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Direct Digital Temperature, Humidity, and Condensate Control for a Dedicated Outdoor Air-Ceiling Radiant Cooling Panel System

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ABSTRACT

The central thrust of this paper is to provide automation and control design guidance for engineers considering dedicated outdoor air systems (DOAS) operating in parallel with ceiling radiant cooling panel systems (CRCP) in nonresidential commercial and institutional applications. The paper identifies the issues that must be addressed in the design of the control system and illustrates that the controls need not be complicated. The simplicity of the controls is demonstrated via a case study of an existing DOAS-CRCP facility. Finally, the control challenges presented by low-occupancy spaces such as offices will be contrasted with those of high-density spaces such as schools and places of assembly.

INTRODUCTION

DOAS-CRCP systems are applicable in low-density spaces typical of offices and for high-density spaces typical of schools and places of assembly. However, in the case of high-density spaces, reheat from recovered energy at the DOAS is necessary to avoid wasteful terminal reheat at off-design conditions. To minimize first cost and terminal reheat, high-density spaces call for a control approach uniquely different from that for low-density spaces where overcooling with the DOAS is extremely rare and terminal reheat is used sparingly.

The DOAS-CRCP system design philosophy is simple and straightforward. The DOAS is used to deliver the required ventilation air to the breathing zone of each occupant without first mixing with recirculated air in a central AHU, thereby decoupling the ventilation function from the main thermal conditioning function. By adequately dehumidifying the ventilation air, it can also serve to remove all of the space latent loads and, of course, the entire OA latent load. Depending upon the DOAS design supply air temperature (can be equal to the required DPT for low-density spaces or as high as room neutral temperature for high-density spaces), the balance of the space sensible load is borne by the CRCP. The supply air temperature has a profound impact on both the first cost of the CRCP and the operating cost by virtue of the extent to which terminal reheat must be used.

The DOAS-CRCP system hardware and control design must consider and address the following issues:

- Comfort cooling
- Comfort heating
- Dehumidification during periods of elevated OA dew-point temperatures
- Humidification during periods of low OA dew-point temperatures
- Indoor air quality (IAQ)
- Air diffusion performance index (ADPI) (Mumma 2004)
- Condensate control, both active and passive (Mumma 2002)
- Spaces with movable sash, which offer additional condensate control challenges (Mumma 2003)
- Internal generation and use patterns
- Selection of the variables to measure and the accuracy of instrumentation
- Transient response of instruments and system to pattern of use and weather changes
- Keep it simple to make the system's design, installation, maintenance, and operation easy
- The control hardware and software
- The need and/or desire for Web-based accessibility
- The need and desire for BACnet compatibility

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- Design documentation, schematics, points list, sequence of operation, and compliance with ASHRAE guideline 13-2000 (ASHRAE 2000)
- Commissioning
- Continuous monitoring and assessment (Mumma 2003)

The above issues will be selectively addressed in this paper.

BACNET-COMPATIBLE WEB-BASED CONTROLS FOR A SINGLE-ZONE DOAS-CRCP SYSTEM

Such an operating system is illustrated in the Figure 1 schematic. Briefly, the OA is preconditioned as necessary with an enthalpy wheel, using the room return air, then cooled and dehumidified further with the cooling coil. The supply air temperature leaving the cooling coil is controlled with the three-way control valve V1. Finally the cold and dry 100% outdoor ventilation supply air is delivered to the space via high induction overhead diffusers.

This system does not have any auxiliary preheat, terminal, or space heating. All heat comes from internal generation, and the OA is tempered with exhaust air heat recovered by the enthalpy wheel. During cold OA conditions when the OA must be tempered, the enthalpy wheel's capacity to recover heat is achieved by modulating the enthalpy wheel on and off as necessary (limited to no more than four on-off cycles per hour) based upon the space conditions.

The supply air temperature during cooling is modulated to satisfy the space conditions down to a DPT of 52°F (11.1°C), but no lower. With the supply air DPT at 52°F (11.1°C), the space DPT is maintained low enough that the CRCP will never form condensation when radiant cooling is used to meet the balance of the space sensible load. Two 5-ton (17.6 kW) air-cooled chillers working in parallel provide chilled water. The chilled water first satisfies the needs of the cooling coil, then the CRCP. The three-way control valve V2 is modulated as necessary to meet the space DBT setpoint, limited by the space DPT. The room return air temperature and relative humidity are used to compute the space DPT. The CRCP inlet water temperature is never permitted to drop below the space DPT. A passive fail-safe condensate sensor is used as a condensation prevention backup. The fail-safe condensate sensor uses a normally open switch, which opens when the first drop of condensate from the supply piping falls on it. The sensor's switch is hard wired into the three-way NC spring return control valve V2's power supply.

