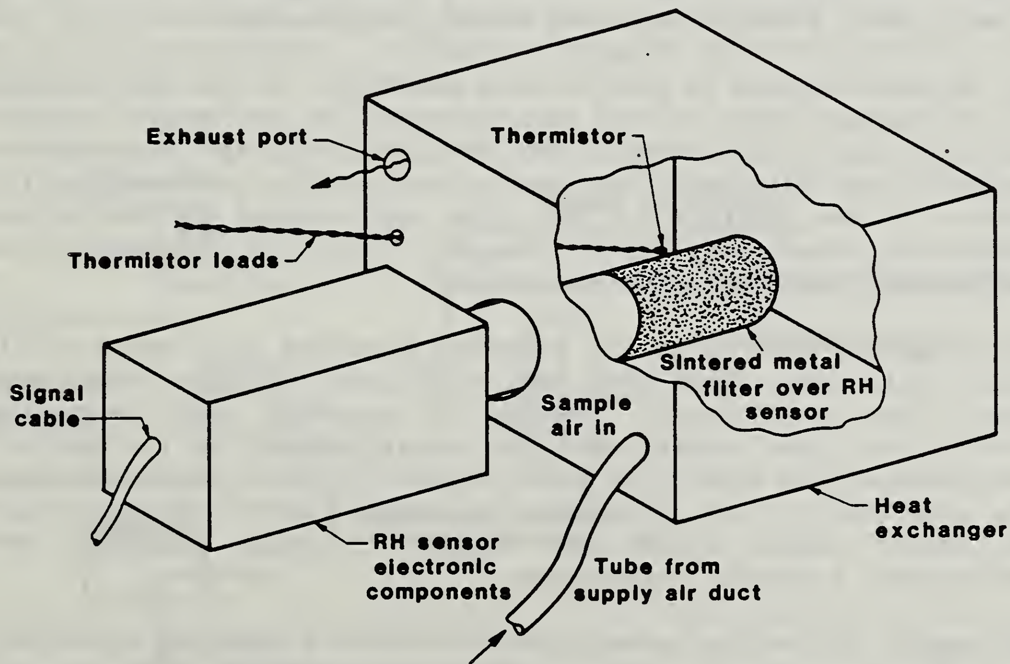


Figure 3.2. Heat exchanger box for measuring supply air RH.

This instrumentation for measuring the relative humidity of the various air streams has some important limitations. Even with the special precautions taken with the supply air RH measurement, accurate measurement of humidities under high humidity conditions did not prove to be reliable. Even though the heat exchanger box fulfilled its function of keeping the measured humidity below 90%, energy balances around the cooling coil indicate that the humidity measurements were sometimes inaccurate in predicting the latent cooling load. This may be due to a combination of drift in the sensor calibration and uneven mixing of air streams in the mixed air chamber giving false indications of the true mixed air humidity. This implies that under some conditions it was not possible to determine the amount of cooling provided by calculating enthalpy changes on the air side. A small error in the measured value of RH results in a large error in the estimate for the latent cooling load .

Chilled water flow rate was measured with an orifice plate and a differential pressure sensor. The orifice plates were part of the original HVAC system design and it was only necessary to connect pressure sensors to the corner taps. It was feared that the orifice plates may be eroded or corroded because of their age. The orifice plate from one of the chilled water lines was removed for inspection and found to be in very good condition.

Using the existing orifice plates for measuring chilled water flow also has some important limitations. Orifice plates generally have a small turndown ratio and are sensitive to disturbances in the flow stream. The piping in the Administration Building does not provide adequate lengths of straight pipe to insure smooth flow. The result of this is that the chilled water flow measurements tend to become unreliable at low flow rates and also at high flow rates, making a water side measurement of cooling load impossible when the chilled water valve is open a small amount or a very large amount.

Zone terminal reheat is used in this building. It was not possible to instrument all of the hot water risers feeding water to the various zones. Instead, the hot water main supply line to the whole building was instrumented. An acoustic "transit time" flow meter was used to measure flow rate and precision thermistors mounted to the surface of the pipe and covered by insulation were used to measure the total temperature change. With this information the total reheat load to the building can be calculated.

Measuring air flow rates for each air handling unit was a difficult task. In almost all cases there was not sufficient straight duct work to establish smooth flow conditions. Because of pressure drop constraints it was not possible to place additional flow straighteners in the ducts. A series of measurements were made in a grid pattern for each duct to determine the average flow rate and to find a location to place a pitot tube to obtain estimates of flow rate. Pitot tubes were mounted in these locations and connected to differential pressure transducers.

All dampers and valves associated with the air handling units were instrumented with slide resistors calibrated for a range of 0 - 100% open. A micro switch was attached to the outdoor air dampers, chilled water valves, and steam preheat valves to provide a digital signal to confirm that the device is completely open (dampers) or completely closed (valves). The digital signal is necessary for sequencing control and eliminates the problem of determining how close to 0% open is closed and how close to 100% open is really open. Although generally reliable, there were times when a micro switch failed preventing an air handling unit from sequencing to the next control device when needed.

Each MUX contains eight signal conditioning cards with four channels each. This permits building a custom signal conditioning circuit for each of the 32 analog input signals. In this way it was possible to filter and convert the various voltage and current output signals from the sensors as needed to produce a standard 0 - 5V full scale signal to the analog to digital converter.

The pneumatic control system controls device sequencing by changing pressure from 3 - 15 psig. Each control device responds to a different part of that pressure range. In order to control each device separately using DDC an interface between the digital control system and the pneumatic actuators was needed. Previous attempts to use a simple solenoid valve arrangement where digital signals were used to open and close either a solenoid valve connected to mains air pressure or a solenoid valve open to the atmosphere to increase or decrease control line pressure respectively resulted in difficulties due to air leaks in the pneumatic lines [6].

Two different types of DDC/pneumatic interfaces were used in this experiment. The first was an inexpensive modification of the solenoid valve arrangement described above. In addition to the two solenoid valves, a commercially available reference capacitor and 1:1 booster relay have been added. The solenoid valves are used to control the pressure in the capacitor. The capacitor is connected to one side of the diaphragm inside a 1:1 booster relay. As the pressure on the control line side of the relay varies from the capacitor reference the diaphragm moves, regulating a bleed and thus equalizing the pressure on the two sides. A schematic diagram of this interface is shown in figure 3.3.

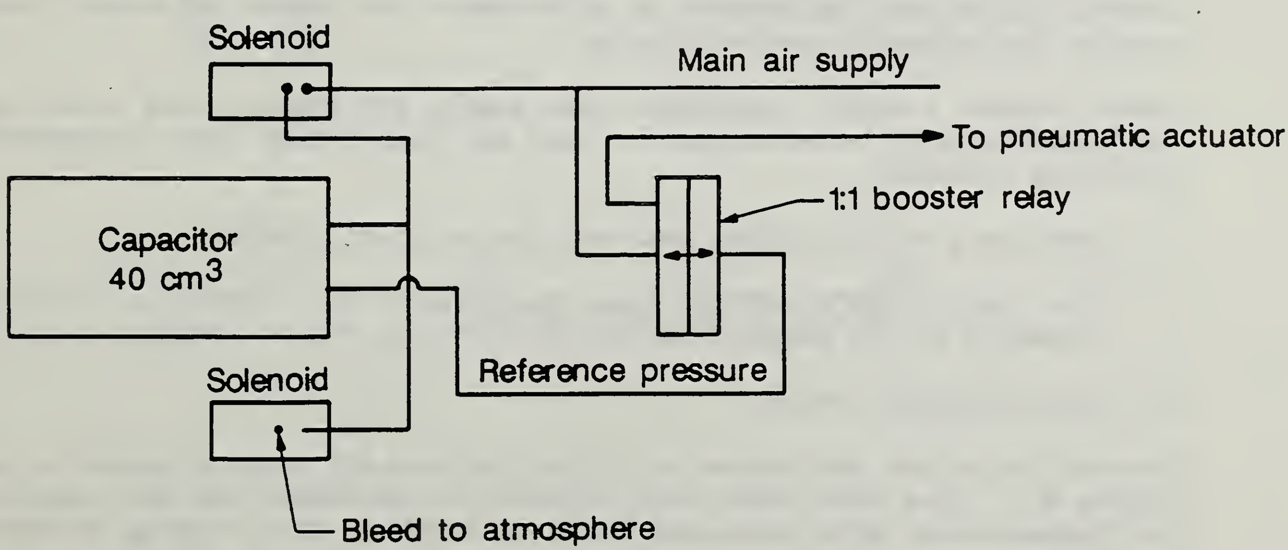


Figure 3.3. Solenoid value digital-to-pneumatic interface

The second type of DDC pneumatic interface used is a motor-driven regulator. The regulator is a special type that allows downstream pressure to be decreased by exhausting air to the atmosphere. The regulator adjustment shaft is fitted with two synchronous motors wired for opposite direction of rotation. Each motor is connected to a separate digital output from the controller and turning on one output allows 24 VAC to drive one of the motors in the desired direction. Thus one output is used to increase pressure, and one output is used to decrease pressure. This interface is much more expensive than the first type. No difference in performance of the two interfaces was detected.

Switching control from the pneumatic controller to the digital controller was accomplished by the use of electronic to pressure (E/P) relays. The relays were set up so that when energized the mains air pressure would be controlled by the digital controller, bypassing the pneumatic controller. This arrangement causes control to automatically switch to the pneumatic controller in the event of a power failure. It also allows plant personnel to override the digital controller in case of an emergency by disconnecting the power supply to the relays.

4. SUPPLY AIR TEMPERATURE CONTROL DURING COOLING SEASON

The plant personnel responsible for maintaining climate conditions in the building follow two strategies for controlling building temperatures, one referred to as "winter control" and the other referred to as "summer control".

The criterion for deciding which conditions apply is the outdoor air temperature. If the outdoor air temperature is 18.3°C (65°F) or warmer, then the "summer control" strategy is used. When outdoor air temperatures are lower the "winter control" strategy is used.

For the Washington D.C. climate this corresponds roughly to a heating season from November to March and a cooling season from April to October. The DDC control system was implemented to approximate the summer and winter strategies used by the pneumatic control system.

Under "summer control" conditions the supply air temperatures (Tsa) for each air handling unit is determined by zone air temperature (Tza) according to the following schedule:

> For Tza $\leq$ 26.6°C (78°F), maintain Tsa at 15.6°C (60°F).
>
> For Tza > 26.6°C (78°F), lower Tsa from 15.6°C (60°F) to 7.2°C (45°F) linearly as Tza ranges from 26.6°C (78°F) to 26.7°C (80°F).

4.1 Direct Digital Control

The ability of the DDC system to follow the zone air reset schedule is shown in figure 4.1. The data shown were selected to represent the full range of zone air temperatures which occurred while controlling the building in this mode. Data from each FID are represented as well as both dry bulb and enthalpy economizer cycles. The solid line indicates the expected reset schedule.

The figure shows that under DDC, supply air temperature was maintained within approximately ± 0.5°C (± 1°F) of the reset schedule. This is consistent with the tuning procedure used to maintain a setpoint temperature within ± 0.5°C (± 1°F). There was no difference in ability to maintain the reset schedule detected between the four FIDs or the two economizer cycles. There was also no drift in performance between data collected in the late summer and fall compared with data collected the following spring and summer.

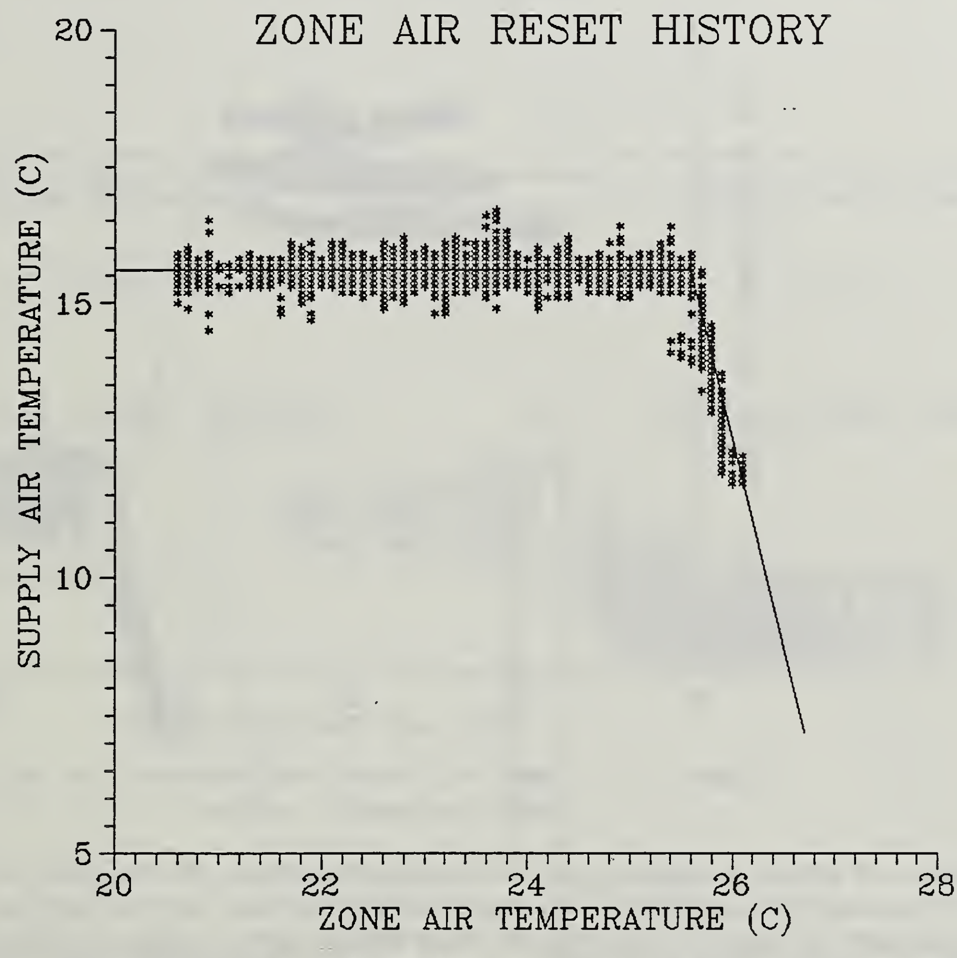


Figure 4.1. Zone air reset schedule performance for all air handling units under DDC.

4.2 Pneumatic Control

Data collected while the pneumatic system was in control show variation in performance between air handling units and also variation in time for the same air handling unit (AHU). Figure 4.2 shows the zone air reset history data from AHU-3 for three different time periods. For each of these periods AHU-3 maintained supply air temperature within a band of about ± 0.4°C (± 0.7°F), which is a tighter control than the DDC system, but the reset schedule being followed drifted around the intended schedule. This is probably due to inadvertent changes made to the control system during maintenance or drift. Evidence of this drifting reset schedule was found in the other air handling units as well.

