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# Overview of Psychrometrics

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**P** psychrometrics is the science of moist air properties and processes, which is used to illustrate and analyze air-conditioning cycles. It translates the knowledge of heating or cooling loads (which are in kW or tons) into volume flow rates (in  $\text{m}^3/\text{s}$  or cfm) for the air to be circulated into the duct system. The approximate composition of dry air by volume is: 79.08% nitrogen, 20.95% oxygen, 0.93% argon, 0.03% carbon dioxide and 0.01% other gases.

Water vapor is lighter than dry air. The amount of water vapor that the air can carry increases with its temperature. Any amount of moisture that is present beyond what the air can carry at the prevailing temperature can only exist in the liquid phase as suspended liquid droplets (if the air temperature is above the freezing point of water), or in the solid state as suspended ice crystals (if the temperature is below the freezing point).

The most exact formulations of thermodynamic properties of moist air in the temperature range of  $-100^\circ\text{C}$  to  $200^\circ\text{C}$  ( $-148^\circ\text{F}$  to  $392^\circ\text{F}$ ) are based on the study performed by Hyland and Wexler.<sup>1,2</sup> More recent studies by Sauer et al.<sup>3</sup> and Nelson et al.<sup>4</sup> provide psychrometric data for moist air in the temperature range of  $200^\circ\text{C}$  to  $320^\circ\text{C}$  ( $392^\circ\text{F}$  to  $608^\circ\text{F}$ ) and humidity ratios from 0 to  $1 \text{ kg}/\text{kg}_{\text{air}}$  at pressures of 0.07706 (corresponding to an altitude of 2250 m [7,382 ft]), 0.101325, 0.2, 1.0, and 5 MPa. Both studies developed the psychrometric data using the most current values of the virial coefficients, enthalpy, and entropy of both air and water vapor. Other psychrometric data were generated by

Stewart et al.,<sup>5</sup> who created psychrometric charts in SI units at low pressures. More psychrometric charts and tables are available in the ASHRAE brochure on psychrometry.<sup>6</sup>

The most commonly used psychrometric quantities include the dry- and wet-bulb temperatures, dew point, humidity ratio, relative humidity, and degree of saturation. These will be briefly defined and discussed.

**Dry-Bulb Temperature.** This is the temperature measured by a dry-bulb thermometer. Several temperature scales commonly are used in measuring the temperature. In the inch-pound (I-P) system of units, at standard atmosphere, the Fahrenheit scale has a water freezing point of  $32^\circ\text{F}$  and a boiling point of  $212^\circ\text{F}$ . In the International System (SI) of units, the Celsius scale has a water freezing point of  $0^\circ\text{C}$  and a boiling point of  $100^\circ\text{C}$ .

**Wet-Bulb Temperature and Thermodynamic Wet-Bulb Temperature.** Wet-bulb temperature is the temperature measured with a wet-bulb thermometer after the reading has stabilized in the airstream. Because of the evaporative cooling effect, the temperature measured with

a wet-bulb thermometer is lower than the dry-bulb temperature, except when the air is saturated. Then, the wet-bulb and dry-bulb temperatures are the same. The thermodynamic wet-bulb temperature is the saturation temperature of moist air at the end of an ideal adiabatic saturation process. The latter process is defined as one of saturating an airstream by passing it over a water surface of infinite length in a well-insulated chamber.

**Dew-Point Temperature.** This is the temperature at which moisture will begin to condense out of the air.

**Humidity Ratio and Relative Humidity.** Humidity ratio is the ratio of the mass of water vapor to the mass of dry air contained in the mixture of moist air. The relative humidity is the ratio of the mole fraction of water vapor in a moist air sample to the mole fraction of water vapor in a saturated moist air sample at the same temperature and pressure.

**Degree of Saturation.** This is the ratio of the humidity ratio of moist air to the humidity ratio of saturated moist air at the same temperature and pressure.

