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Binary Enthalpy Wheel Humidification Control in Dedicated Outdoor Air Systems

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ABSTRACT

The central focus of this paper is the operation and control of a total energy recovery device, or enthalpy wheel (EW), during the heating and intermediate seasons when the outside dew-point temperature (DPT) is below the desired supply air DPT. For the most part, control of the EW during hot and humid conditions is being executed properly. On the other hand, experience has shown that the heating season operation is an important and frequently ignored aspect of the energy recovery operation. Consequently, the benefits that are available with proper EW control and operation during the "noncooling" season have been overlooked. So there are no simple and universally accepted EW humidification performance control sequences currently in existence for low DPT, outdoor air conditions (i.e., dry outdoor air conditions). After providing an overview of EW fundamentals, a simple binary EW control is introduced and evaluated in a university campus facility for humidification under dry outdoor air conditions. It was found that use of an EW can reduce the energy consumption for humidification but does not eliminate the potential need for an auxiliary humidifier. Finally, binary control of the EW for supply air temperature control is also addressed.

INTRODUCTION

Dedicated outdoor air systems (DOAS) (Mumma 2001), when used, are generally required to employ total energy recovery, or an enthalpy wheel (EW), by *ANSI/ASHRAE/IESNA Standard 90.1-2004, Energy Standard for Buildings Except Low-Rise Residential Buildings* (ASHRAE 2004b). The enthalpy wheel transfers excess moisture and sensible heat contained in the outdoor airstream to the relatively dry and cool exhaust airstream during the summer (i.e., precooling and dehumidification). Similarly, the entering outdoor air (OA) is heated and humidified during the winter by recovering sensible heat and moisture from the relatively warm and humid exhaust air. This free heating and humidification is the advantage that should not be overlooked in the EW application. However, observed systems with EWs have often not utilized the EW to maximum benefit, particularly during periods of low ambient dew-point temperatures (DPTs). When the OA is dry, humidification of the supply air (SA) is required to maintain the space relative humidity (RH)—a key health and thermal comfort factor in buildings. *ANSI/ASHRAE Standard 55-2004, Thermal Environmental Conditions for Human Occupancy* (ASHRAE 2004a), recommends that the RH be maintained in the 30%–60% range.

Most technical literature on EWs is focused on their operation as an aid during cooling to reduce both the design load and energy use. Consequently, no simple and universally accepted EW humidification performance control sequence currently exists for low DPT OA conditions, hereafter referred to as *dry conditions*. The objective of this paper is first to justify the use of the EW for humidification under dry conditions, then introduce a simple binary EW control. The EW binary control was evaluated in a university campus facility (Mumma and Jeong 2005).

Enthalpy Wheel Overview

In the mid 1970s, two EW products were introduced to the HVAC industry. One was the oxidized aluminum wheel made of corrugated aluminum foil. The corrugated aluminum foil assembly is dipped into a bromide solution to cause the aluminum to oxidize and form a layer of alumina, a known desiccant. The second EW product introduced then used silica gel

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as the desiccant. The silica gel desiccant was bonded to an aluminum foil assembly, or matrix.

In the 1980s, molecular sieves, also known as synthetic zeolite desiccants, that could be designed at the molecular level emerged. Fabrication of silica and other compounds were derived from the semiconductor industry. Manufacturing processing advances that allowed a breathable layer of desiccant to be bonded to the corrugated aluminum foil surface made molecular sieve EWs possible.

The type of desiccant used determines the moisture transfer performance of the EW, while the sensible heat transfer of the wheel depends on the thermal properties of the matrix-desiccant material combinations. Currently the vast majority of EWs employ either silica gel or molecular sieve desiccants.

Silica Gel. Silica gel can absorb up to 40% of its own weight in water and withstand relatively high acidic environments. Because of its good water vapor adsorption characteristic, or sorption isotherm, over a wide range of relative humidities, silica gel is a highly favored solid desiccant. In addition, it has no known toxic properties. However, the adsorption capacity of silica gel decreases significantly with increasing temperature. Strong alkalis (e.g., ammonia) degrade silica gel.

Molecular Sieves. Molecular sieves have an equilibrium capacity of up to 20% by weight water. Molecular sieves have no known toxic properties, but exposure to air with high concentrations of strong acids can be harmful.