The DOAS is constant volume, with no provision for space pressurization control. However, the space pressure is constantly monitored, and the relief fan performance periodically adjusted, to ensure long-term pressurization. It is desired to keep the space slightly pressurized (approximately 0.001 in. w.g. [0.25 Pa]) to avoid the introduction of latent loads by way of infiltration. This is easily achieved, even in the very leaky early 1900s construction building where all six enclosure planes are subjected to exterior vapor and atmo-

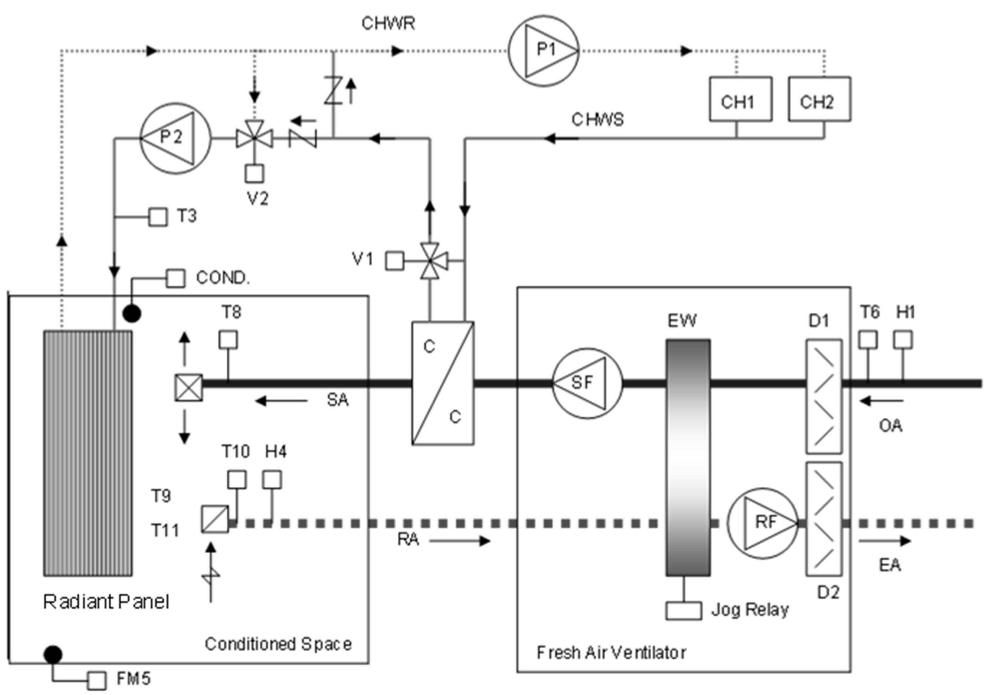

Figure 1 *A single-zone DOAS-CRCP system.*

spheric pressure. Introduction of infiltration at the envelope not only permits the undesirable transport of moisture but also makes controlling the thermal climate near the exterior walls difficult during both summer and winter. As far as energy consumption is concerned, air leakage into the space is much more costly (almost seven times) than bringing that air into the building by way of a quality total energy recovery (recovery effectiveness of 85%) DOAS. It is also very desirable to return as much of the supplied air to the enthalpy wheel for total energy recovery, so overpressurization must be avoided. ASHRAE Standard 90.1-2001 addresses the issue of building envelope tightness, and it is strongly recommended that in new construction the building envelope conform or exceed Section 5.2.3.

> **5.2.3 Envelope Air Leakage** (ASHRAE 2001)
>
> **5.2.3.1 Building Envelope Sealing.** The following areas of the *building envelope* SHALL be sealed, caulked, gasketed, or weather-stripped to minimize air leakage:
>
> (a) Joints around *fenestration* and door frames
>
> (b) Junctions between walls and foundations, between *walls* at building corners, between *walls* and structural *floors* or *roofs*, and between *walls* and *roof* or *wall* panels
>
> (c) Openings at penetrations of utility services through *roofs, walls,* and *floors*
>
> (d) Site-built *fenestration* and *doors*
>
> (e) Building assemblies used as ducts or plenums
>
> (f) Joints, seams, and penetrations of vapor retarders
>
> (g) All other openings in the *building envelope*. Outside air intakes, exhaust outlets, relief outlets, stair shaft, elevator shaft smoke relief openings, and other similar elements shall also be very low leakage.
>
> **5.2.3.2 Fenestration and Doors.** Air leakage for *fenestration* and *doors* shall be determined in accordance with NFRC 400. Air leakage shall be determined by a laboratory accredited by a nationally recognized accreditation organization, such as the National Fenestration Rating Council, and shall be *labeled* and certified by the manufacturer. Air leakage shall not exceed 1.0 cfm/ft^2 for glazed swinging entrance doors and for revolving doors and 0.4 cfm/ft^2 for all other products.

This DOAS-CRCP cooling-only system was built and exists to do the following:

Controls related:

- Overcome/answer the negative perception of ceiling radiant cooling held by much of the industry.
- Demonstrate that the space sensible and latent loads can be decoupled using DOAS.
- Prove that condensation formation and subsequent damage need never occur, even in the leaky single-glazed non-ideal early 1900 building space used for the project.
- Demonstrate the simplicity of the Web-based BACnet-compatible DDC used for the integrated systems.
- Provide an educational resource for university students, faculty, staff, owners, investors, and design professionals worldwide via first-hand site visits or via virtual tours and real-time data displays (available since Web-based) at www.doas-radiant.psu.edu.

Not controls related:

- Provide first-hand thermal comfort experience working in a radiant cooling field.
- Demonstrate that the sensible load of the space can be met with radiant panels when applied in parallel with a DOAS, using only about 20% of the ceiling area.
- Provide a basis for comparison of the DOAS-CRCP indoor environment with that of conventional all-air VAV systems.