## Psychrometric Processes

**Sensible Heating or Cooling.** This is the process of heating or cooling the air without changing its moisture content. It is represented by lines of constant humidity ratio on the psychrometric chart. Sensible heating is accomplished when the air passes over a heating coil. Sen-

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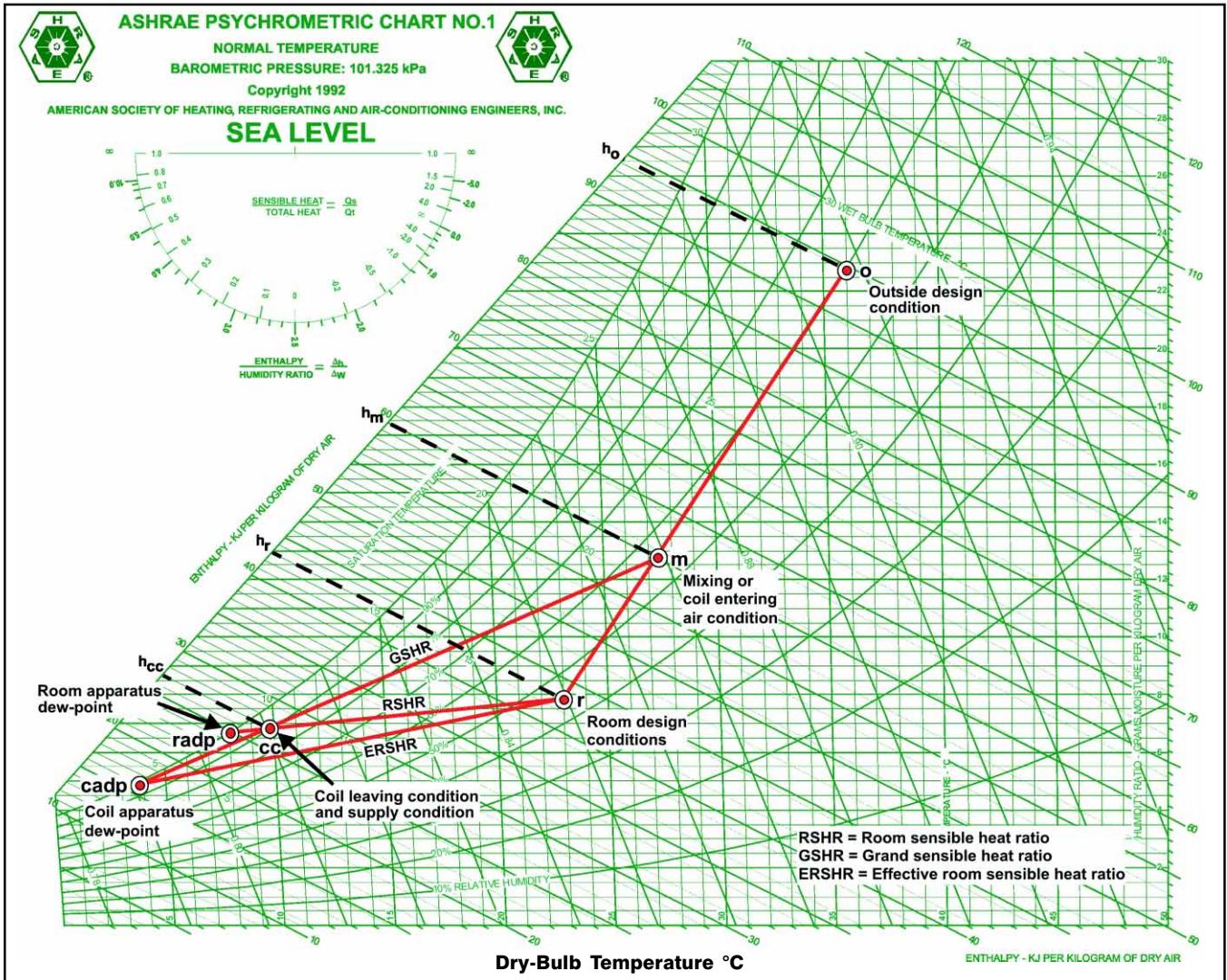


Figure 1: Psychrometric depiction shows coil bypass factor, sensible heat ratios.

sible cooling is accomplished when the air passes over a cooling coil with a surface temperature above the dew-point temperature of the air.