ENTHALPY WHEEL HUMIDIFICATION

EW control, in HVAC applications in general and DOAS specifically, has been addressed in the open literature (Mumma 2001). When humidity control is addressed during dry conditions, the literature calls for the EW speed to be modulated as necessary to maintain a DPT setpoint, then sensibly heat or cool the air as necessary by a variety of methods. However, modulation of an EW to maintain the supply air DPT setpoint in the dry condition can lead to surprises. The EW total, sensible, and latent effectivenesses (ratio of actual heat transfer to that of an infinite area counterflow heat exchanger) at design operating speeds are generally all about the same. However, at reduced speeds, the effectiveness of each component drops, with the latent effectiveness dropping faster than the sensible (Stiesch et al. 1995). In some wheel designs, this can lead to an unexpected increase in the subsequent sensible cooling load.

Consequently, some researchers (Simonson and Besant 1999) indicated that the wheel rotating speed is impractical to use as a control parameter. Another surprise is the degree of speed control sensitivity required to meet a target DPT, since the majority of the effectiveness reduction generally occurs in the lowest 20% of the wheel speed modulation where the gain is very high. Finally, some EWs exhibit a negative latent effectiveness at speeds of 0–2 rpm (Simonson et al. 2000a). These potentially surprising performance traits are a result of the complex and highly nonlinear heat and mass transfer characteristics of the EW.

Wheel bypass control (Simonson et al. 2000b) may also be used to modulate the EW effectiveness. In this approach, the SA condition is maintained by mixing OA preconditioned by the EW rotating at full speed with unconditioned OA bypassed around the EW. This approach overcomes some of the surprises discussed above, but EW face and bypass dampers add considerably to the size of the already large equipment. It also introduces stratified air that can lead to coil freeze-up problems.

Confronted with the surprises discussed above, the authors will suggest a simple and effective way to overcome them by using a binary (ON or OFF) control of the EW when used for humidification during operation in the dry condition.

Enthalpy Wheel Humidification Example

Before discussing the binary EW control issues, the following example is presented in an effort to provide an understanding of the performance, energy, and cost associated with using the EW for humidification in dry conditions. For the example, assume the following:

- Internally load-dominated building with 100 people (standing), assumed latent load 250 Btu/h·person (73.3 W/person). Building design latent load 25,000 Btu/h (7.3 kW).
- 2000 cfm (940 L/s) OA ventilation for the building.
- Room design condition 72°F (22°C) dry bulb temperature (DBT), 30% RH. This corresponds to a humidity ratio (W) of 35 gr/lbm$_{DA}$ (5.0 g/kg$_{DA}$) and an enthalpy (h) of 22.7 Btu/lbm$_{DA}$ (35 kJ/kg$_{DA}$).

Consider a dry OA condition of 55°F (12.8°C) and 20% RH (W = 12.8 gr/lbm$_{DA}$ [1.8 g/kg$_{DA}$], h = 15.2 Btu/lbm$_{DA}$ [17.4 kJ/kg$_{DA}$]). Under these conditions, the latent load would cause the humidity ratio of the DOAS supply air to increase by 18.4 gr/lbm$_{DA}$ (2.6 g/kg$_{DA}$) as it passed through the space. Without humidification, the resulting room RH would be 26.7%. In order to get the humidity up to 30%, assuming an EW effectiveness of 80%, the EW would need to operate at a very slow modulating speed to achieve an effectiveness of only 17% or operate at full speed 21% of the time. The psychrometrics of the process are illustrated in Figure 1, and a moisture mass balance is illustrated in Figure 2.

If the building occupancy were to drop to 25%, with the same dry OA condition, the 25 occupants would cause the space RH to be only 15%. At the lower limit, with no occupant moisture addition, the space RH would be 11%, with or without the EW, assuming no auxiliary humidification. In order to bring the building RH up to 30% when 25% occupied, the EW effectiveness would need to be 79%. Under these conditions, an 80% effective EW would be operating at full speed continually. Sample operating costs, for this reduced occupancy condition, will be considered next.