SPECIFIC CONTROL FUNCTIONS

A control logic schematic diagram for the single-zone DOAS-CRCP system is presented in Figure 2. The logic consists of seven parts. Each part will be briefly discussed below.

1. *Setpoints*

The setpoints consist of the 100% OA ventilation supply air temperature and the summer and winter operative temperature setpoints. Operative temperature, the arithmetic average of the space DBT and the space mean radiant temperature (MRT), is used as the space-controlled variable. The summer setpoint is used to control the cooling performance of the cooling coil and radiant panels. The winter setpoint is used to modulate the enthalpy wheel when the OA must be tempered in the winter.

2. *System on/off control*

This section has three functions. First, since there is no auxiliary heating in the space, the DOAS system is shut down when the space MRT drops below the setpoint minus the throttling range set in the "If >" microblock. Second, there is provision to manually set the occupancy status on or off to accommodate scheduled vacancy, such as vacations. Third, and finally, there is provision to shut the system down if, during the winter, frost could form in the enthalpy wheel (a condition that can occur when the line on the psychrometric chart connecting the two EW entering air state points intersects the saturation curve). Mumma (2001) and Freund et al. (2003) addressed the effective ways to avoid frost or freeze problem on the EW surface during the winter operation. This precaution is required since there is no preheat available in the system. However, it has yet to occur since the space has no active humidification, and the room RH is low in the winter. The code written inside the freeze control microblock follows on page 552:

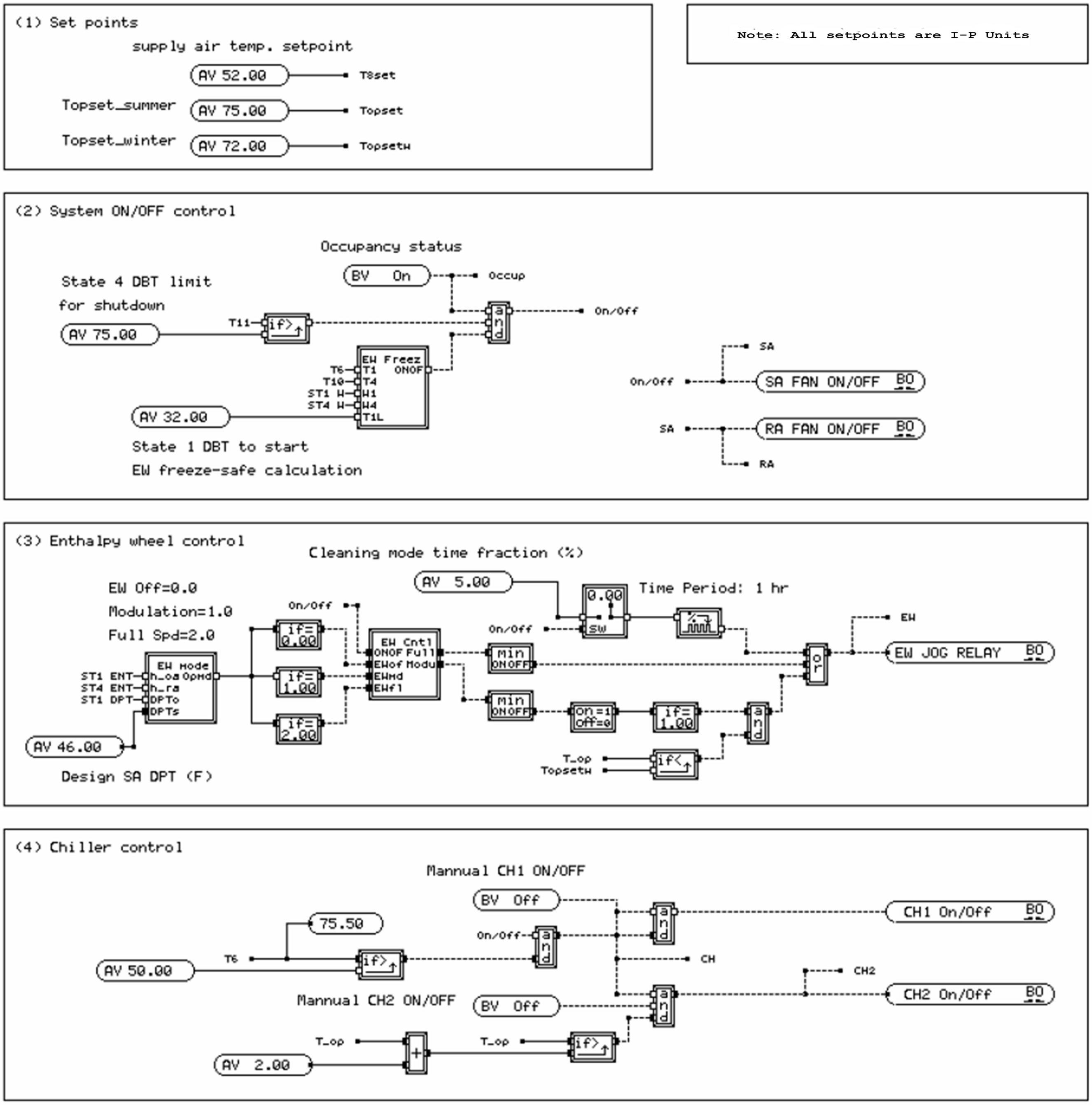

Figure 2 *Single-zone DOAS-CRCP system control logic diagram.*

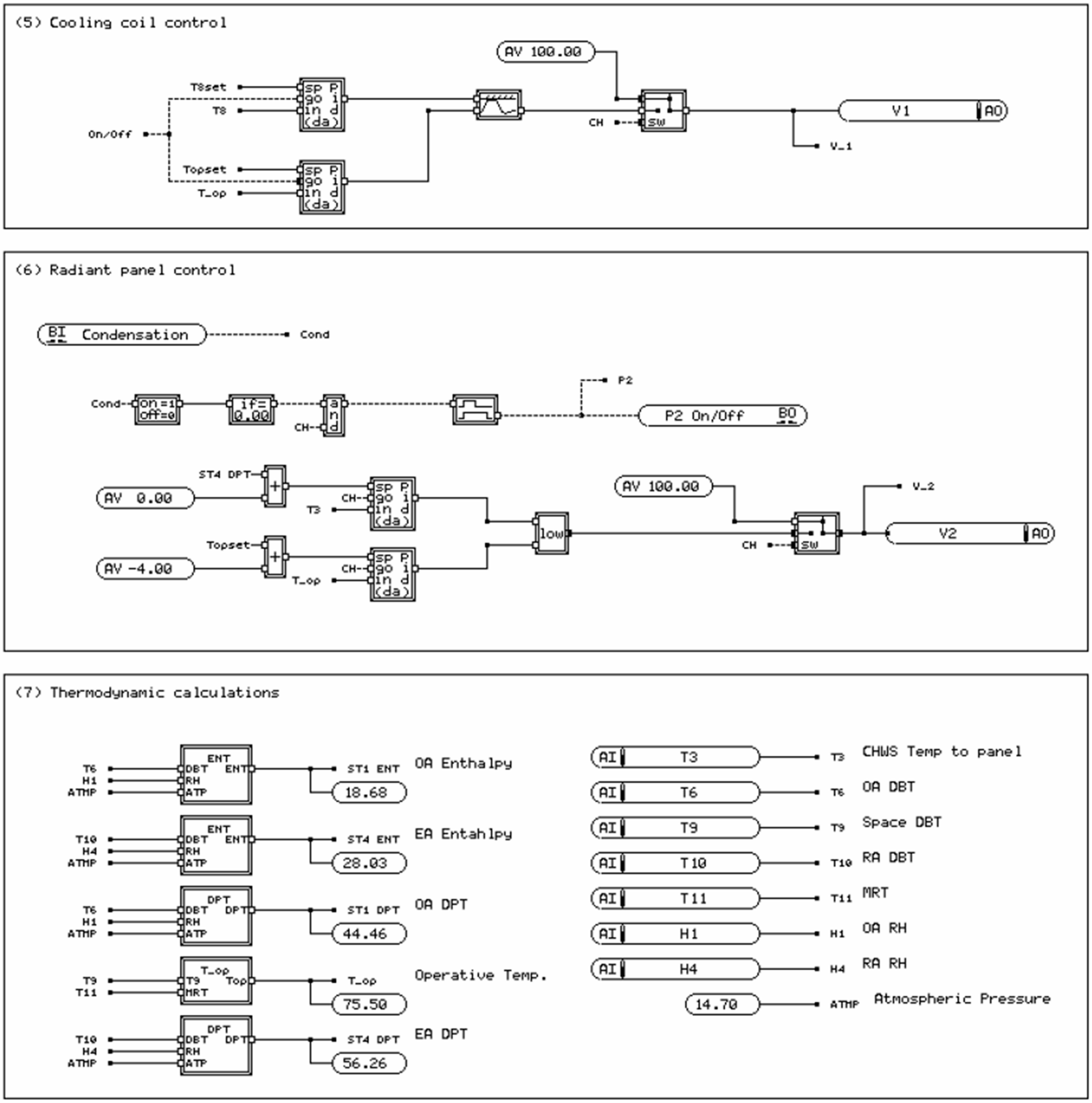

Figure 2 *(continued)*

```
TITLE EW Freeze        // Defining the name of the freeze control microblock

AINPUT T1              // OA DBT [F] : Analog input
AINPUT T4              // EA DBT [F] : Analog input
AINPUT W1              // OA humidity ratio [gr/lbm] : Analog input
AINPUT W4              // EA humidity ratio [gr/lbm] : Analog input
AINPUT T1L             // OA DBT lower limit to activate EW freeze control [F]
                         : Analog input
DOUTPUT ONOFF          // Output : Digital output

Var A,B,D,E,F,G, alfa  // Defining variables used in this code

If (T1<=T1L) then
Begin
A=(W4-W1)/(T4-T1)      // Slop of the line connecting the OA and EA state points
                          on the psychrometric chart

B=W1-A*T1              // Y-intercept of the line function passing through both
                          OA and EA state points on the psychrometric chart

E=0.0122               // E, F, and G are the coefficients of the quadratic equation
F=0.2712-A                derived by equating the saturation curve and the line
G=5.1476-B                (Mumma 2001).

D=POW(F,2)-4*E*G       // Discrimination (D) of the quadratic equation

If (D < 0.0) then      // If D is less than 0, the line does not meet or intersect
  ONOFF=on                the saturation curve (i.e. no frost problem on EW).

If (D>=0.0) then       // If D is equal to or higher than 0, the line is the tangent or
                          the intersect line to the saturation curve.
    Begin
    alfa=(-F+SQRT(D))/(2*E)     // Positive solution of the quadratic equation

    If (alfa>=T1)then           // If the positive solution is less than OA DBT,
      ONOFF=off                    the frost problem might occur on EW surface.
    Else                           (i.e. EW should be off)
      ONOFF=on
  End
End
else
ONOFF=on

EXITPROG       // End of the freeze control microblock
```

3. *Enthalpy wheel control*

The enthalpy wheel operates in one of four modes:

- Full on when it reduces the enthalpy of the OA entering the CC, as when it is hot and humid
- Full off when it is warm and humid, but operation would increase the enthalpy of the OA entering the CC
- Modulating in the winter to temper the OA entering the space to avoid overcooling
- A cleaning cycle, necessary when the enthalpy wheel is off to prevent it from becoming an unwanted filter (in this mode, the wheel rotates for a few minutes each hour, or about 40 revolutions/on cycle)

The first three modes are achieved by use of the two microblocks, EW mode and EW control. The code for each of these microblocks follows:

- EW mode microblock code:

```
TITLE EW mode       // Defining the name of the EW operation mode microblock

AINPUT h_oa         // OA enthalpy [Btu/lbm] : Analog input
AINPUT h_ra         // EA enthalpy [Btu/lbm] : Analog input
AINPUT DPTo         // OA Dewpoint temperature [F] : Analog input
AINPUT DPTs         // SA DPT set point [F] : Analog input
AOUTPUT Opmd        // Enthalpy wheel operation mode : Analog output
                       (0=Off;  2= Full speed; 1= Modulation)

If (h_oa>h_ra) and (DPTo>DPTs) then     // Defining the hot and humid region
Opmd=2.0                                   on the psychrometric chart