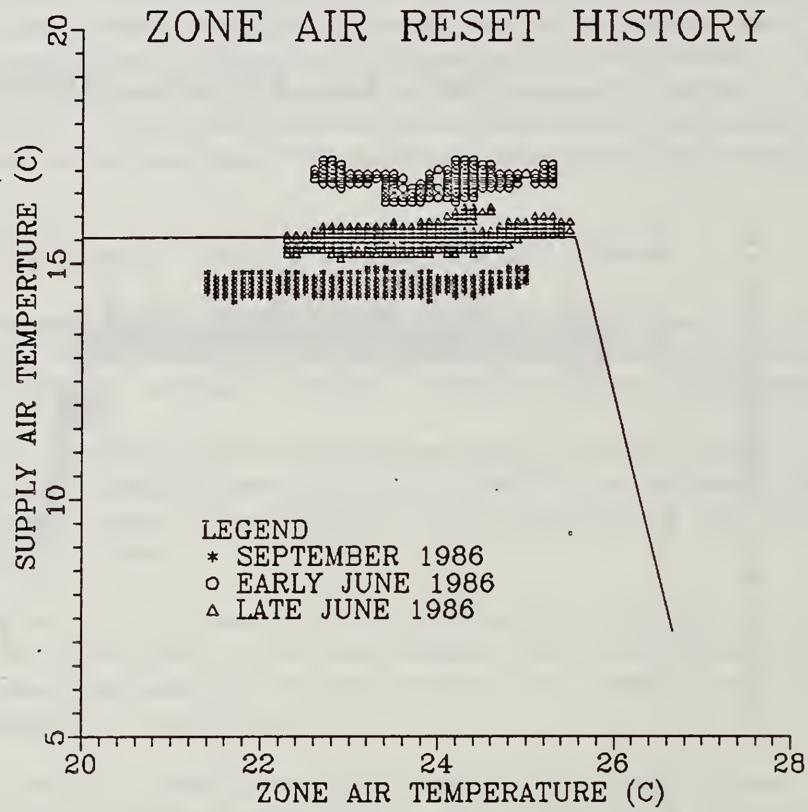


Figure 4.2. Zone air reset performance for AHU-3 under pneumatic control

Figure 4.3 shows a comparison of the performance of the four air handling units under pneumatic control. In each case the data are selected from a group of consecutive or nearly consecutive days which span a range of zone air temperatures. It can be seen that each AHU is following a different reset schedule and there is considerable variation in the spread of supply air temperatures for a given zone air temperature. AHU-3 consistently maintained tighter control than the other units with a spread of about ± 0.4°C (± 0.7°F). The worst spread was for AHU-6, which is about ± 2°C (± 3.6°F). The air handling units vary in design, but the control devices are all of the same type. These data suggest that the pneumatic control system is capable of maintaining control as well as the DDC system but in practice it is often not the case because of difficulty in keeping the controllers tuned and the desired reset schedule precisely adjusted.

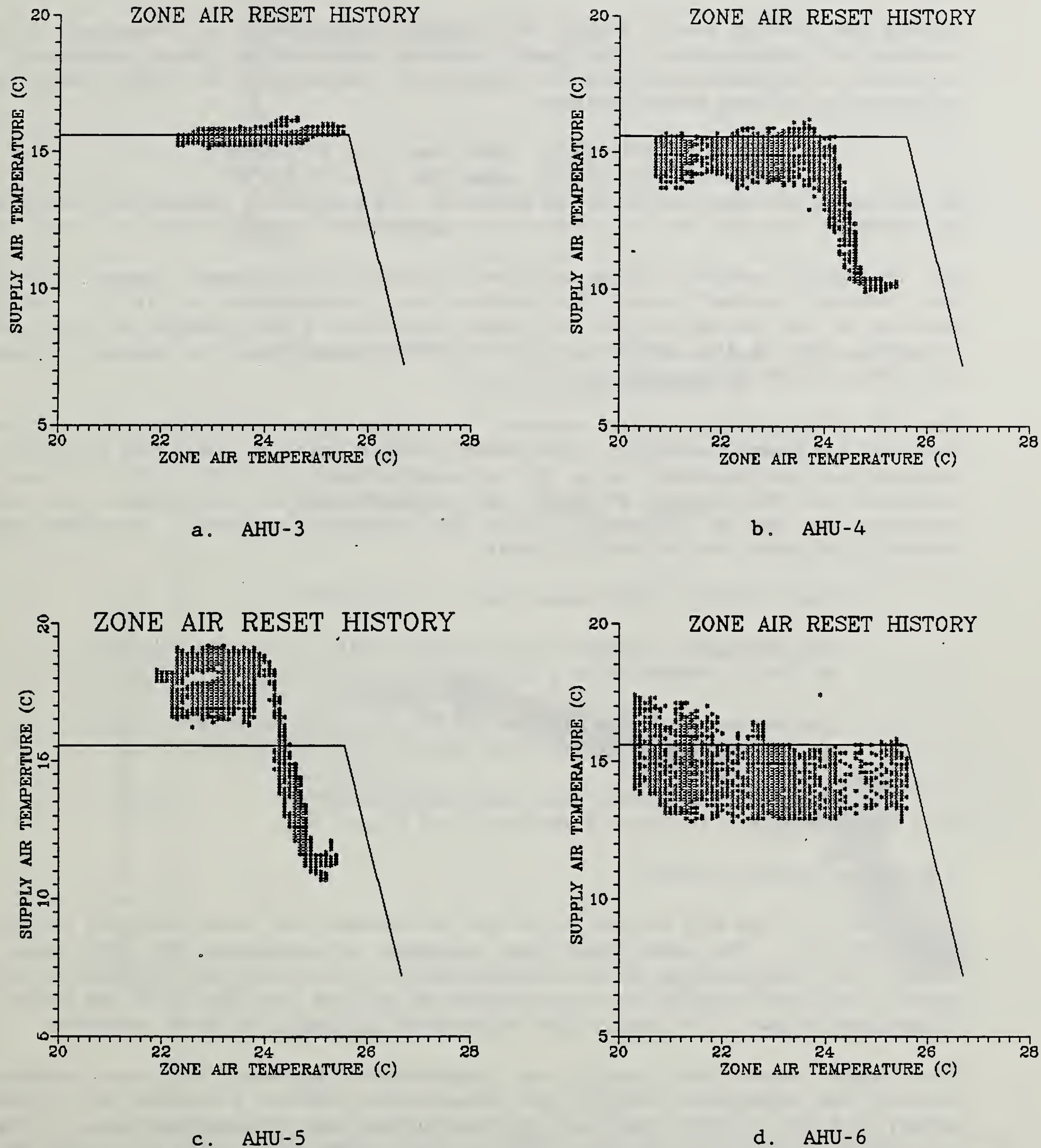


Figure 4.3. Zone air reset performance for air handling units under pneumatic control.

5. SUPPLY AIR TEMPERATURE CONTROL DURING HEATING SEASON

During the heating season supply air setpoint temperature is determined by the outdoor air temperature. The reset schedule requested by plant management is a linear relationship between the supply air temperature and the outdoor air temperature defined by the points:

$$T_{sa} = 18.3°C\ (65°F) \quad \text{when } T_{oa} = 18.3°C\ (65°F)$$
$$T_{sa} = 23.9°C\ (75°F) \quad \text{when } T_{oa} \leq 1.7°C\ (35°F)$$

As it turned out when the data was analyzed, the supply air temperature continued to increase linearly as the outdoor air temperature dropped below 1.7°C (35°F).

The pneumatic control system switches automatically between "summer control" and "winter control" when the outdoor air temperature is 18.3°C (65°F). Because of the design of the two reset schedules, a step change in supply air setpoint from 18.3°C (65°F) to 15.6°C (60°F) takes place as control switches from winter mode to summer mode.

The DDC system requires the operator to change reset strategies from "winter control" to "summer control". To avoid problems on days where the outdoor air temperature was expected to be in the neighborhood of 18.3° C (65° F) and to eliminate the step change in supply air temperatures, the DDC outdoor air reset schedule was set up differently than the pneumatic schedule. The DDC reset schedule followed the following format:

T_{sa} = 23.9°C (75°F) when $T_{oa} \leq$ 1.7°C (35°F)

T_{sa} decreases linearly from 23.9°C (75°F) to 19.7°C (67.5°F) as T_{oa} increases from 1.7°C (35°F) to 18.3°C (65°F).

T_{sa} decreases linearly from 19.7°C (67.5°F) to 15.6°C (60°F) as T_{oa} increases from 18.3°C (65°F) to 21.1°C (70°F).

T_{sa} = 15.6°C (60°F) when $T_{oa} \geq$ 21.1°C (70°F)

This reset schedule is shown graphically in figure 5.1.

5.1 Direct digital control

The ability of the DDC system to follow the outdoor air reset schedule is shown in figure 5.2. The data shown were selected to represent the full range of outdoor air temperatures which occurred while controlling the building in this mode. Data from each FID are represented as well as both dry bulb and enthalpy economizer cycles. The solid line represents the expected reset schedule.

The figure shows that supply air temperature followed the reset schedule closely and maintained supply air temperatures within a spread of approximately ± 0.8°C (1.4°F) over most of the outdoor air temperature range. There is a bulge in the data between 18°C and 20°C where the supply air temperature rose above the setpoint. Examination of the data from those days showed that the outdoor air dampers were wide open but not enough cooling was being provided by the outdoor air. The chilled water valve should have opened to provide further cooling but it did not.

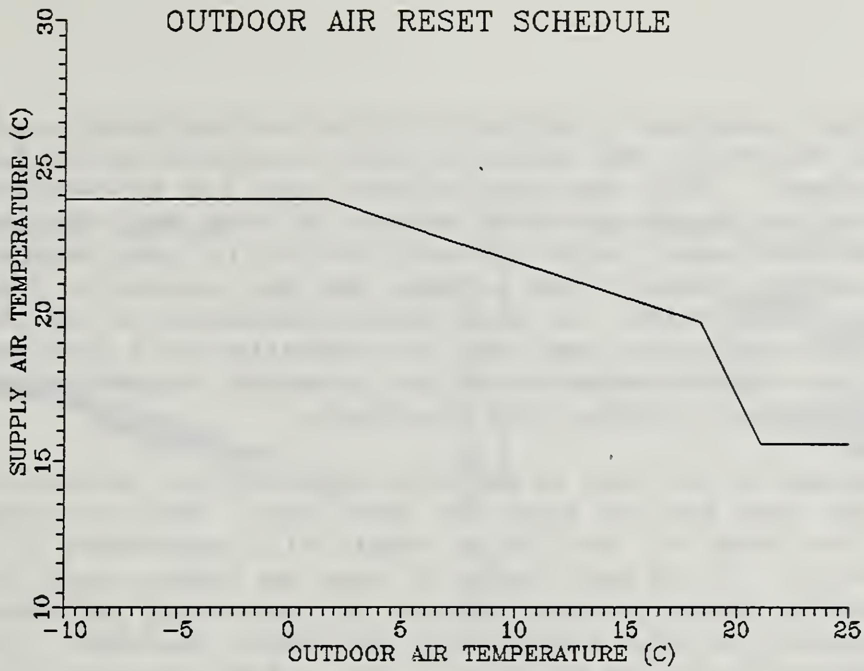


Figure 5.1. DDC outdoor air reset schedule.

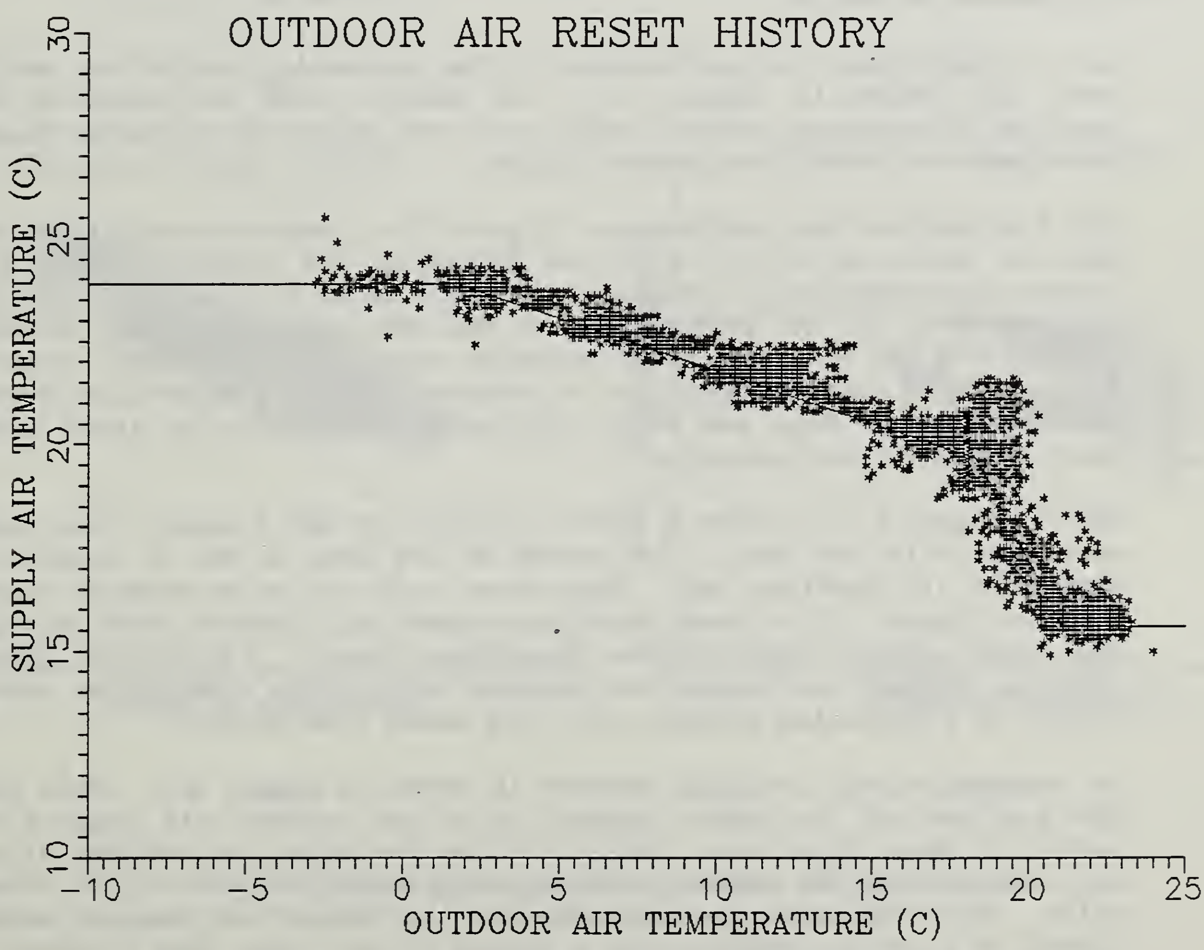


Figure 5.2. Outdoor air reset performance for all four air handling units under DDC

Problems occasionally surfaced with the microswitches used to provide a digital signal to notify the controller that a control device had reached the end of its travel. This was particularly true for microswitches connected to the outdoor air damper actuator because of dirt that was carried in by the air. The chilled water valve probably failed to open because dirt prevented the microswitch contact from closing and the controller never sequenced to the chilled water valve. An open circuit indicates to the controller that dampers are not completely open and the controller will continue to try to open the dampers. Digital signals were not recorded along with the other data so it is not possible to confirm this hypothesis.