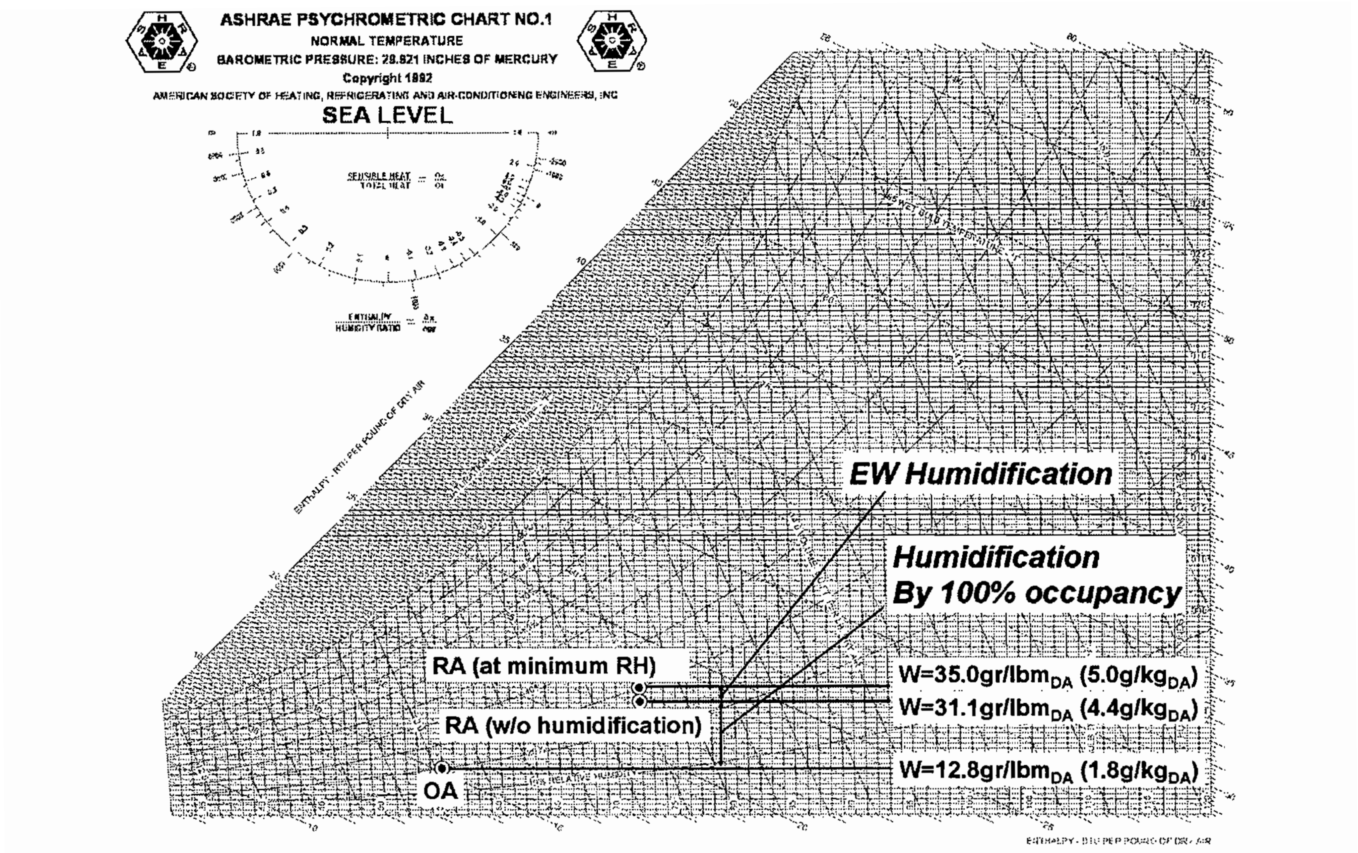

Figure 1 *Psychrometric process of the EW humidification example.*

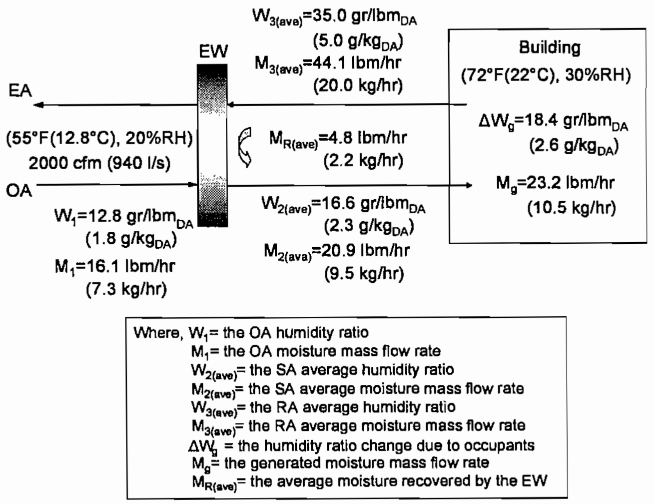

Figure 2 *Moisture mass balance in the EW humidification example.*

For the sample operating cost analysis, the following assumptions will be made:

- Chiller electrical consumption rate: 0.7 kW/ton (5.0 COP)
- Electricity, $0.08/kWh or $23.50/million Btu ($0.022 MJ)
- Efficiency of a gas heating plant to produce steam for humidification, 80%
- Gas, $14.00/million Btu ($0.013/MJ)

The 80% effective EW would elevate the 55°F (12.8°C) SA temperature to 70.9°F (21.6°C), which would subsequently need to be cooled back down to 55°F (12.8°C). That chiller load from 2000 cfm (940 L/s) of air is 2.85 tons, which would cost $0.16 per hour to operate. The humidification would be accomplished via the EW.

If a steam humidifier, rather than an EW, had been used to humidify the OA, the supply air humidity ratio would have to be elevated with the humidifier from 12.8 gr/lbm$_{DA}$ (1.8 g/kg$_{DA}$) to 30.4 gr/lbm$_{DA}$ (4.3 g/kg$_{DA}$), which would cost $0.42 per hour. In this example, humidification with the steam humidifier cost 220% more than it would to use the EW and sensibly cool.

It may be noted that for the example OA and space conditions, the ratio of humidifier cost and chiller cost remain constant as a function of the slope of the line between the two state points. In the dry condition, increasing the slope of the line causes the ratio of humidifier cost to chiller cost to increase, and vice versa.