If (h_oa<=h_ra) and (DPTo>DPTs) then    // Defining the warm and humid region
  Opmd=0.0                                 on the psychrometric chart

If (h_oa<=h_ra) and (DPTo<=DPTs) then   // Defining the region for the EW
  Opmd=1.0                                 modulation on the psychrometric
                                           chart
EXITPROG      // End of the EW operation mode microblock
```

- EW control microblock code:

```
TITLE EW control     // Defining the name of the EW control microblock
DINPUT ONOF       //  Input from the occupancy mode : Digital input
DINPUT EWof       // EW off mode : Digital input
DINPUT EWmd       // EW modulation mode : Digital input
DINPUT EWfl       // EW full speed mode : Digital input
DOUTPUT Full      // Output for activating EW full speed operation
                     : Digital output
DOUTPUT Modu      // Output for activating EW modulation operation
                     : Digital output

IF (ONOF=on) and (EWof=on) and (EWmd=off) and (EWfl=off) THEN
BEGIN                                   // Input signals to define EW off mode
  Modu=off
  Full=off
END

IF (ONOF=on) and (EWof=off) and (EWmd=on) and (EWfl=off) THEN
BEGIN                           // Input signals to define EW modulation mode
  Modu=on
  Full=off
END

IF (ONOF=on) and (EWof=off) and (EWmd=off) and (EWfl=on) THEN
BEGIN                           // Input signals to define EW full speed mode
  Modu=off
  Full=on
END

IF (ONOF=off) THEN              // Under the unoccupied mode
BEGIN
  Modu=off
  Full=off
END

EXITPROG        // End of the EW control microblock
```

4. ***Chiller control***

   This is a quite simple control, which sends a signal to the air-cooled chiller and chilled water pump P1 to operate whenever the OA temperature rises above a setpoint. Since there are two 5-ton (17.6 kW) units, the second unit is only enabled when the space operative temperature exceeds setpoint plus an offset. The chiller is equipped with hot gas bypass, so it is capable of large cooling load turn-down ratios. It is also equipped with condensed refrigerant heaters that permits low-temperature operation should that be desired.

5. ***Cooling coil control***

   This control employs two direct acting PID loops, one producing an output based on the supply air temperature and the other based upon the space operative temperature. The outputs from these two PID loops are compared, with the supply air temperature PID output establishing the upper limit of the signal sent to the cooling coil control valve V1. This control limits the supply air dry-bulb temperature to no less than setpoint, even if the space operative temperature is too high. Provision is also made to open the control valve when the chiller is off.

6. ***Radiant panel control***

   This section handles the operation of both the panel pump P2 and the panel three-way temperature control valve V2.

   Whenever the chiller is on and the passive fail-safe condensate sensor is dry (normally open switch closed), the panel pump is energized. The pump remains on for 15 minutes after condensate is sensed by the passive fail-safe condensate sensor, which severs the power supply to the spring return control valve V2, closing it. With the valve closed, the panel loop is totally isolated from a source of cooling and continues to pick up room heat, elevating all surface temperatures well above the space DPT.