The spread in the data is slightly wider for the outdoor air reset data than it was the case for the zone air reset data. This is probably due to the fact that over much of this range supply air temperature is controlled by damper modulation. It is much harder to tune the dampers than the chilled water valve to provide steady control because of the strong influence of the outdoor air temperature on the sensitivity to damper position. There is no apparent difference in quality of control between FIDs or between the dry bulb economizer and the enthalpy economizer.

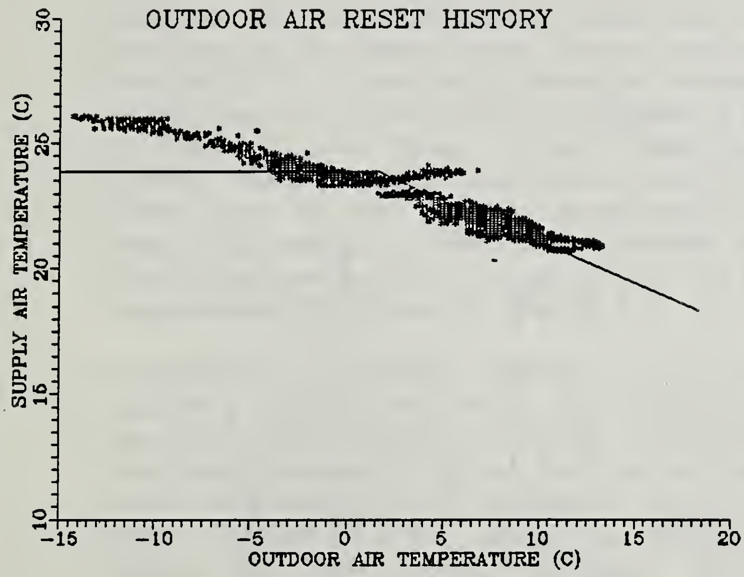
5.2 Pneumatic Control

Data illustrating the performance of the pneumatic controllers during "winter mode" are shown in figure 5.3. As before, each air handling unit has a distinct performance pattern which does not match the expected reset schedule depicted as a solid line in the figures.

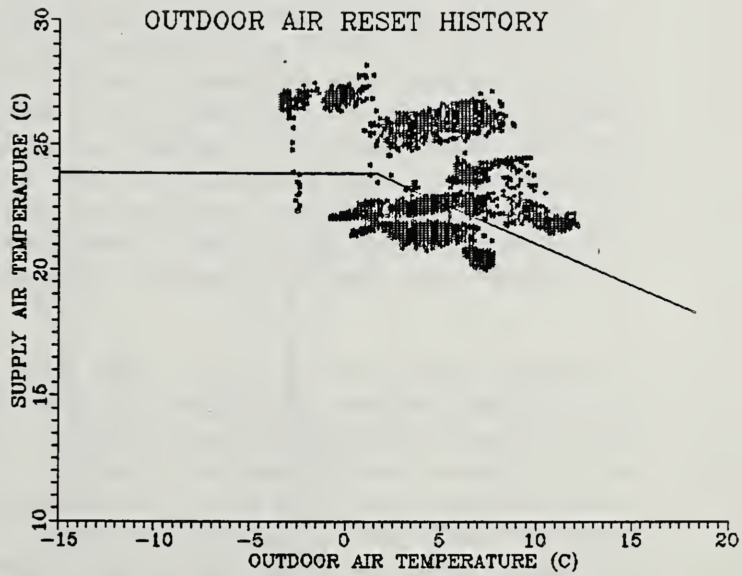
AHU-3 showed the best performance (figure 5.3a), maintaining a tight temperature band of about ±1.0°C (1.8°F) and following the reset schedule closely for outdoor air temperatures ranging from 2.0°C to 13.0°C (35.6°F to 55.4°F). This is comparable to the performance of the DDC control system. At temperatures below 2.0°C (35.6°F) the reset schedule continues its linear trend instead of maintaining a constant setpoint as expected. This is probably a better control strategy but it does not match the description given by plant personnel for their planned reset schedule.

AHU-5 (figure 5.3.c) shows a pattern similar to AHU-3 except that there is much more spread in the data. The spread in the data is due to sequencing trouble with this air handling unit. Comparison with the steam preheat valve position data in figure 6.10.c shows that the outdoor air dampers tend to fight against the steam preheat valve in the temperature range - 5°C to 10°C (23-50°F). In fact the outdoor air dampers and preheat valve had a tendency to swing open and closed in alternating fashion in a very short time period.

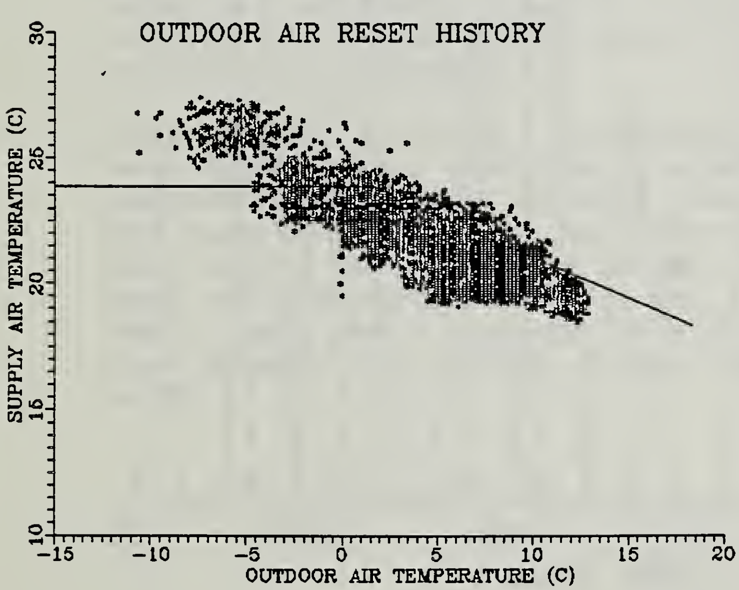
An example of this swinging problem is shown in figure 5.4. This figure shows the position of the steam preheat valve and outdoor air dampers for a time period of about 20 minutes. The solid line indicates the position of the outdoor air dampers and the dashed line represents the position of the steam preheat valve. Both the steam preheat valve and the outdoor air dampers swing open and closed in a cyclic fashion with a period of just less than 2 minutes. The two cycles are about 180 degrees out of phase.



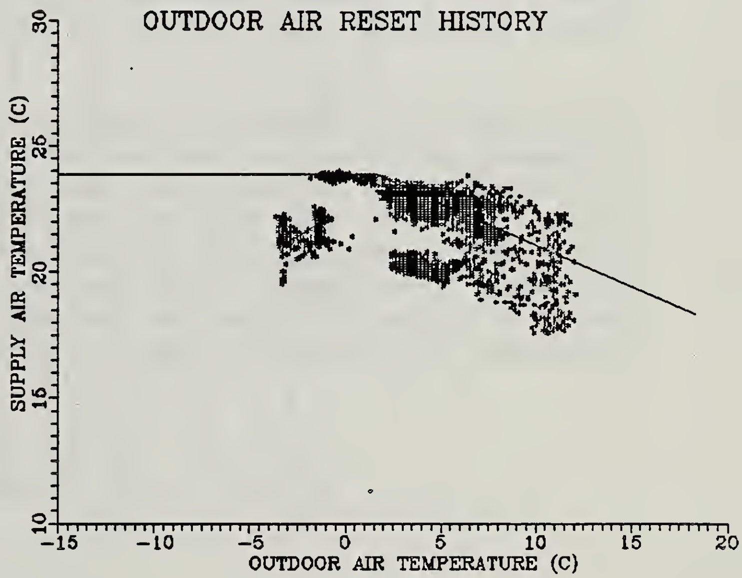
a. AHU-3



b. AHU-4



c. AHU-5



d. AHU-6

Figure 5.3. Outdoor air reset performance under pneumatic control

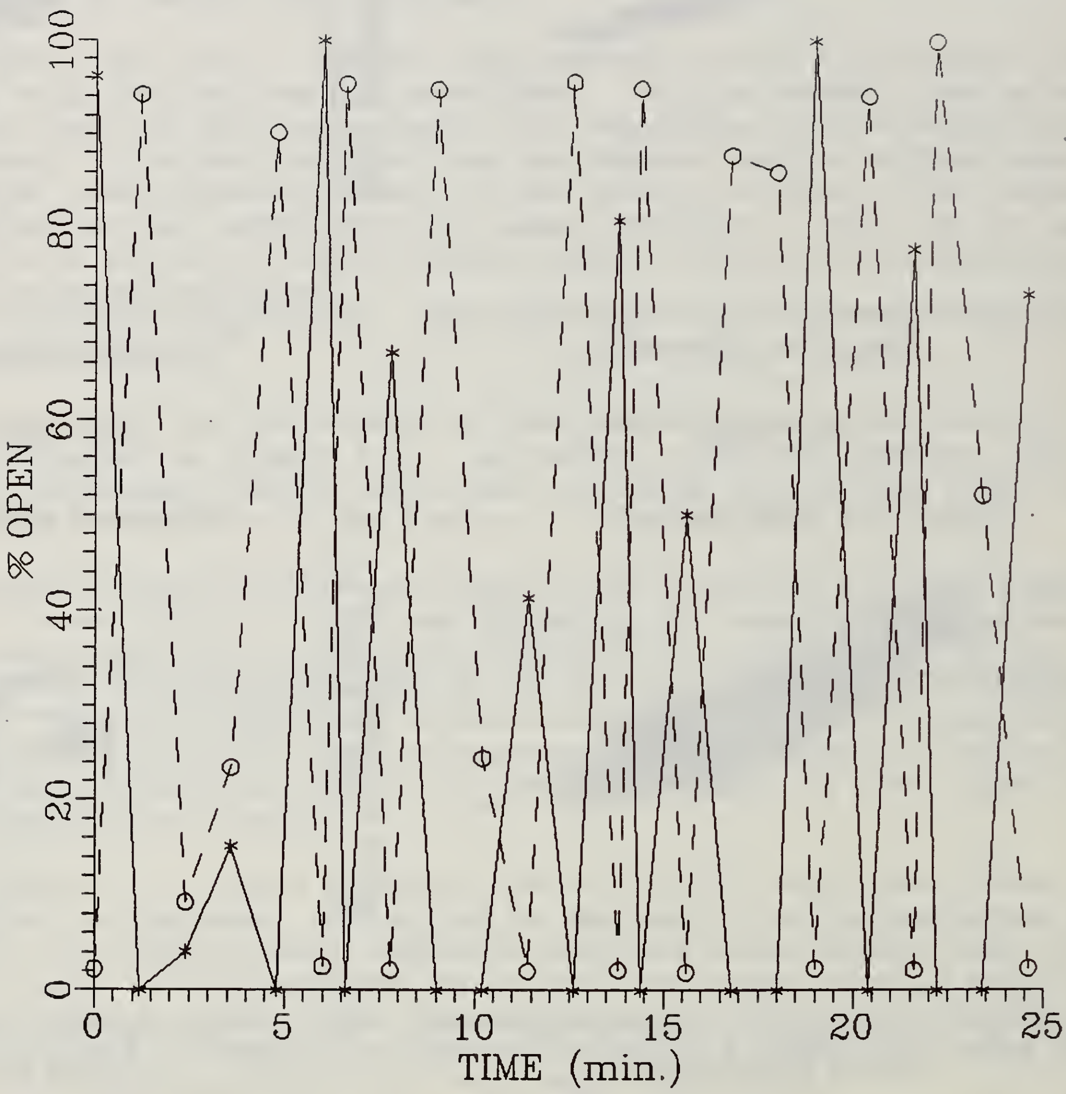


Figure 5.4. Damper and preheat value swinging on AHU-5 under pneumatic control.

The effect of this swinging action on the mixed air temperature and the supply air temperature is shown in figure 5.5. It can be observed that both of these air temperatures swing up and down in conjunction with the steam valve and dampers. The maximum peak to peak mixed air temperature swing about 15°C(27°F). The supply air temperature swings are smaller, approaching 2.5°C (4.5°F).
The ability of the DDC system to control this air handling unit under similar conditions is illustrated in figures 5.6 and 5.7. The first 30 minutes of data in these figures shows the unit under pneumatic control. At that point the DDC system comes on line and takes control of the air handling unit. Figure 5.6 shows that the DDC system immediately locks the outdoor air dampers closed and damps out swings in the steam preheat valve over a period of about 20 minutes. The corresponding stabilization of the mixed air temperature and the supply air temperature is shown in figure 5.7.

The ability of the DDC system to control this unit indicates that the pneumatic system's problem was with the controller and not with the control devices or the air lines leading to their actuators. This is because the DDC system uses the same pneumatic lines and actuators. Several attempts were made by the plant maintenance staff to remedy this problem but they were never fully successful.
AHU-4 (figure 5.3.b) showed a different type of problem. The data in this figure fall into distinct regions. The time span represented is quite long but changes due to drifting of minor adjustments made during routine maintenance cannot explain these results. In many cases two distinct regions of operation appear for the same day. The controller would be maintaining a particular supply air temperature value for several hours and then suddenly a step change in supply air temperature would take place, but without a corresponding change in outdoor air temperature.

AHU-6 (figure 5.3.d) also had considerable scatter in the supply air temperature reset history data. There was a catastrophic failure in one of the pneumatic components of this unit in March, causing the controller to loose control of the steam preheat valve. The faulty part was isolated and replaced. After this service the performance of the unit dramatically improved. Figure 5.8 shows the performance of AHU-6 for a two day period immediately after the repairs were made. Although it still does not strictly follow the intended reset schedule, the control is much tighter and the performance is comparable to AHU-3.