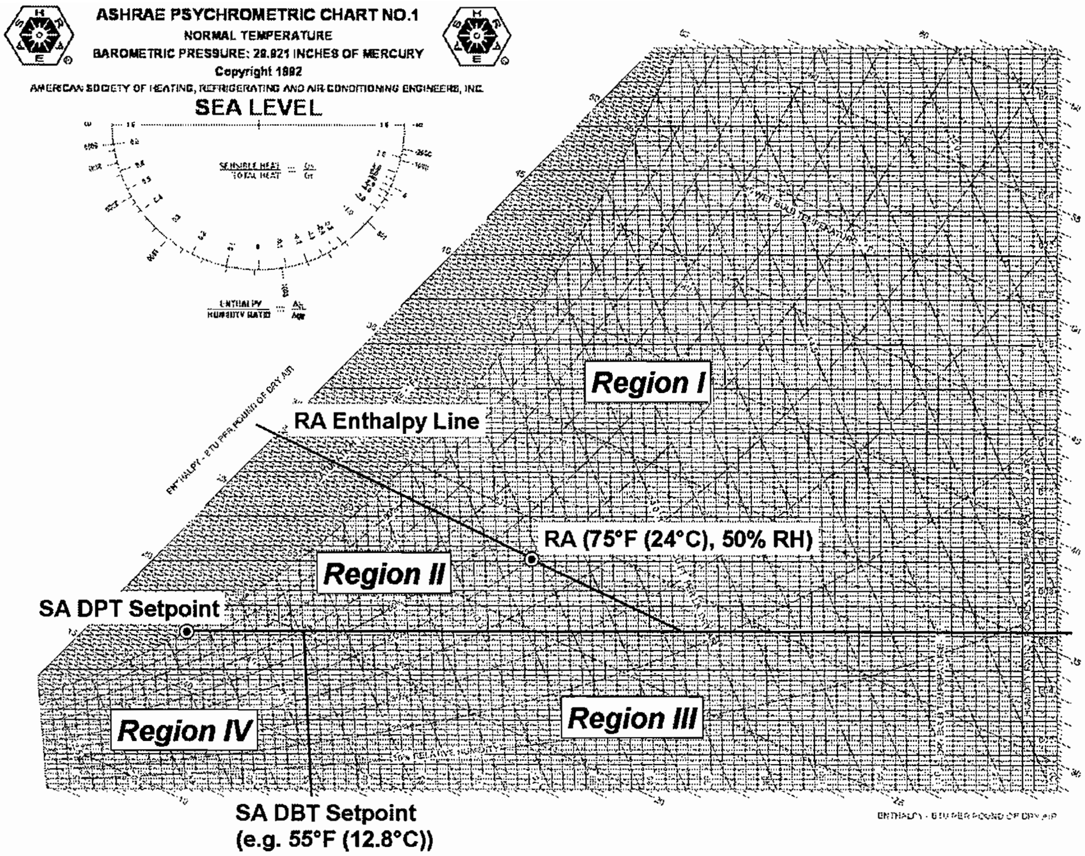

Figure 3 *DOAS operating regions.*

BINARY EW HUMIDIFICATION CONTROL

In this article, a simple binary (i.e., full-speed and OFF) EW control is proposed as a practical method for modulating the EW humidification performance. The dry condition (where humidification is required), as shown in Figure 3, is the region under the horizontal line (SA DPT setpoint line) and consists of two regions (Regions III and IV) separated by the vertical line representing the SA DBT setpoint.

The basic idea is to control the EW either at "full-speed" or "OFF" in order to maintain the space RH higher than a prescribed lower limit (Figure 4) during the DOAS "dry region" operation. This control does not utilize an SA DPT setpoint; rather, it is the space or return air RH that is used to control humidification. To avoid short cycling of the EW near the RH setpoint, there should be a minimum ON-OFF time limit or deadband where the controller's output signal changes from "OFF" to "full speed" mode. Details of the EW control for each DOAS operating region are discussed in following sections.

Binary Control in Region III

Region III defines OA conditions that are below the DPT necessary to maintain acceptable space RH, and DBTs exceeding the SA DBT setpoint (55°F [12.8°C] in this example). For illustration purposes, Region III is divided into two regions, one bounded by OA DBTs between 55°F (12.8°C) and 75°F (23.9°C) and a second bounded by OA DBTs greater than or equal to 75°F (23.9°C) (the example space DBT).

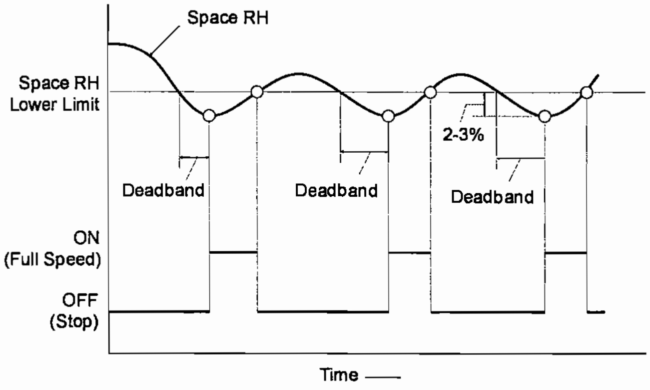

Figure 4 *Binary EW controller response.*

The first region is illustrated in Figure 5a. The binary EW control in this region places the EW in the "ON" position when the space or return air RH is below setpoint, recovering both heat and moisture. The resulting EW leaving conditions exceed the desired SAT, so the air is sensibly cooled to the desired SAT setpoint. The use of the EW for humidification