**Humidification (with Heating or Cooling).** This is the process of introducing moisture into the airstream. In winter, humidification frequently is required because the cold outside air, infiltrating into a heated space or intentionally brought in to satisfy the space ventilation requirement, is too dry. In summer, humidification is usually done as part of an evaporative cooling system. Humidification is achieved in various ways that range from using spray washers to passing the air over a pool of water to injecting steam.

The process is represented on the psychrometric chart as a line of constant wet-bulb temperature when the sprayed water is not externally heated or cooled. When there is external heating or cooling, the process is represented by a line to the right or to the left of the wet-bulb temperature line, respectively.

Depending on the magnitude of water heating, the humidification process line can be oriented in such a way that results

in an increase in the dry-bulb temperature of the airstream at the exit of the dehumidifying device. In the extreme case of spraying cold water in the airstream, such that the water temperature is less than the dew-point temperature of water vapor in air, the spraying process will actually result in air dehumidification.

**Cooling and Dehumidification.** This process is used in air-conditioning systems operating in hot, humid climates. It is accomplished by using a cooling coil with a surface temperature below the dew-point temperature of water vapor in air. On the psychrometric chart, the process is represented by a line in which both the dry-bulb temperature and the humidity ratio decrease. Because not all the air molecules going through the cooling coil physically contact the coil surface, the air condition at the exit of the coil usually is not saturated (but close to the saturation curve). This is reflected by the use of the so-called coil bypass factor, which is defined as the ratio of the temperature difference between the leaving coil air condition and coil apparatus dew point and that between the entering air

condition and coil apparatus dew point (see *Figure 1*). This is expressed as:

$$B_F = \frac{T_{cc} - T_{cadp}}{T_m - T_{cadp}}$$

Coil bypass factors range from 0 (when no dehumidification is achieved by the coil) to 1 (when maximum dehumidification is achieved by the coil). *Figure 1* shows the apparatus dew point and the coil bypass factor. The figure also shows the lines representing the room sensible heat ratio (RSHR), the coil (or grand) sensible heat ratio (GSHR), and the effective room sensible heat ratio (ERSHR). These are defined according to the following equations:

$$RSHR = \frac{\dot{Q}_{R,S}}{\dot{Q}_{R,S} + \dot{Q}_{R,L}}$$

$$GSHR = \frac{\dot{Q}_{G,S}}{\dot{Q}_{G,S} + \dot{Q}_{G,L}}$$

$$ERSHR = \frac{\dot{Q}_{R,S} + B_F \dot{Q}_{O,S}}{[\dot{Q}_{R,S} + B_F \dot{Q}_{O,S}] + [\dot{Q}_{R,L} + B_F \dot{Q}_{O,L}]}$$