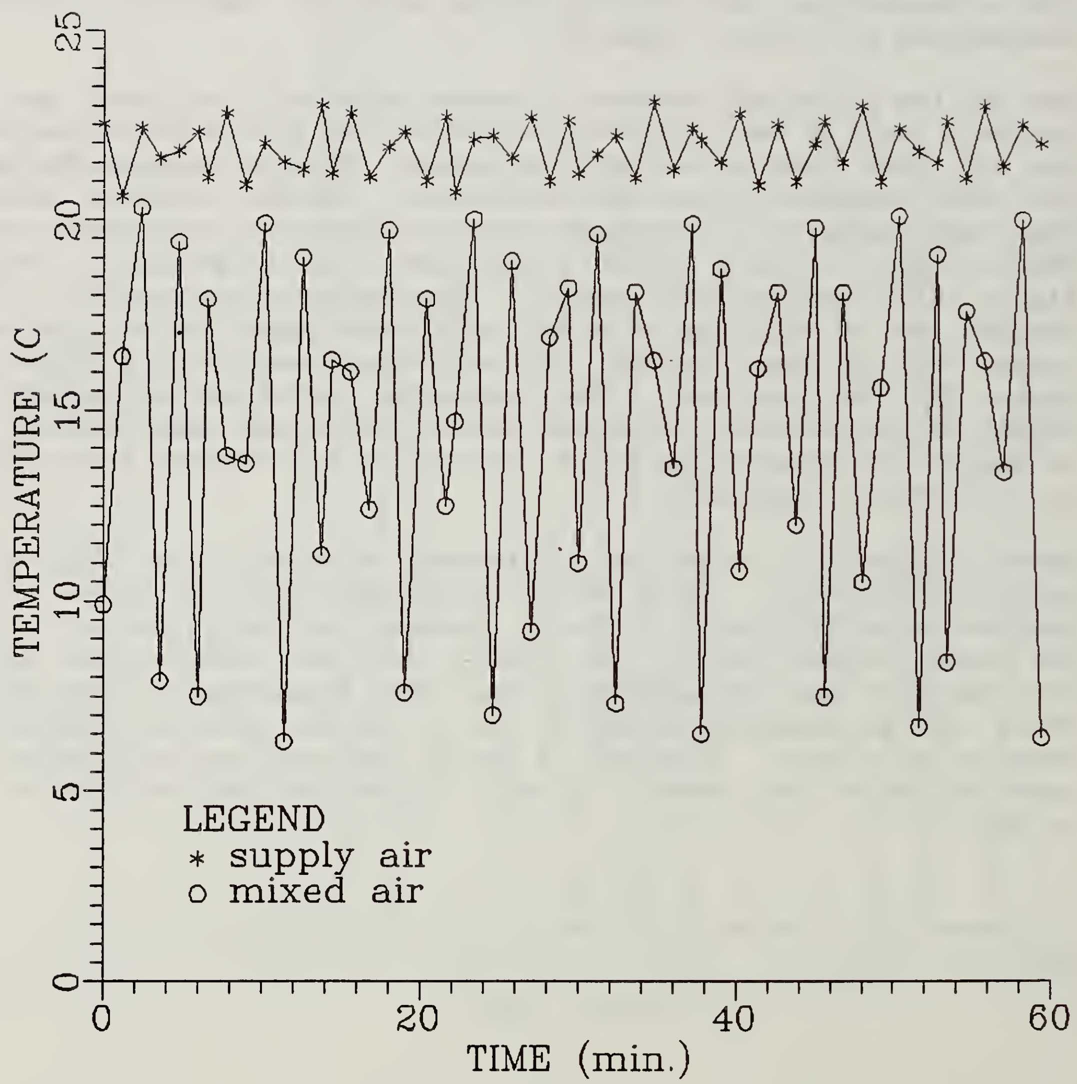


Figure 5.5. Influence of damper and preheat swinging on mixed and supply air temperatures, pneumatic control

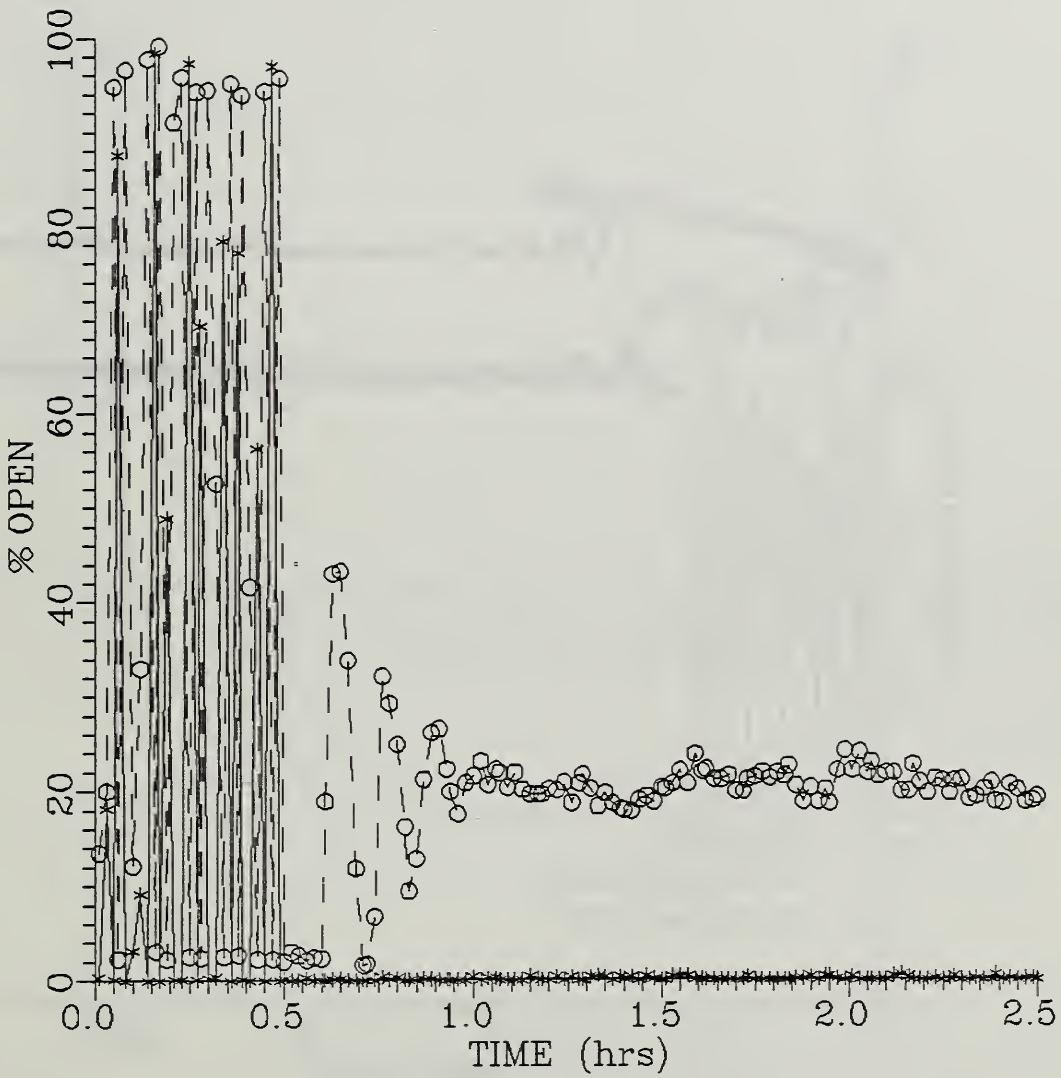


Figure 5.6. Transition from pneumatic control to DDC stops swinging problem

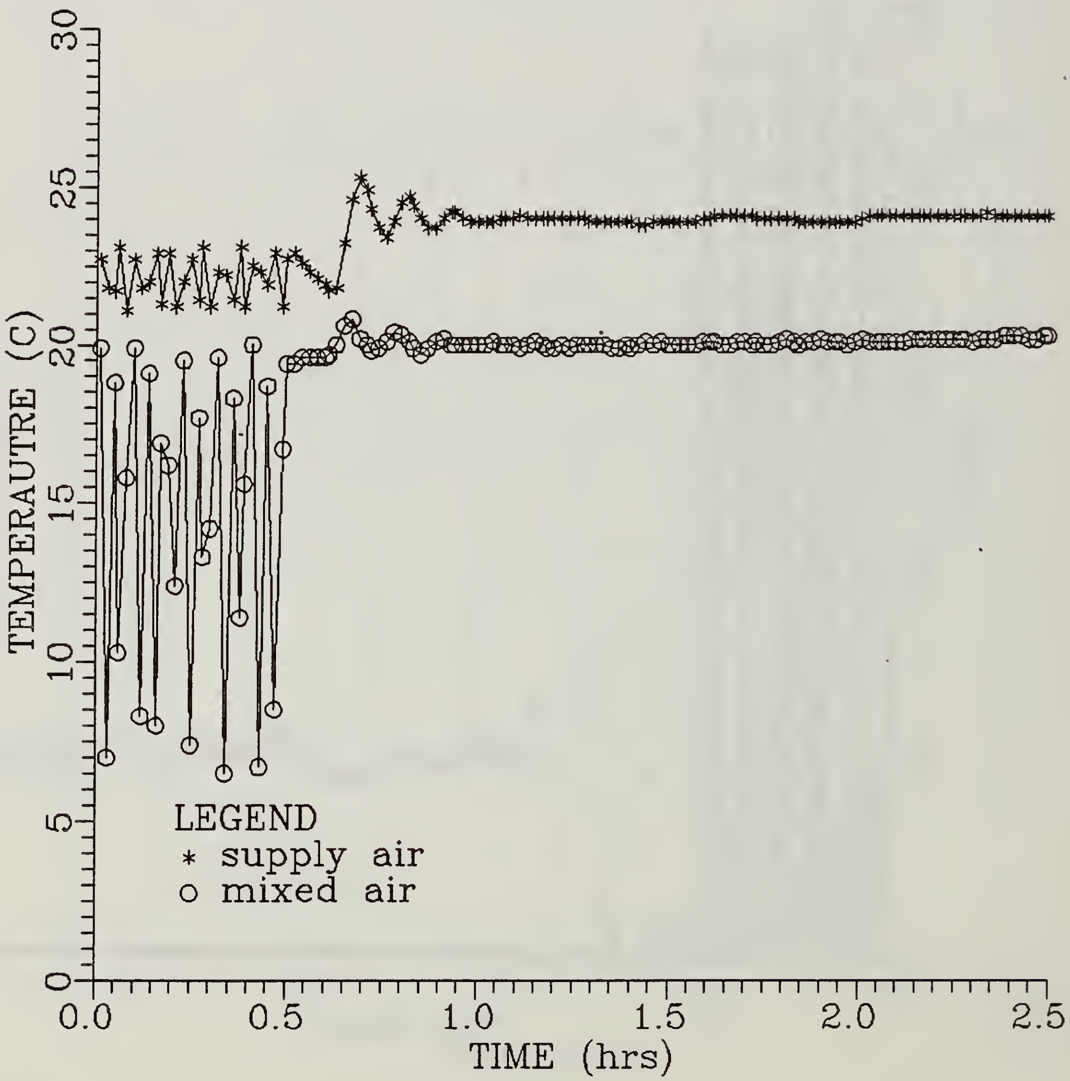


Figure 5.7. Supply air and mixed air temperature response to transition from pneumatic to DDC

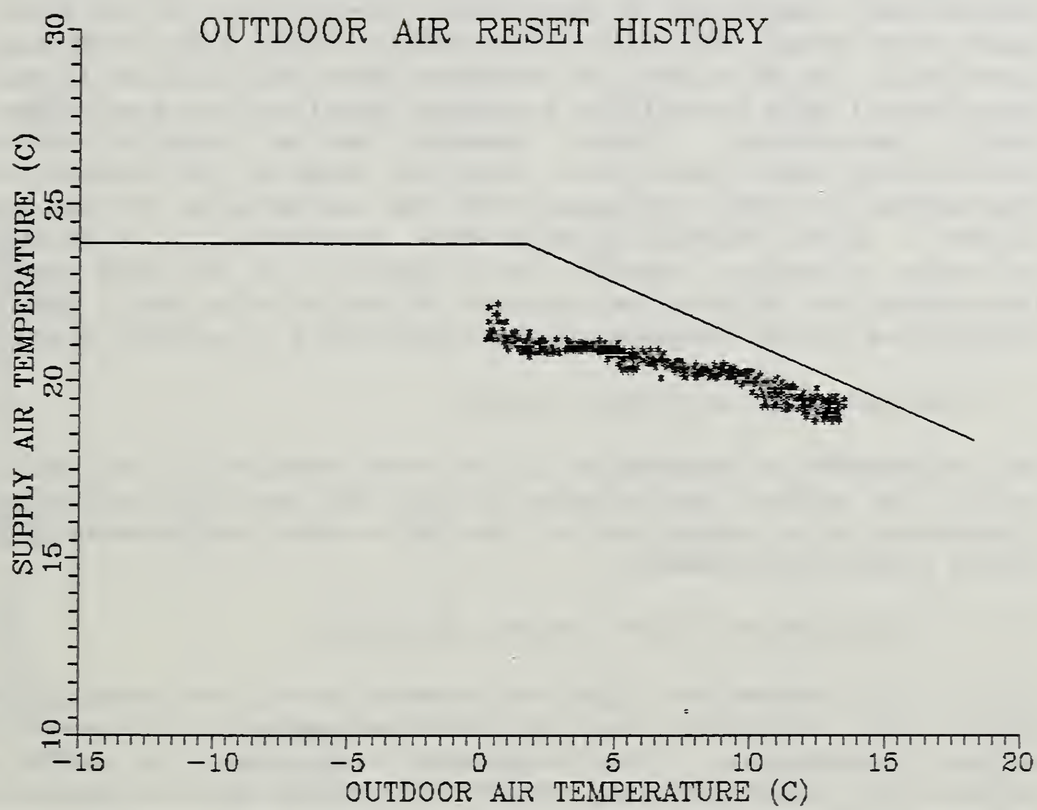


Figure 5.8. Outdoor air reset performance of AHU-6 under pneumatic control after repairs.

6. PERFORMANCE TRENDS FOR STRATEGIES TESTED

While it would be desirable to compare energy consumption for the different data sets, it is a very difficult task to take performance data from selected days and compare energy consumption with data associated with different strategies different days, weather conditions, and internal loads. This problem was compounded by measurement limitations in air flow rates, chilled water flow rates, and relative humidities under some conditions, as discussed previously. In an attempt to overcome these difficulties it was decided to use experimental data to validate a computer model and run simulations to investigate energy performance. These results may be found in reference [1]. The experimental data were also used to examine performance characteristics, contrasting the DDC strategies with the performance of the pneumatic control system. These characteristics were determined by examining the relative positions of control devices as a function of building load. Outdoor air temperature was selected as a measure of the building load. From this information differences in the response of the controllers to similar loads can be seen.

6.1 Performance of economizer cycles

The performance of economizer cycles were examined in two ways, an analysis to verify the correct performance of the DDC dry bulb and enthalpy economizer algorithms and a comparison of the DDC control performance with the pneumatic system control performance.

6.1.1 Verification of DDC dry bulb economizer

The dry bulb economizer algorithm selects one of four possible actions based on outdoor air temperature and two fixed parameters, changeover temperature and minimum temperature. The changeover temperature is essentially a maximum outdoor air temperature for which the dampers will be opened for cooling the building. The minimum temperature is the temperature below which the dampers will be forced closed to prevent freezing of the cooling coil. The four possible actions taken by the economizer algorithm are:

1. Lock outdoor air dampers closed and use mechanical cooling.
2. Lock outdoor air dampers closed and do not use mechanical cooling.
3. Lock outdoor air dampers open and use mechanical cooling.
4. Allow outdoor air dampers to be modulated and do not use mechanical cooling.

Further details of the dry bulb economizer algorithm can be found in reference [2].

Performance data from AHU-3 under DDC dry bulb economizer control were selected for a wide range of outdoor air temperatures to validate the performance of this algorithm. The positions of the outdoor air dampers were assumed to be in one of four possible states. These states were completely open, completely closed, between half open and fully open, and between half open and fully closed. Figure 6.1 contains four histograms to indicate the number of times the outdoor air dampers were in each of the four states. The number of occurrences of each damper state is plotted as a function of the outdoor air temperature.