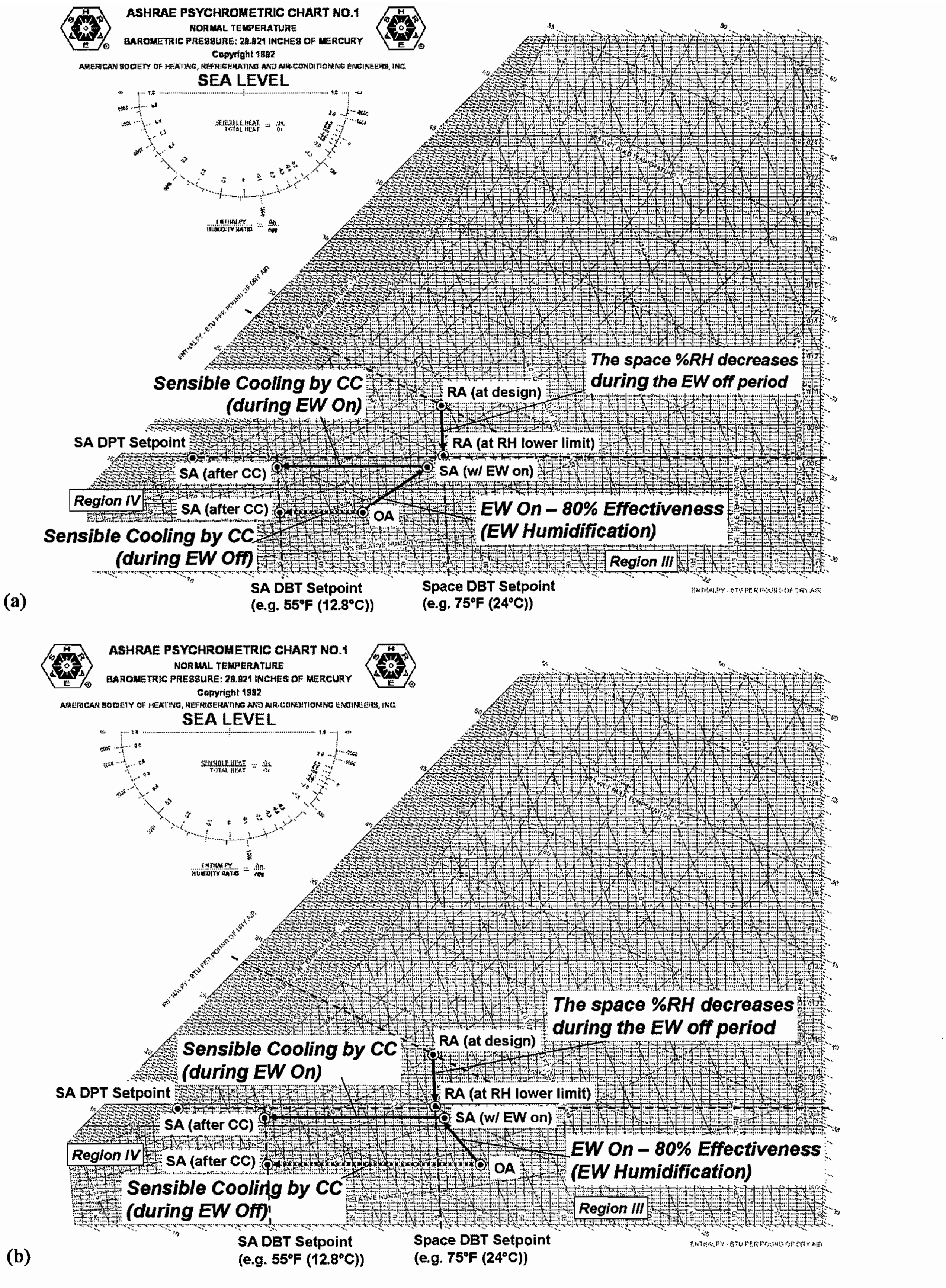

Figure 5 *Psychrometric process in Region III—(a) SA DBT setpoint < OA DBT < space DBT; (b) OA DBT ≥ space DBT.*

here increases the cooling energy use (if not from an economizer source) beyond that needed to simply sensible cool. Once the space or return air RH setpoint has been met, the binary control places the EW in the "OFF" mode. Sensible cooling is still required.

In the second region, illustrated in Figure 5b, the binary EW control behaves identically to that of Figure 5a. The difference is that operating the EW (in the "ON" mode) for humidification results in a decrease in the DBT of the air, thus reducing the sensible cooling performed by the cooling coil compared to times when the EW is in the OFF mode.

Note, when the EW operates in Region III, latent cooling at the cooling coil should be avoided. In other words, the cooling coil chilled-water supply temperature setpoint should be high enough to avoid condensation formation on the cooling coil. Otherwise, the humidification accomplished with the EW will be nullified.