   The normal operation for the constant volume, variable temperature CRCP, controlled by the three-way valve V2, is based upon two direct acting PID control loops. One PID loop is producing an output based upon the space DPT plus an offset. The other PID loop is producing an output based upon the space operative temperature plus an offset. The lowest output of these two PID loops is selected to control the three-way valve V2. This logic allows the radiant panels to meet the sensible load not met by the DOAS so long as the water temperature does not drop below the space DPT plus an offset.

7. ***Thermodynamic calculations***

   Temperature and relative humidity measurements are used to compute either enthalpy for the control of the enthalpy wheel or dew-point temperatures to avoid condensation at the radiant panels.

EXTENSION OF THE SINGLE-ZONE DOAS-CRCP SYSTEM CONTROL TO A LARGE MULTIZONE FACILITY

Low Occupancy Density Spaces

Consider expansion to a predominately low occupancy density building typical of offices. In such cases, considerable first cost savings can be realized by using a variable volume flow/constant temperature cool water supply control for the CRCPs (Conroy and Mumma 2001). Eliminated is the need for a circulating pump serving each thermostatically controlled zone. In addition, relative humidity measurements would not be required in each space to ensure condensation avoidance, provided the DOAS supply air DPT is maintained at the design DPT of each space. Finally, if the spaces have movable sash, the condensation prevention control would require window position sensors (similar to security systems). When a window is sensed open for a zone, and the OA DPT is equal to or above the zone design DPT, the zone CRCP control valve must be closed (Mumma 2003). This interlock causes the CRCP to terminate sensible cooling when OA dehumidification is required, a consequence of the choice occupants of the zone are free to make.

High Occupancy Density Spaces

In high-density spaces, such as schools or places of assembly, where the OA requirement may be well over 0.5 cfm/ft^2 (0.098 L/s/m^2), served with a DOAS delivering air with a DPT of 48-50°F (8.9-10.0°C) and saturated, the OA is capable of meeting in excess of 75% of the design space sensible cooling load. In such a situation, a small area (about 15% of the ceiling, meaning low first cost) of CRCPs is needed to meet the balance of the space sensible load. However, at off-design sensible loads, but full occupancy and latent load, the low SAT leads to the use of terminal reheat, which can be significant under some conditions. If the sensible load in all spaces is at off-design but fully occupied, the sensible wheel (SW) illustrated in Figure 3 is used to elevate the SAT, based on the zone with a sensible load nearest its design, thus reducing wasteful reheat energy use.

In addition, when the latent load in all spaces drops below design, the OA temperature leaving the CC can be elevated and still maintain the design space % RH, governed by the space with a latent load nearest its design. As the CC leaving air temperature is increased, the supply air capacity to do sensible cooling may be diminished provided the SW is off.

Consequently, the CC leaving temperature upper limit is the lower of either that required by the space with a latent load nearest its design or the space with a sensible load nearest its design.

It may be observed the dehumidification at the CC is not required when the OA humidity ratio is less than that required to meet the space latent loads (about 50 grains/lb [7.15 g/kg] at design but could go up to the upper 60 grains/lb [8.58 g/kg] at off-design occupancy). For approximately 60% of the oper-

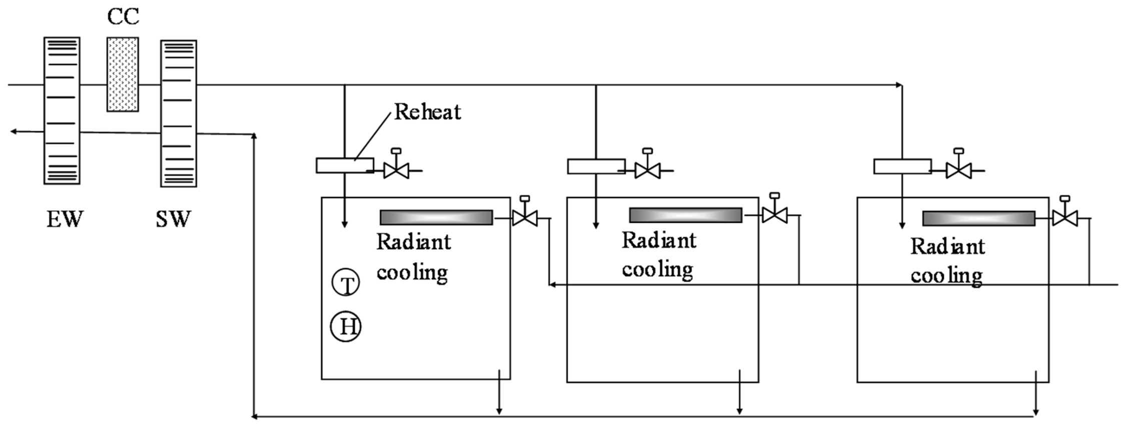

Figure 3 *A multi-zone DOAS-CRCP system.*

ating hours at 40N latitude locations, the OA humidity ratio is less than 50 grains/lb (7.15 g/kg), in which case cooling (combination of CRCP and the CC) is only needed to meet the space sensible loads. A majority of these hours, the cooling may be available with waterside-free cooling, a subject beyond this paper.