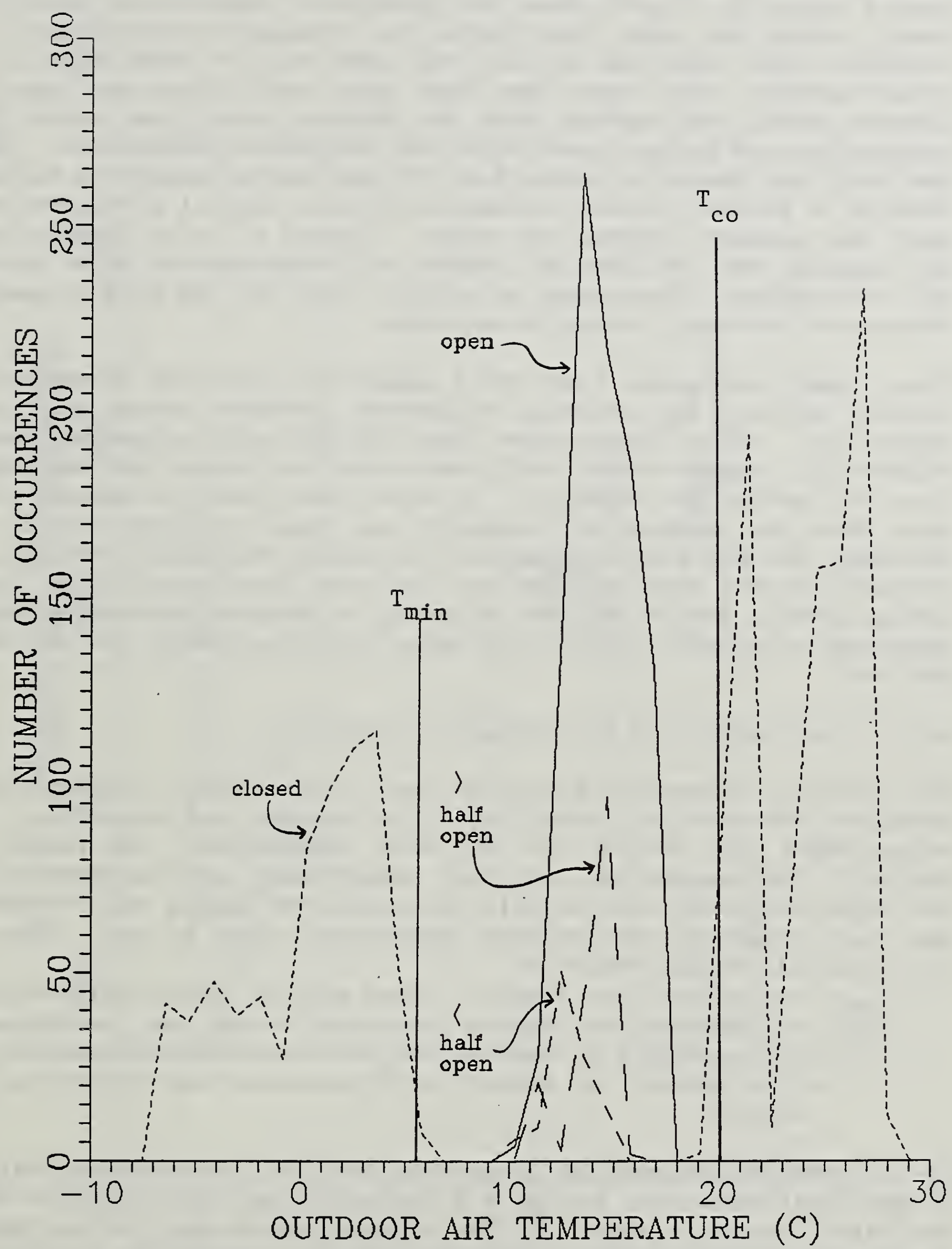


Figure 6.1. Histogram of damper positions for AHU-3 under DDC with dry bulb economizer

Theoretically, if the algorithm were operating properly, the outside air damper should always be closed above the changeover temperature (20°C or 68°F during these tests) and open just below the changeover temperature. Figure 6.1 indicates that this was in fact the case for the days shown. It should be noted however, that cases have been seen where there was some small overlap between these two regions with the dampers being open above the changeover temperature and being closed below the changeover temperature. This was due to the fact that there is a dead band in the control algorithm between sequencing changes to prevent rapid fluctuations between control modes when conditions are near the boundary between two modes. Figure 6.1 also shows that the outdoor air dampers were not open at outdoor air temperatures below the minimum value of 5.5°C (42°F). These results indicate that the dry bulb economizer algorithm functioned correctly during these tests.

These same histograms from AHU-3 under DDC dry bulb economizer control are plotted against the enthalpy difference between return and outdoor air in figure 6.2. This figure shows that the dry bulb economizer never opened the outdoor air dampers under conditions where the outdoor air enthalpy was greater than the return air enthalpy. It also shows that the dampers were not always open when the outdoor air enthalpy was lower than the return air enthalpy. Although the dry bulb economizer did reduce mechanical cooling load by using outdoor air for cooling, the data indicate that some further improvement in energy savings may be achieved by using an enthalpy economizer which could take advantage of outdoor air cooling under conditions where the dry bulb economizer did not.

6.1.2 Verification of DDC enthalpy economizer

The enthalpy economizer algorithm used four measured values from the EMCS in order to determine the enthalpies of the outdoor and return air. The measured values were the return air dry bulb temperature, the return air relative humidity, the outdoor air dry bulb temperature, and the outdoor air dewpoint. The algorithm must also be able to access the supply air setpoint temperature and one parameter, the minimum temperature, must be set. The algorithm has four possible output decision:

1. Lock outdoor air dampers closed and use mechanical cooling.
2. Lock outdoor air dampers closed and do not use mechanical cooling.
3. Lock outdoor air dampers open and use mechanical cooling.
4. Allow outdoor air dampers to be modulated and do not use mechanical cooling.

If the outdoor air enthalpy is greater than the return air enthalpy by at least a small differential, set at 1.2 kJ/kg dry air (0.5 BTU/lbm dry air), then decision 1 above is made. If the outdoor temperature is less than the minimum temperature than decision 2 is made. If the outdoor air enthalpy is less than the return air enthalpy by at least a small differential, greater than both the minimum temperature and the supply air setpoint, then decision 3 is made. If the outdoor air enthalpy is less than the return air enthalpy by at least a small differential, the outdoor air temperature is both greater than the minimum temperature and less than the supply air setpoint, then decision 4 is made. A more detailed description of the enthalpy economizer can be found in reference [2].

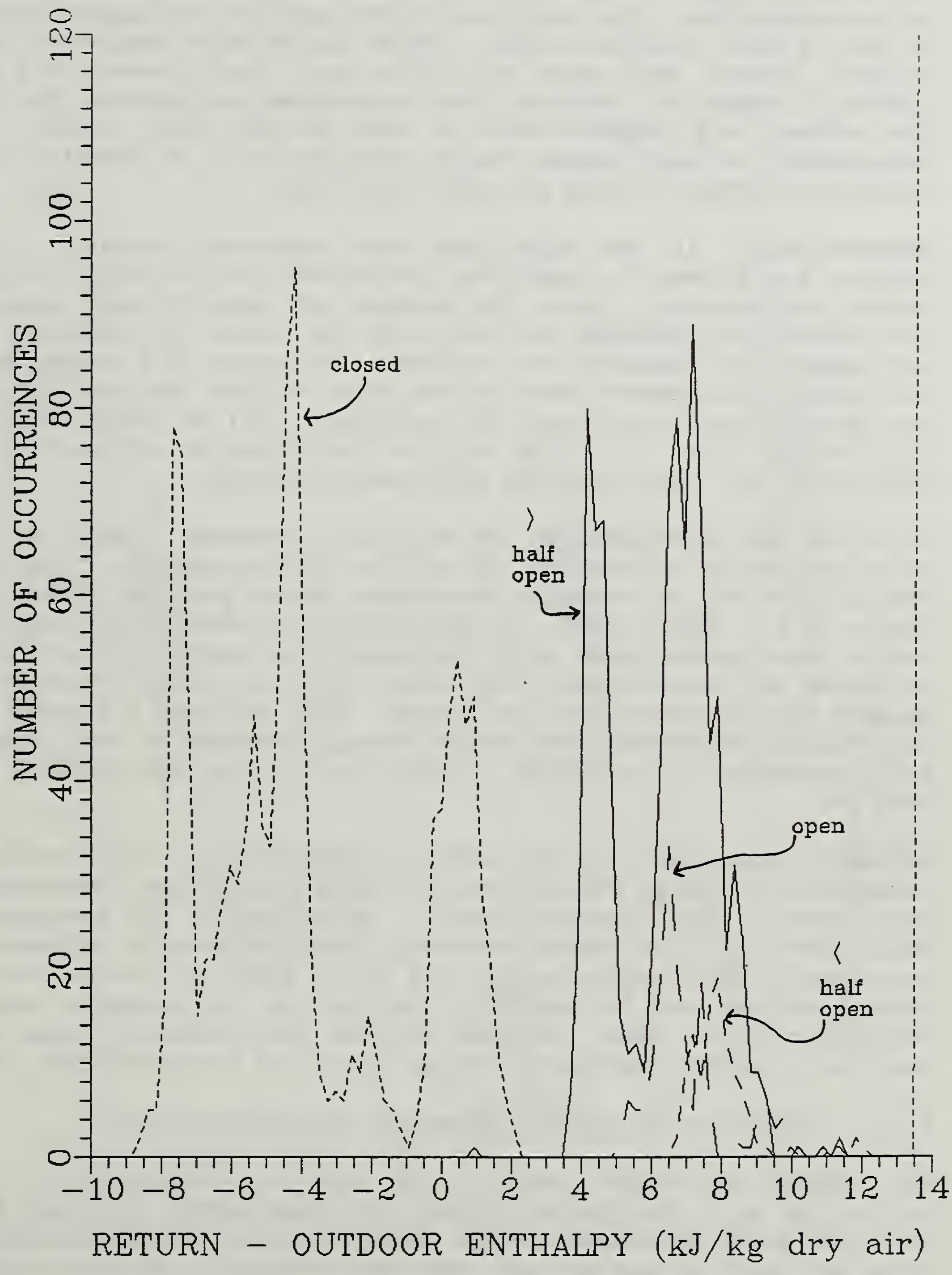


Figure 6.2. Histogram of damper position for AHU-3 under DDC with dry bulb economizer.

Performance data from AHU-3 under DDC enthalpy economizer control were selected for a wide range of outdoor air temperatures to verify the correct performance of this algorithm. The positions of the outdoor air dampers were assumed to be in one of four possible states. These states were completely open, completely closed, between half open and fully open, and between half open and fully closed. Figure 6.3 contains four histograms to indicate the number of times the outdoor air dampers were in each of the four states. The number of occurrences of each damper state is plotted as a function of the enthalpy difference between return air and outside air.

Theoretically, if the algorithm were operating properly, the outdoor air dampers would never be open when the outdoor air enthalpy is greater than the return air enthalpy. Also, the outdoor air dampers would never be closed when the outdoor air enthalpy is less than the return air enthalpy and the outside air temperature is above the minimum. In figure 6.3 it may be observed that the outdoor air dampers were in fact open at times when the outdoor air enthalpy was greater than the return air enthalpy. All of these occurrences however, fall within the 1.2 kJ/kg dry air differential allowed by the algorithm indicating that the algorithm performed correctly.

To verify the performance of the dry bulb economizer, damper position histograms were plotted as a function of outside air temperature. For completeness, a similar plot of the enthalpy economizer damper position histograms is shown in figure 6.4. Notice that in the enthalpy economizer histograms there is no single temperature above which the dampers are always closed. Instead there is a spread of temperatures from about 20°C to 24°C (68-75°F) for which the dampers may be either open or closed. This provides a further indication that the enthalpy economizer can reduce energy consumption when compared to the dry bulb economizer by providing outdoor air cooling when the dry bulb economizer does not.

Enthaply economizers do not always outperform dry bulb economizers from the standpoint of energy consumption. Several factors are important in determining this issue. They include climate, selection of the parameters for the dry bulb economizer, and sensor accuracy. See for example references [7- 9]. The experimental data collected in this study does not conclusively show how much energy savings may be possible from the use of enthalpy economizers in the Washington D. C. area. Because of the high humidity found in this area it would be expected that savings large enough to be significant could result.

6.1.3 Comparison of DDC and pneumatic economizer control

The outdoor air damper position for each air handling unit, while under DDC, is plotted as a function of outdoor air temperature in figure 6.5. The points in these plots represent hourly average values for temperature and position. Both dry bulb economizer and enthalpy economizer data are shown. The solid lines represent a best fit to the data. For AHU-5 and AHU-6 the best fit curves are linear and for AHU-3 and AHU-4 the best fit curves are a power fit.