Binary Control in Region IV

In Region IV, the OA DBT is below freezing much of the time, so to avoid low-temperature incidences (freezing) at the cooling coil (if chilled water), a freeze-proof preheat coil is required to elevate the OA DBT to about 40°F (4.4°C). During periods when the space or return air RH meets or exceeds setpoint, and the EW is off, the OA temperature can be elevated to the SAT DBT setpoint with a sensible heat recovery device such as sensible wheel (SW), if it is included in the DOAS arrangement. If sensible heat recovery is not included in the arrangement, the preheat coil can be used to bring the OA up to the desired SAT.

The binary control logic for this region, as illustrated in Figure 6, places the EW in the "ON" mode whenever the space or return air RH is below setpoint. And if necessary, the air is sensibly cooled, either with a cooling coil or by a parallel sensible cooling system installed in the space. In either case, waterside free cooling should be considered. If the space or return air RH is above setpoint, the EW is placed in the "OFF" mode.

Auxiliary Humidification

There are at least two situations where the EW may not be able to provide sufficient moisture recovery to maintain the minimum space RH prescribed by Standard 55-2004. One is at low occupancy levels. The other is extremely low OA DPTs that would require the EW effectiveness to exceed its capability. In either of these cases, in order to operate within ASHRAE standards, auxiliary humidification will be required. It should be noted, however, that not all buildings

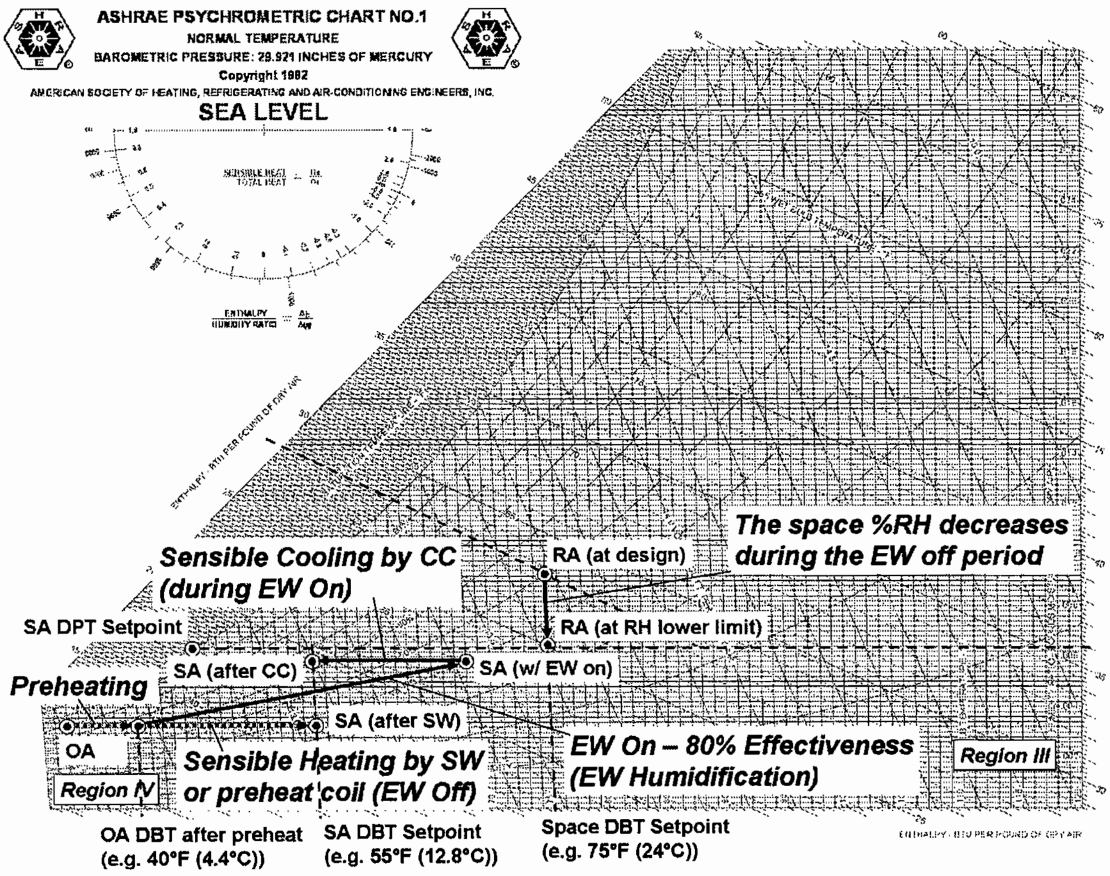

Figure 6 *Psychrometric process in Region IV.*

have been constructed in sufficient compliance with Standard 90.1-2004 to take an indoor RH of 30% in the winter without condensation problems. Some owners may not wish to use extra energy for humidification.