The sequence of operation for the system illustrated in Figure 3 follows:

1. EW control as discussed for the single-zone system
2. CC
   (a) Modulate the CC control valve to maintain the room with the highest relative humidity at 55%.
   (b) Or modulate the CC control valve to ensure none of the space DBTs exceed the setpoint (75°F [23.9°C]) when the SW is off. In other words, this mode is not operative whenever the SW is being modulated.
3. Space temperature control:

   Use the room DBT to operate the radiant panel (RP) control valve and reheat (RH) coil control valve in sequence to meet setpoint.
4. Modulate the SW (hence, the SAT) by way of the VFD slowly until one of the panel control valves is wide open. The “MAX” microblock shown in the Figure 4 sensible wheel VFD control logic selects the CRCP with the most open control valve. The same logic is used to determine the maximum space relative humidity or room air temperature of the spaces.

```
TITLE MAX        // Defining the name of the maximum selection microblock

AINPUT IN1,IN2,IN3     // Actual panel control valve positions [%] : Analog input
AOUTPUT OMAX           // The most widely opened valve position : Analog output

VAR IN12

IN12=MAX(IN1,IN2)          // Select more open valve position between the first two,
OMAX=MAX(IN12,IN3)            and then, compare it with the last one to determine the
                              most widely open panel valve position.

EXITPROG       // End of the maximum selection microblock
```