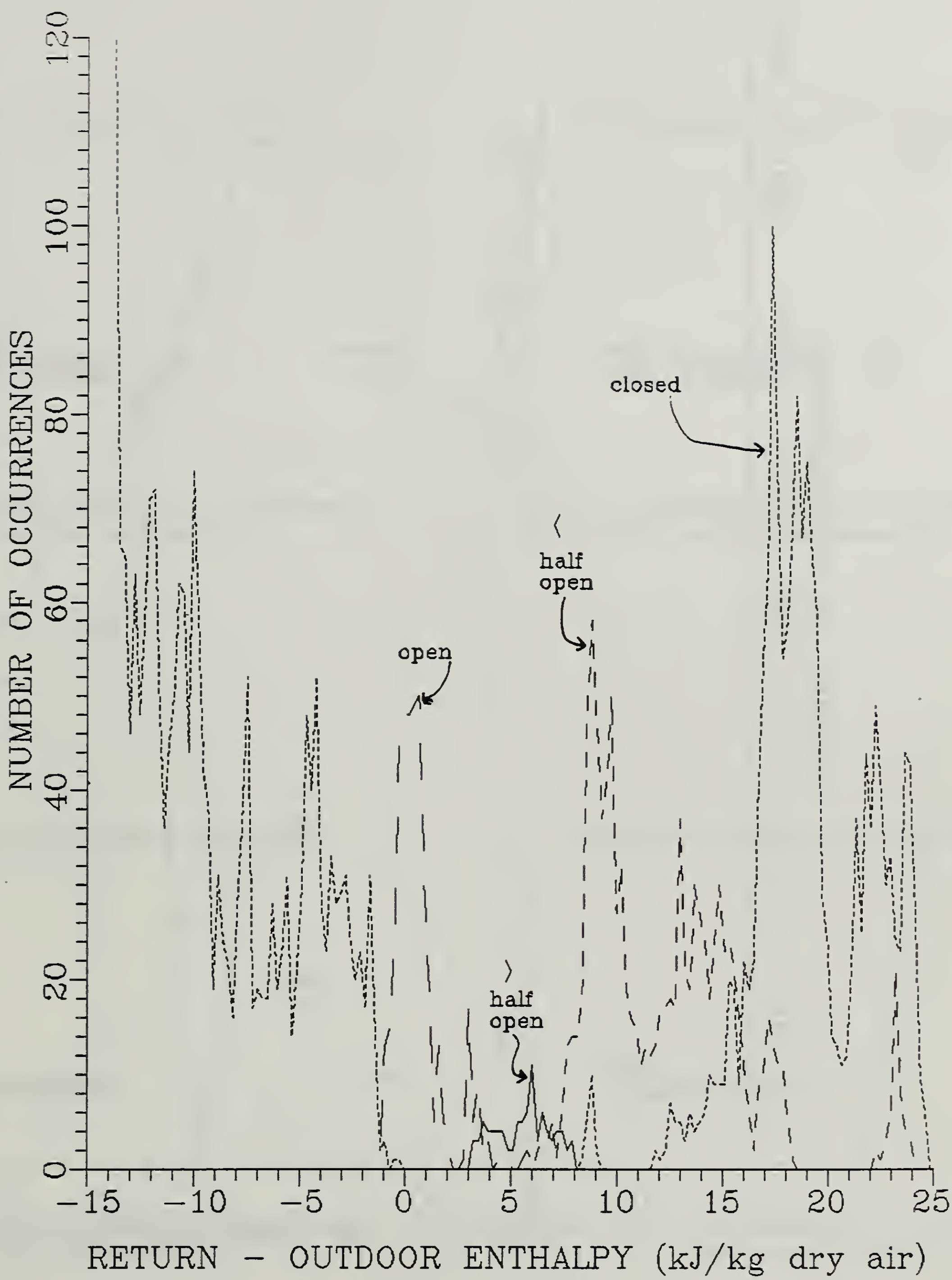


Figure 6.3. Histogram of damper positions for AHU-3 under DDC with enthalphy economizer

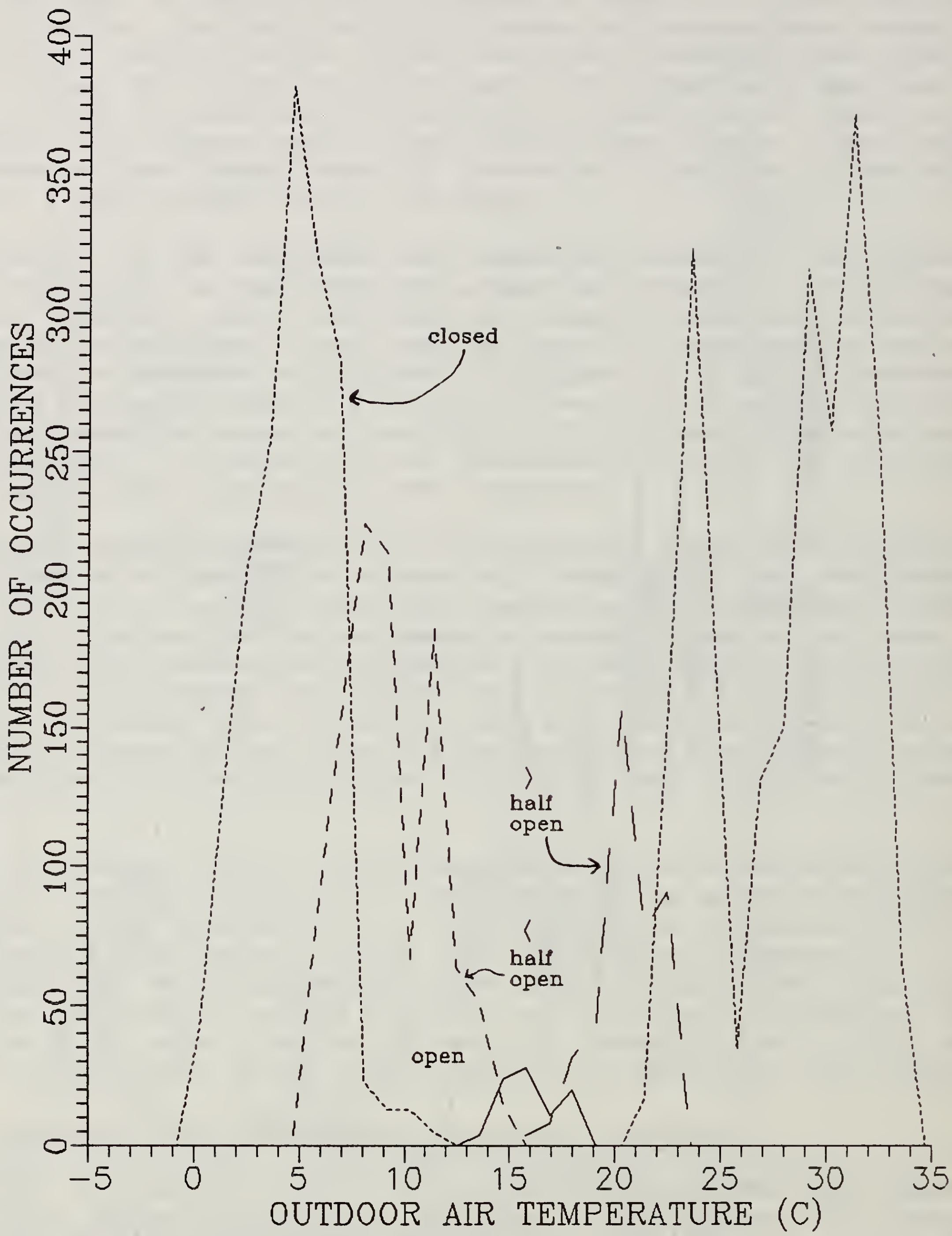
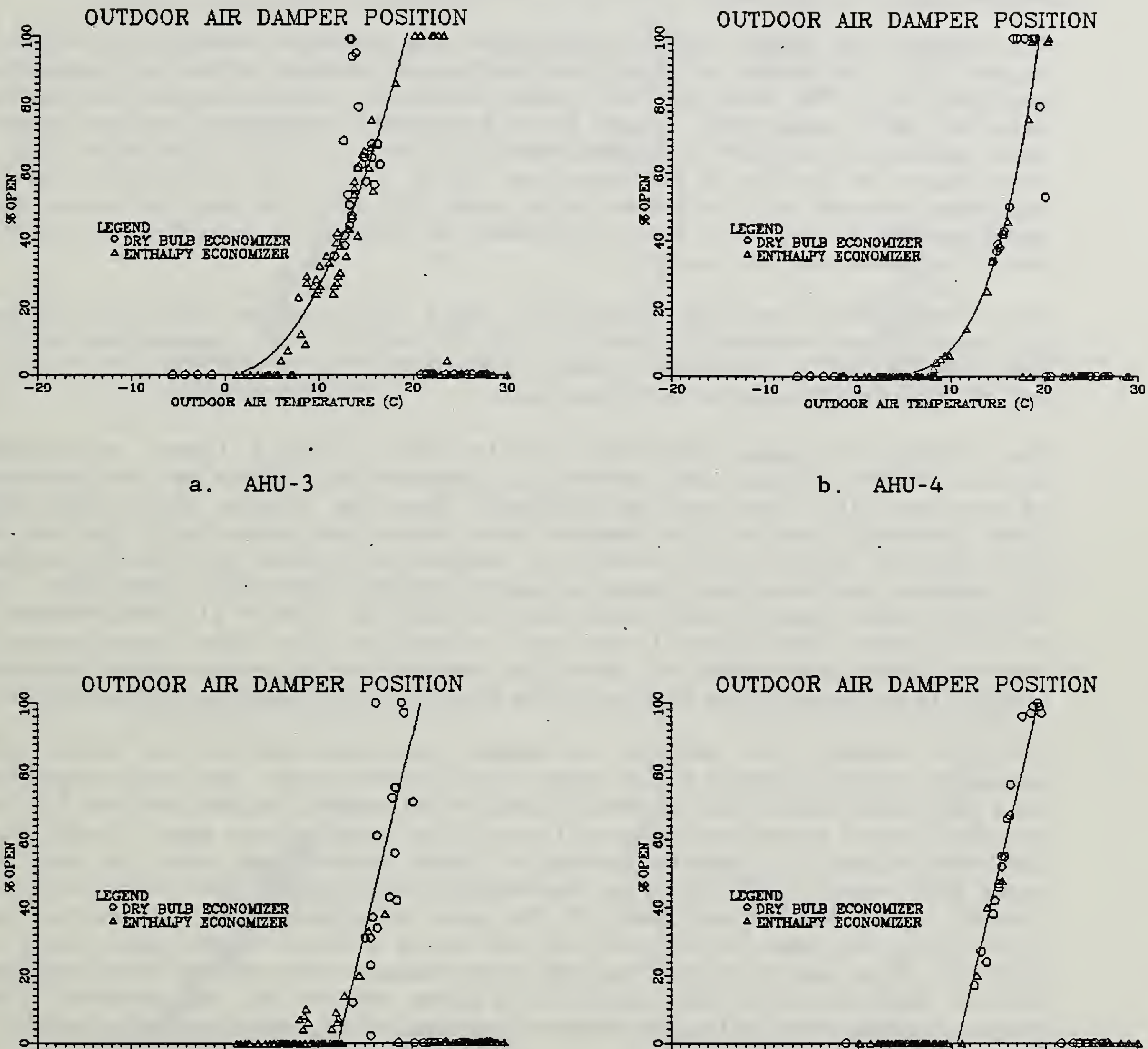


Figure 6.4. Histogram of damper positions for AHU-3 under DDC with enthalphy economizer.



a. AHU-3 b. AHU-4

c. AHU-5 d. AHU-6

Figure 6.5. Outdoor air damper position as a function of outdoor temperature for each air handling unit under DDC

Each air handling unit shows somewhat different characteristics with regard to outdoor air damper position. This result is expected because of variations in the design of the units and differences in the load in the four zones being served. The temperature range over which outdoor air is used for cooling is similar for all four units, about 8 - 20°C (46.4 - 68°F).

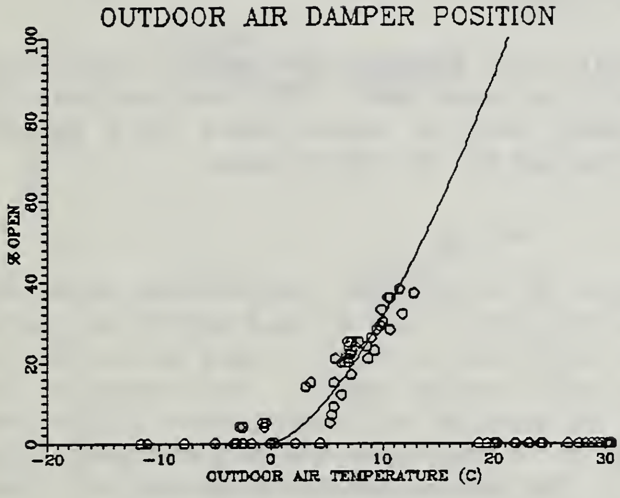
The outdoor air damper position histories for pneumatic control are shown in figure 6.6. The points in these plots are hourly average values for temperature and position. The data for AHU-3 under pneumatic control closely matches the data for AHU-3 under DDC, except for a few points indicating that the dampers were opening at outdoor air temperatures below 0°C (32°F). The solid line in this figure is the fit to DDC data from figure 6.4.a. It illustrates the good agreement between data collected while under DDC with the data collected while under pneumatic control. This unit comes the closest to behaving the same way under pneumatic and DDC control.

The outdoor damper position history for AHU-4 shows random scatter for outdoor air temperatures between 2°C and 18°C (35.6°F and 64.4°F). Comparison with the position history of the steam preheat valve in section 7 will show that this is due to sequencing trouble with this unit.

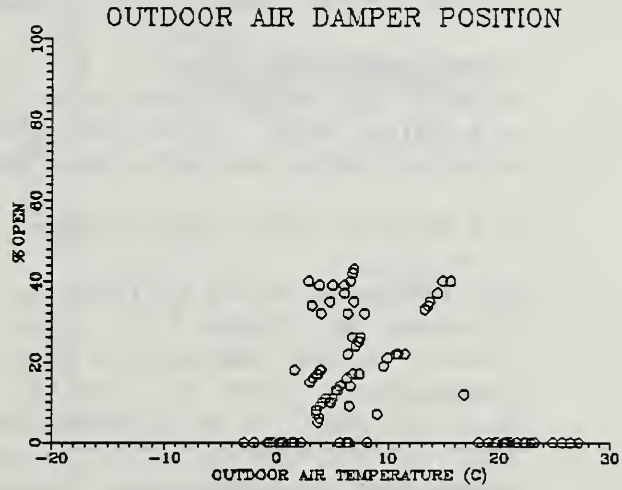
The outdoor air damper position plot for AHU-5 shows a linear relationship between damper position and outdoor air temperature. The slope and intercept of the best fit line are both different from the results of the DDC data. Under pneumatic control, the dampers open sooner and more slowly than was the case with DDC control. For outdoor air temperatures below 12°C (54°F), outdoor air dampers are more open under pneumatic control than when under DDC. The best fit lines suggest this trend will continue to outdoor air temperatures up to 20°C (68°F), but there is no data to confirm this trend under pneumatic control. The temperature at which the dampers begin to open under pneumatic control is dangerously low because of the possibility of freezing the cooling coil.

The plot showing the outdoor air damper position history for AHU-6 under pneumatic control (figure 6.6.d) shows two distinct curves. One curve represents data collected before the pneumatic failure discussed in the section 5.2, and the other curve represents data collected after repairs were made. Both curves indicate outdoor air dampers opening at lower temperatures than the same unit under DDC control, but the curve representing data taken after repairs is much closer. For damper positions of 20% open or greater the two curves have essentially the same slope, with the DDC curve shifted to the right about 2°C (3.6°F). This indicates that for AHU-6 the dampers open sooner under pneumatic control than under DDC and also for a given outdoor air temperature in the range of damper modulation the dampers are open wider under pneumatic control.

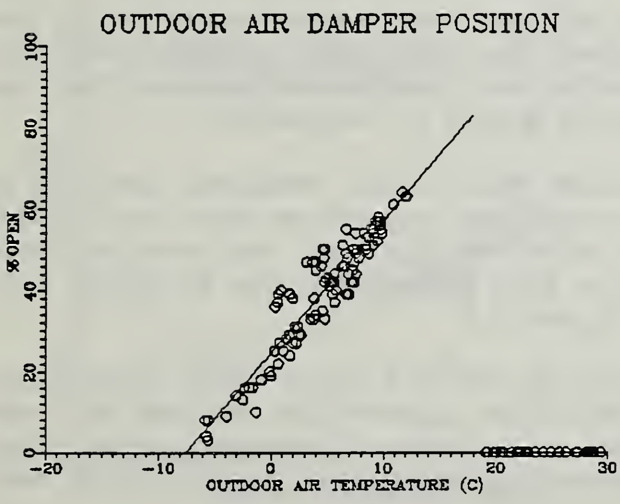
A first look at these data would suggest that the pneumatic control system took better advantage of outdoor air for cooling because for a given outside air temperature, the dampers were open wider under pneumatic control than they were under DDC. It will be shown in section 6.3 that this is not the case because the dampers are opening at low enough temperatures to require steam preheat to maintain supply air temperatures. Note also that AHU-5 and AHU-6 tend to maintain supply air temperatures lower than the reset schedule in the outdoor air temperature range for damper modulation (see figures 5.3.c and 5.3.d).