The auxiliary humidifier, if used, would be best placed in the conditioned space. Placing it in the relatively cold DOAS supply ductwork could easily lead to problems with water in the ductwork.

BINARY ENTHALPY WHEEL TEMPERATURE CONTROL

Binary control of the EW can be used to accomplish SAT setpoint (e.g., 55°F [12.8°C]) without regard for humidification as well. In this case, the control only applies in Region IV. In order to meet a desired SAT, the EW must be duty cycled. The duty cycle concept involves adjusting the EW on-time within a cycle period to achieve the desired SAT. The on-time is a function of the return air temperature, the OA DBT, the desired SAT, and the EW sensible effectiveness. To limit the number of times the EW is energized per hour and, hence, the wear and tear on the drive, the period is often set at 15 minutes. As a result, the on- and off-times are frequently long enough for the EW SAT to nearly reach its steady-state "ON" or "OFF" value, which will always be above and below the desired SAT.

Consequently, control of the heating and cooling coils when in the duty cycle mode becomes an issue. Since the SAT will drop below the desired SAT when the wheel is off in the cycle, but heating is not desired, the heating coil control valve must be closed during duty cycling. Similarly, when the EW is on in the cycle, the SAT will rise above the desired SAT, but cooling is not desired, so the cooling coil control valve must be closed during duty cycling. Duty cycling can only operate down to a lower limit, a temperature just above that necessary to trip the low-limit temperature sensor. In order to avoid tripping the entire system off, with the resulting indoor environmental quality problems, the EW is not permitted to duty cycle below an OA DBT of 40°F (4.4°C). A freeze-proof preheat coil can make this provision. An example of the duty cycle trending as the OA temperature rises above 40°F (4.4°C) is illustrated in Figure 7.

A by-product of using binary SAT control in Region IV is that much of the time the EW is in the "ON" mode, and humidification is being accomplished. However it is the controlled variable.

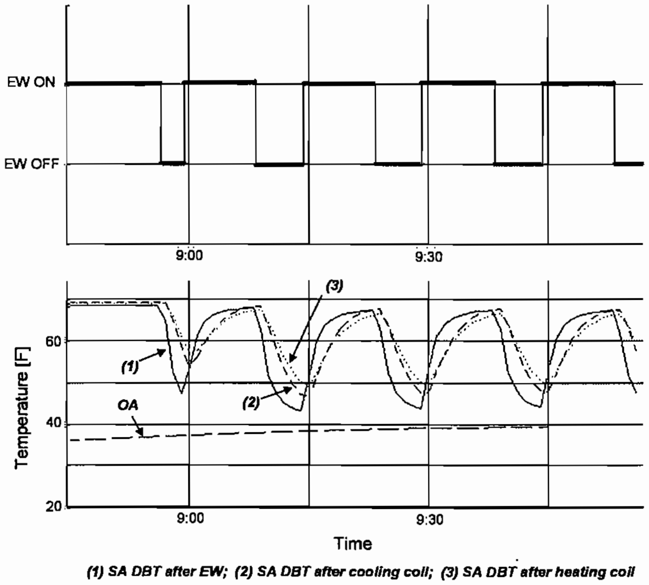

Figure 7 *Binary EW temperature control (humidification is occurring during the EW on modes, but no sensible cooling is necessary.*

CONCLUSION

A simple, proven, and generally applicable binary EW humidification control has been presented. The control overcomes the surprising issues discussed above that arise when modulating EW speed control is attempted during humidification. It was noted that use of an EW does not eliminate the potential need for an auxiliary humidifier. It has also been illustrated that it is less expensive to operate the chiller to achieve sensible cooling after the EW during dry OA conditions than to not use an EW and simply humidify the OA. In Regions III and IV, there is an energy penalty to humidify, but it is less when using the EW to humidify the OA than to have an auxiliary humidifier. Humidification is a worthy investment and operational expense for occupant health and productivity.

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