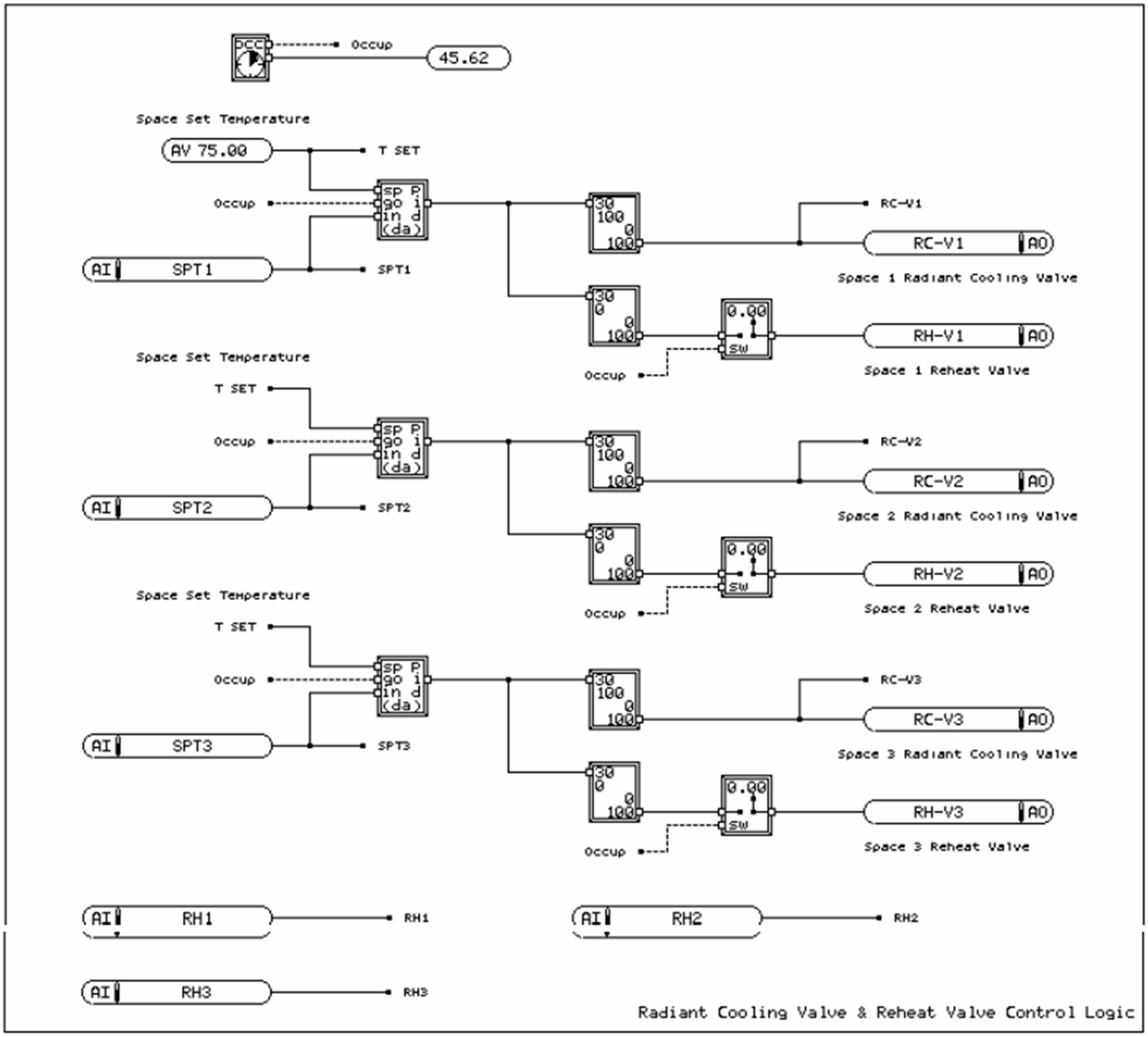

Figure 4 *Multi-zone DOAS-CRCP system control logic diagram.*

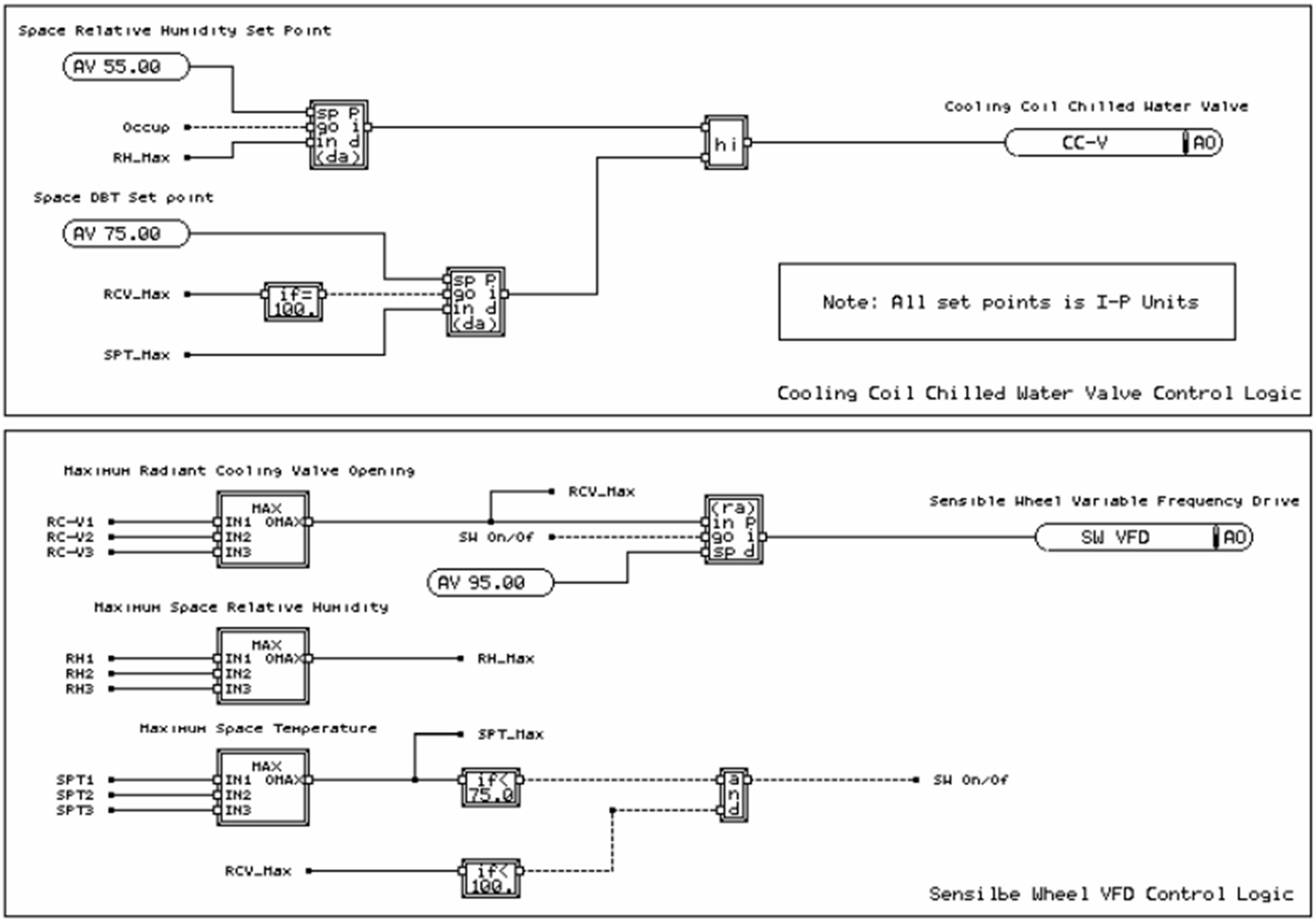

Figure 4 (continued)

This is a control that might be called a critical zone DBT and DPT reset scheme. It holds great potential for allowing the DOAS system in high occupancy density applications to supply, at design, low temperature air. At this point in time, the industry holds to the theory that in such applications the DOAS SAT must be neutral to avoid any terminal reheat, elevating the first cost of the parallel system (Trane 2003). The negative impact of this theory disqualifies most DOAS-CRCP applications based upon high first cost. With the control just discussed, first cost is controlled, and most terminal reheat is eliminated. A logic diagram for the control just discussed is presented in Figure 4.

CONCLUSIONS

An actual single-zone DOAS-CRCP control system and its logic have been presented. In addition, the issues associated with condensation control have been addressed. Finally the single-zone control logic has been extended to include large multizone buildings. Emphasis has been placed upon the significant design and control differences between low-occupancy and high-occupancy multi-zone facilities. Proper design and use of controls in high occupancy facilities permit low supply air temperatures, thus minimizing both first cost, compared to a neutral supply air temperature system, and the reheat energy used by conventionally controlled low supply air temperature systems.

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