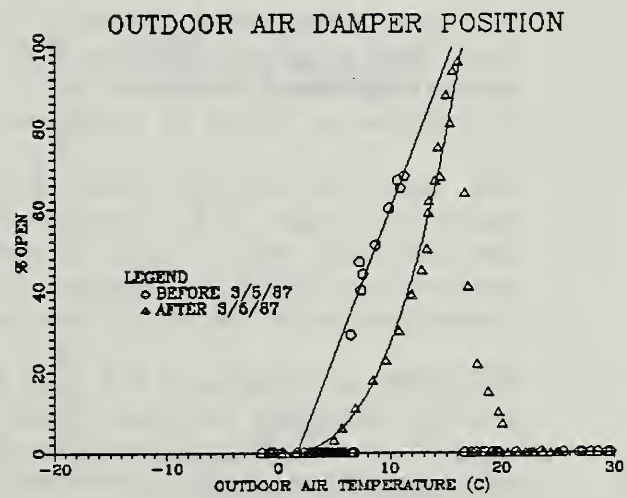
a. AHU-3



b. AHU-4



c. AHU-5



d. AHU-6

Figure 6.6. Outdoor air damper position as a function of outdoor temperature for each AHU under pneumatic control.

Under DDC the lowest temperature at which the dampers were allowed to be open was 5.6°C (42°F). This value was chosen to prevent any possibility of freezing the cooling coil. This particular temperature is supposed to be the temperature at which the freeze protection logic of the pneumatic control system is to become active, opening the steam preheat valve.

Under pneumatic control, all of the units had outdoor air dampers open with outdoor air temperatures below 5.6°C (42°F) at least once. This was particularly a problem with AHU-4 and AHU-5. There were no cases where this problem occurred while the units were being controlled by the DDC system.

6.2 Chilled water valve control

Chilled water valve position as a function of outside air temperature under DDC is shown in figure 6.7. The results for AHU-3, AHU-4, and AHU-5 all agree closely in the temperature range 20°C to 32°C (68 to 90°F). Data are scarce at temperatures above 32°C (90°F) for all units except AHU-5. The trend of the data for AHU-5 is an interesting shape. As outside air temperature climbs from 20°C to 32°C (68 to 90°F) the chilled water valve opens quickly at first, then slows down and the curve flattens out. The valve modulates around 40% open until at temperatures above 32°C (90°F) it opens rapidly to about 80%.

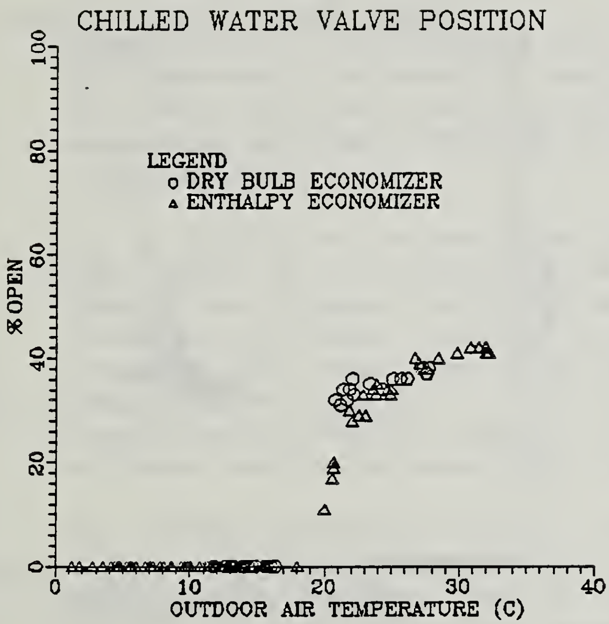
This trend makes sense when the reset schedule is considered. The controller is modulating the valve to maintain a setpoint of 15.6°C (60°F) until the outdoor air temperature reaches about 32°C (90°F). As the outdoor air temperature climbs higher the zone air temperature starts to climb above 25.6°C (78°F) and the reset schedule sharply decreases the supply air temperature. This shows up as the steep climb in chilled water valve position.

The data from AHU-6 indicate that the chilled water valve tended to be open less for a given outside air temperature than the other units. This is a surprising result because AHU-6 is a smaller unit and it was expected that more chilled water would be required to maintain supply air setpoint.

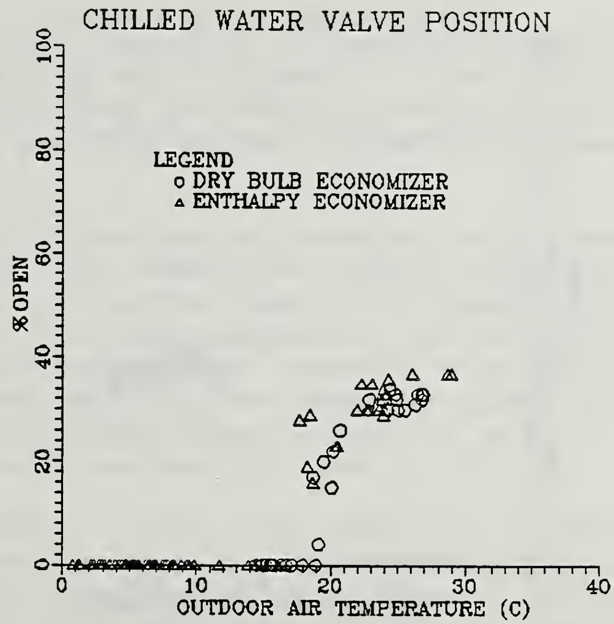
The data for chilled water valve position while under pneumatic control are shown in figure 6.8. The results for AHU-3 are comparable with the DDC data for the same unit. This is consistent with the fact that the zone air reset history as shown in figures 4.1 and 4.3a also agree (the data in figure 6.8.a correspond with the early June data of figure 4.2).

The data in figures 6.8.b and 6.8.c show the chilled water valve opening more quickly than was the case under DDC. This also agrees with the zone air reset data shown in figure 4.3. Both of these units began to sharply reduce supply air temperature before the zone air temperature reached the 25.6°C (78°F) mark.

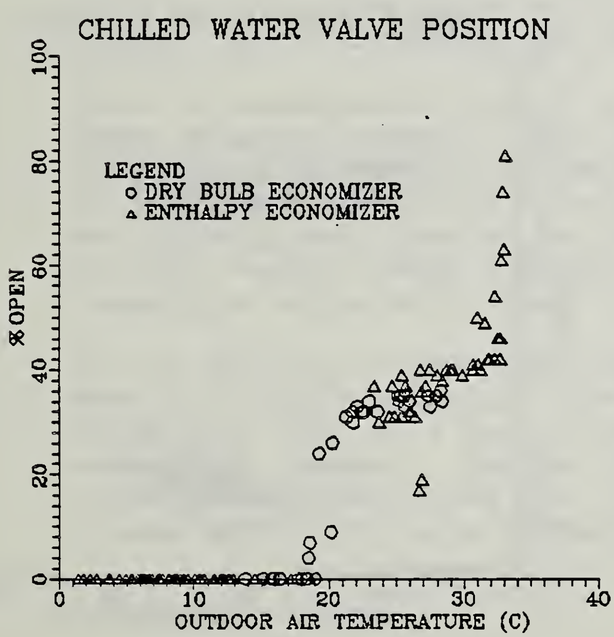
The data for AHU-6 show more scatter than was present under DDC, but the amount of valve opening is in the same general area. This also agrees with the zone air reset history data in figure 4.3. The zone air reset data for AHU-6 had considerable spread but approximately followed the expected reset schedule.



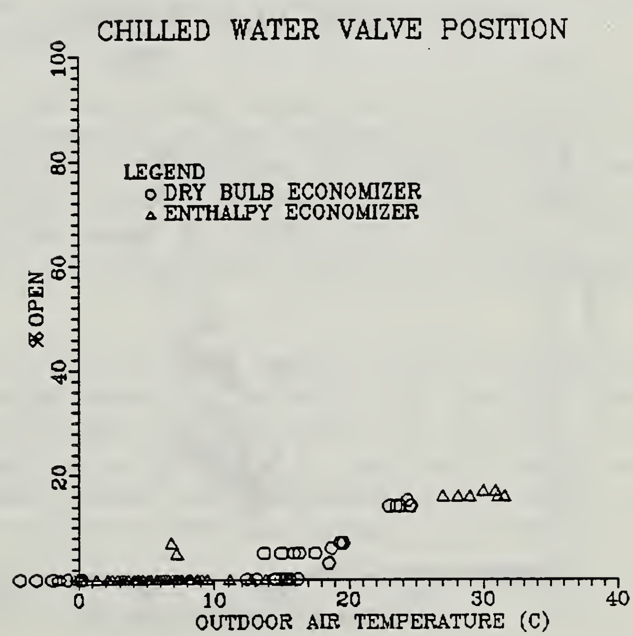
a. AHU-3



b. AHU-4



c. AHU-5



d. AHU-6

Figure 6.7. Chilled water valve position as a function of outdoor temperature for each AHU under DDC

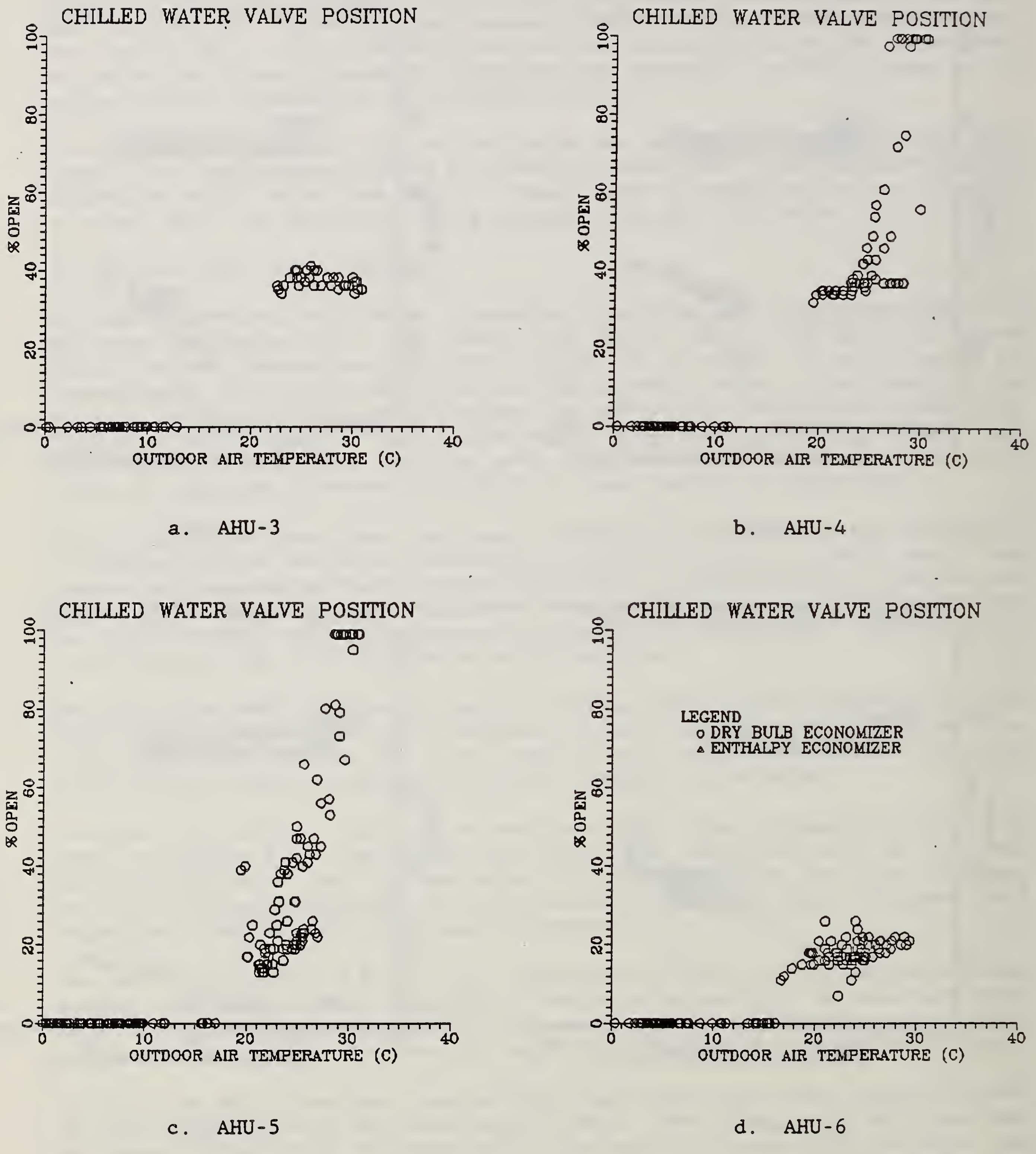


Figure 6.8. Chilled water valve position as a function of outdoor temperature for each AHU under pneumatic control

6.3 Steam preheat valve control

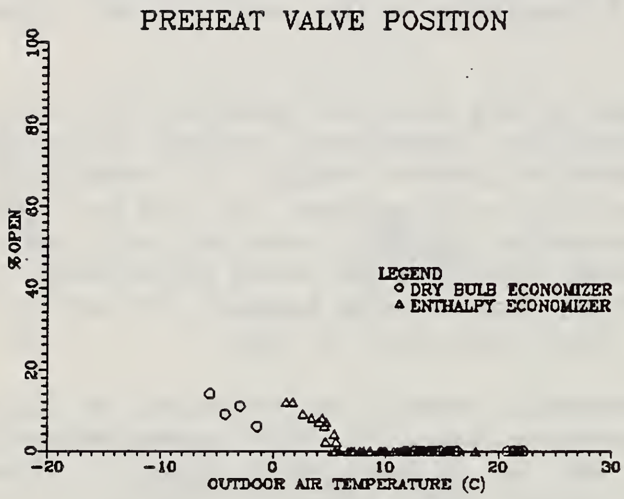
The position of the preheat valve under DDC control as a function of outdoor air temperature is shown for each air handling unit in figure 6.9. The results for AHU-3 and AHU-4 are very close. The slope for AHU-6 is steeper. Some sequencing problems developed with AHU-5 resulting in the scattered data shown in figure 6.9.c.

It is significant to note that for three of the four air handling units under DDC, there is no overlap in the outdoor air temperature regions where the dampers and preheat valve are being used to control supply air temperature. There is no conflict between trying to cool with outdoor air and heat with steam at the same time. The one exception to this occurred with AHU-5. Comparison of figures 6.5.c and 6.9.c shows that in a few cases the outdoor air dampers were about 8% open for outdoor air temperatures between 9°C and 11°C. At these same temperatures this preheat valve was about 8% open.

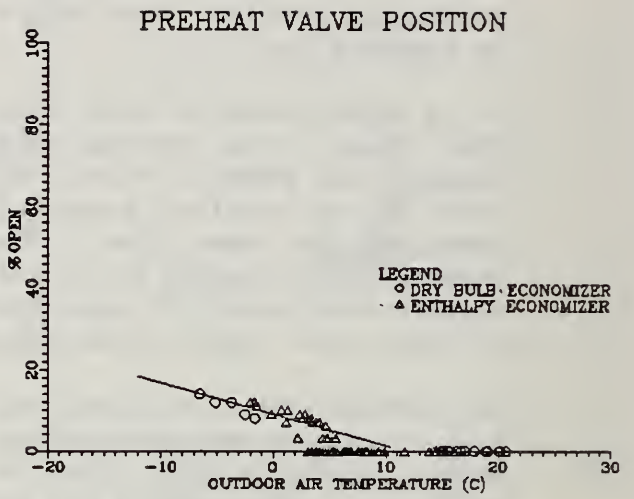
The preheat valve position data for pneumatic control are presented in figure 6.10. Comparing the preheat valve position data for AHU-3 under pneumatic control with the data from DDC shows that the preheat valve opens at higher outdoor air temperatures and opens more quickly under pneumatic control than it does under DDC. This is consistent with the differences in the supply air reset pattern shown in figures 5.2 and 5.3.a. Instead of maintaining a constant supply air setpoint when outdoor air temperature drops below 1.7°C (35°F), the pneumatic controller continues to raise the setpoint. This of course requires more steam and accounts for the difference in preheat valve position curves. AHU-5 data follows the same pattern.

There is considerable scatter in the preheat valve position data for AHU-4 under pneumatic control. This is consistent with the scatter in supply air temperatures and outdoor air damper positions. Comparison of figures 6.6.b and 6.10.b clearly shows that the steam preheat valve and the outdoor air dampers are fighting each other in the temperature range 0 - 10°C (32 - 50°F). This not only wastes energy but also results in the poor control of supply air temperature indicated in figure 5.3.b.

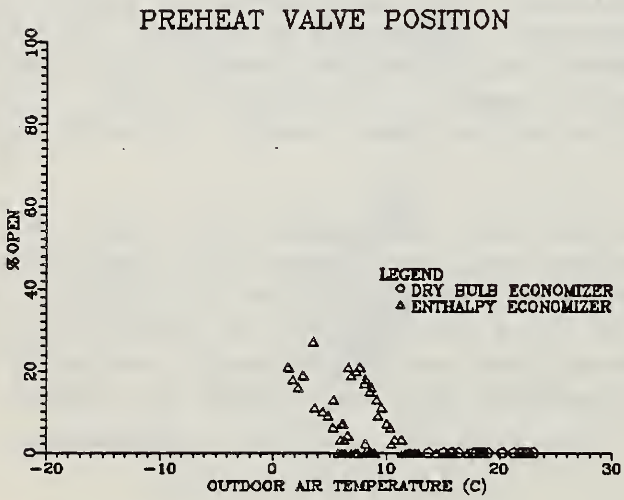
All of the data for AHU-6 in figure 6.10.d are from before the repairs were made to the unit in March. The scattered data for outdoor air temperatures above 7°C fall in a region where the steam preheat valve is fighting the outdoor air dampers. The best fit line is a fit only to non zero data for outdoor temperatures below 7°C. This data looks quite reasonable and falls in a range where there is no indication of conflict with the outdoor air dampers.



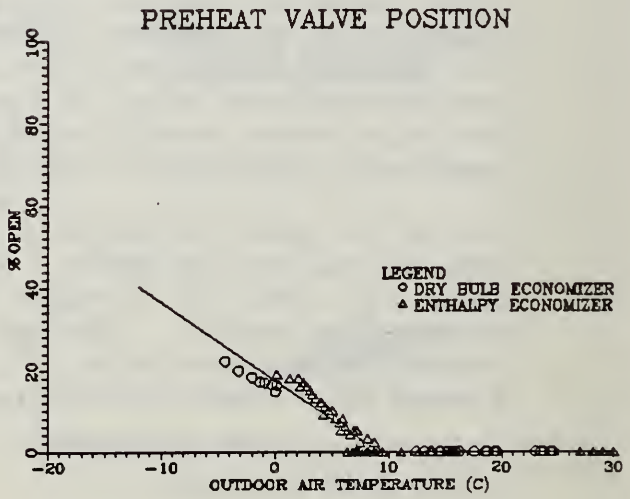
a. AHU-3



b. AHU-4

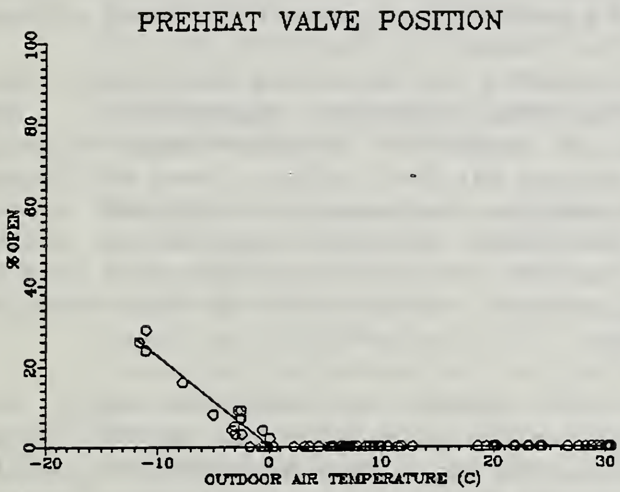


c. AHU-5

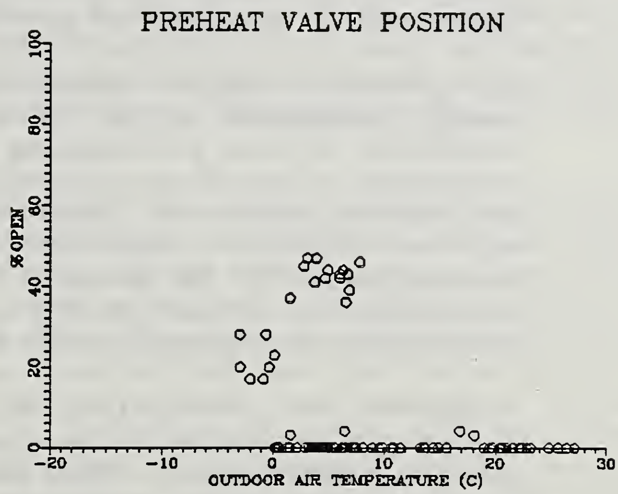


d. AHU-6

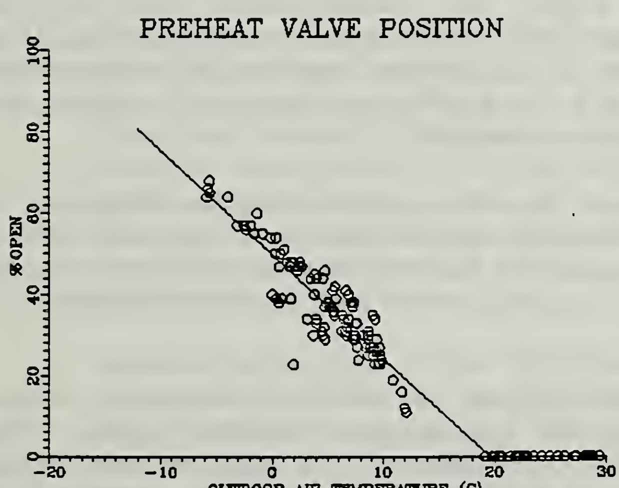
Figure 6.9. Preheat valve position as a function of outdoor temperature for each AHU under DDC



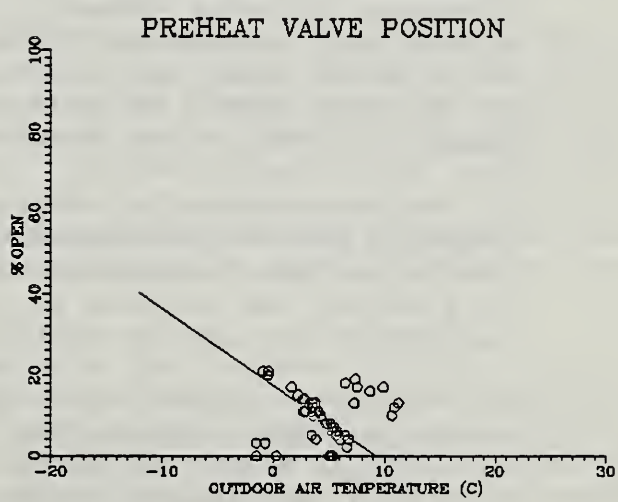
a. AHU-3



b. AHU-4



c. AHU-5



d. AHU-6

Figure 6.10. Preheat value position as a function of outdoor temperature for each AHU under pneumatic control

7. SUMMARY AND CONCLUSIONS

A distributed, microprocessor-based EMCS was developed and installed in an eleven story office building in Gaithersburg, Maryland. Over a period of one year the performance of this system under various control strategies was investigated, along with the performance of a conventional pneumatic control system.

The pneumatic control system in this building is connected to a site wide energy management system which has nighttime shutdown capabilities. The controller on each air handling unit is also capable of implementing a dry bulb economizer cycle to take advantage of outdoor air for cooling, zone air reset, and outdoor air reset. The control strategies implemented in the DDC system were an attempt to match the outdoor air reset schedule used in the winter heating season by the pneumatic system and the zone air reset schedule used by the pneumatic system in the cooling season. Both dry bulb and enthalpy economizers were tested in the DDC system.

Comparison of the ability of the control systems to maintain supply air temperature according to the planned reset schedules showed that the DDC system performed much better. Under DDC all of the air handling units showed virtually the same performance with respect to their ability to maintain the desired reset schedule. Supply air temperature was maintained within ± 0.5°C (1°F) of the scheduled value. This applied to both outdoor air and zone air reset schedules. No difference was detected between using the dry bulb economizer and the enthalpy economizer in this regard.

The pneumatic control system showed different performance for each air handling unit. AHU-3 maintained control as tightly or sometimes better than the DDC controller. AHU-3 also came the closest to following the planned reset schedules differing primarily in the supply air temperatures for very low outdoor air temperatures (below 2°C or 36°F). The other three air handling units varied widely in their ability to maintain the supply air temperature. In the worst case a deviation of ± 3.5°C (± 6.3°F) was observed. Each unit seemed to follow its own version of a reset schedule.

It was not possible to directly compare the energy consumption between the pneumatic and DDC systems because exact weather conditions can not be duplicated. General performance trends for both the pneumatic and DDC systems were investigated by plotting the position of control devices as a function of outdoor air temperature for each air handling unit

This analysis indicated that during the heating season the pneumatic control system used more steam heating than the DDC system under similar loads. This was at least in part due to the fact that for outdoor air temperatures below 0°C (32°F) the pneumatic controllers tried to maintain supply air temperatures higher than the planned setpoint. Another contributing factor was the fact that for outside air temperatures in the range 0 - 10°C (32 - 50°F), AHU-4, AHU-5, and AHU-6 all had instances where the outdoor air dampers were open to provide cooling from outdoor air while the steam preheat valve was open to provide heating.

The results from the cooling season showed that the pneumatic control system provided more mechanical cooling as indicated by the relative positions of the chilled water valve under DDC and pneumatic control. Here the difference is most likely due to the fact that the pneumatic controllers maintained supply air temperatures below the planned setpoint, thus using more chilled water. Again AHU-3 was an exception to this rule. A comparison of the performance of the DDC dry bulb economizer and enthalpy economizer did not show any apparent difference in chilled water valve position as a function of outdoor air temperature, indicating that there was little or no difference in chilled water usage for these strategies.

Analysis of outdoor air damper position during the cooling season for the DDC enthalpy and dry bulb economizer cycles did however, provide some evidence that the enthalpy economizer utilized outdoor air cooling under conditions when the dry bulb economizer could not. This is an expected result in the humid climate found in the Washington D.C. area. The fact that this was not apparent as a reduction in mechanical cooling may be a result of the fact that valve position as a function of outdoor air temperature is a very rough indicator of the amount of mechanical cooling provided. It is also possible that data were collected on only a few days when the difference in performance between the two economizer cycles would be apparent, providing little evidence of the true potential. Computer simulation may be a more reliable indicator of the benefits of using an enthalpy economizer.

AHU-3 serves the building zone which contains offices used by the top administration officials, including the director of NBS. As a consequence this unit receives higher priority maintenance and service from plant personnel. The performance of AHU-3 suggests that if sufficient effort were put into tuning and maintaining the other controllers the pneumatic system could perform as well as the DDC system.

The information obtained in this study suggests that one principle advantage of the DDC system is that it is easier to set up the reset schedules and to see that they are maintained. One problem with the pneumatic control system is that the tuning of the system drifted with time and was sensitive to inadvertent changes made during routine maintenance. The DDC system did not suffer from these shortcomings. This does not mean that it is not necessary to retune for changes in operating conditions, it only means that the tuning parameters once set will not drift to different values or be effected by any hardware maintenance performed on the controller.

Another advantage of the DDC control system is the increased ability to obtain information about the performance of the controllers. This permits problems to be discovered earlier and also provides much useful information for diagnosing their cause. There were several times during the course of this experimental work when our data collection process pointed out problems with the pneumatic control system that were unknown to plant personnel. There were also occasions where a problem was suspected and they came to us to collect data on a particular unit to provide information which could be used to isolate probable causes or check that repairs made did in fact solve the problem.

In summary, the DDC system performed better and consumed less energy than the pneumatic control system. These differences could be reduced considerably or eliminated by careful maintenance of the pneumatic control system. DDC appears to provide greater long term stability of performance and better information about the performance of the system to assist in identifying problems early and diagnosing their cause. The DDC system also provides greater flexibility to change control strategies.

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11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

A distributed, microprocessor based direct digital control (DDC) energy management and control system was developed and installed in an eleven story office building in Gaithersburg, Maryland. Over a period of one year the performance of this system under various control strategies was investigated along with the performance of a conventional pneumatic control system. The quality of control and performance trends for the two control systems were compared.

Overall, the DDC system was found to maintain better control of the supply air temperature and to follow reset schedules more closely than the pneumatic system. One air handling unit performed as well under pneumatic control as it did under DDC in maintaining a supply air setpoint, but it did not precisely follow the reset schedule. Each air handling unit was found to have different performance characteristics while under pneumatic control, but all units behaved essentially the same under DDC.

The results indicate that a pneumatic system can perform as well as a DDC system but more effort is required to maintain system performance. The DDC system was found to be more flexible and it is easier to insure that multiple air handling units follow the same control strategy with the DDC system. Instrumentation associated with the DDC system proved to be very useful in troubleshooting problems with the pneumatic system.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

control; computer; DDC; maintenance; monitoring; office building; pneumatic; trends

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