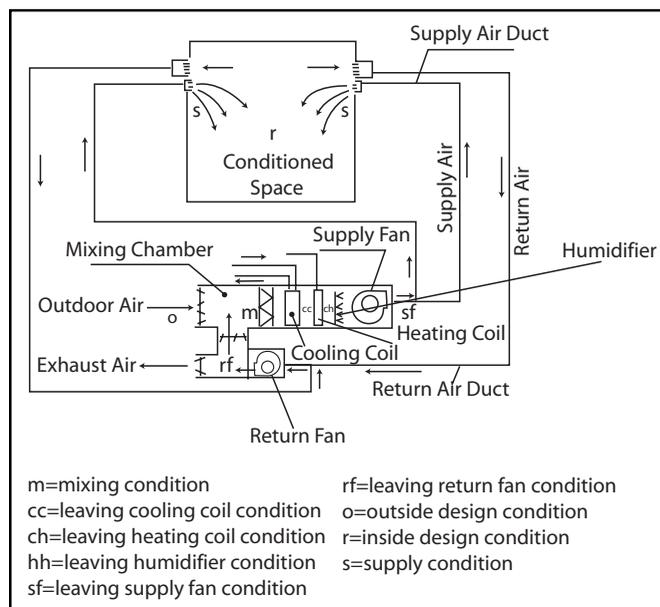
where  $\dot{Q}$  represents the loads. Subscripts *R*, *O*, and *G* represent room, outside, and grand, respectively, while *S* and *L* represent sensible and latent (loads), respectively. The effective sensible heat ratio is interwoven with both the coil apparatus dew-point temperature and the coil bypass factor, with the sole intention of simplifying psychrometric calculations. The mass flow rate using the effective room sensible heat ratio can be computed from the following equation:

$$\dot{m}_s = \frac{(\dot{Q}_{R,S} + B_F \dot{Q}_{O,S})}{\rho C_p (T_r - T_{cadp})(1 - B_F)}$$

where  $T_r$  is the indoor (room) design temperature and  $T_{cadp}$  is the coil apparatus dew-point temperature. The mass flow rate term represents the quantity of air per unit time (kg/s or lb/h) supplied to the conditioned space. The previous equation is not exact since the product of the specific heat ( $C_p$ ) and the temperature difference was used in lieu of the enthalpy difference. However, the specific heat of air does not change much with temperature in the air-conditioning temperature range, therefore, the error introduced by the earlier approximation is negligible.

**Heating and Dehumidification.** This is also referred to as desiccant (or chemical) dehumidification, which takes place when air is exposed to either solid or liquid desiccant materials. The mechanism of dehumidification in this case is either absorption (when physical or chemical changes occur) or adsorption (when there are no physical or chemical changes).

During the sorption process, heat is released. This heat is the sum of the latent heat of condensation of the absorbed water



**Figure 2: Basic air-conditioning system.**

vapor into liquid plus the heat of wetting. The latter quantity refers to either wetting of the surface of the solid desiccant by the water molecules, or the heat of solution in the case of liquid desiccant. Dehumidification by solid desiccants is represented on the psychrometric chart by a process of increasing dry-bulb temperature and a decreasing humidity ratio. Dehumidification by liquid desiccants is also represented by a similar line, but when internal cooling is used in the apparatus, the process air line can go from warm and moist to cool and dry on the chart.

**Mixing of Airstreams.** This usually refers to either adiabatic mixing of two or more airstreams or to bypass mixing. In the former process, two or more streams are mixed together adiabatically forming a uniform mixture *m* in a mixing chamber. In this case, mass, energy, and water vapor balances yield the following equations:

$$\dot{m}_1 + \dot{m}_2 + \dots + \dot{m}_j = \dot{m}_m$$

$$\dot{m}_1 h_1 + \dot{m}_2 h_2 + \dots + \dot{m}_j h_j = \dot{m}_m h_m$$

$$\dot{m}_1 W_1 + \dot{m}_2 W_2 + \dots + \dot{m}_j W_j = \dot{m}_m W_m$$

Bypass mixing usually happens in air-handling units where the airflow is divided into upper hot-deck and lower cold-deck streams. In a summer air-conditioning operation, the upper hot deck acts as a bypass airstream to moderate the temperature of the otherwise overcooled air leaving the cooling and dehumidifying coil. In winter, the lower cold deck acts as the bypass stream, by mixing with the warm air after it has passed over the heating coil.

### Air-Conditioning Cycles and Systems

An air-conditioning cycle is a combination of several air-conditioning processes. Different systems are characterized

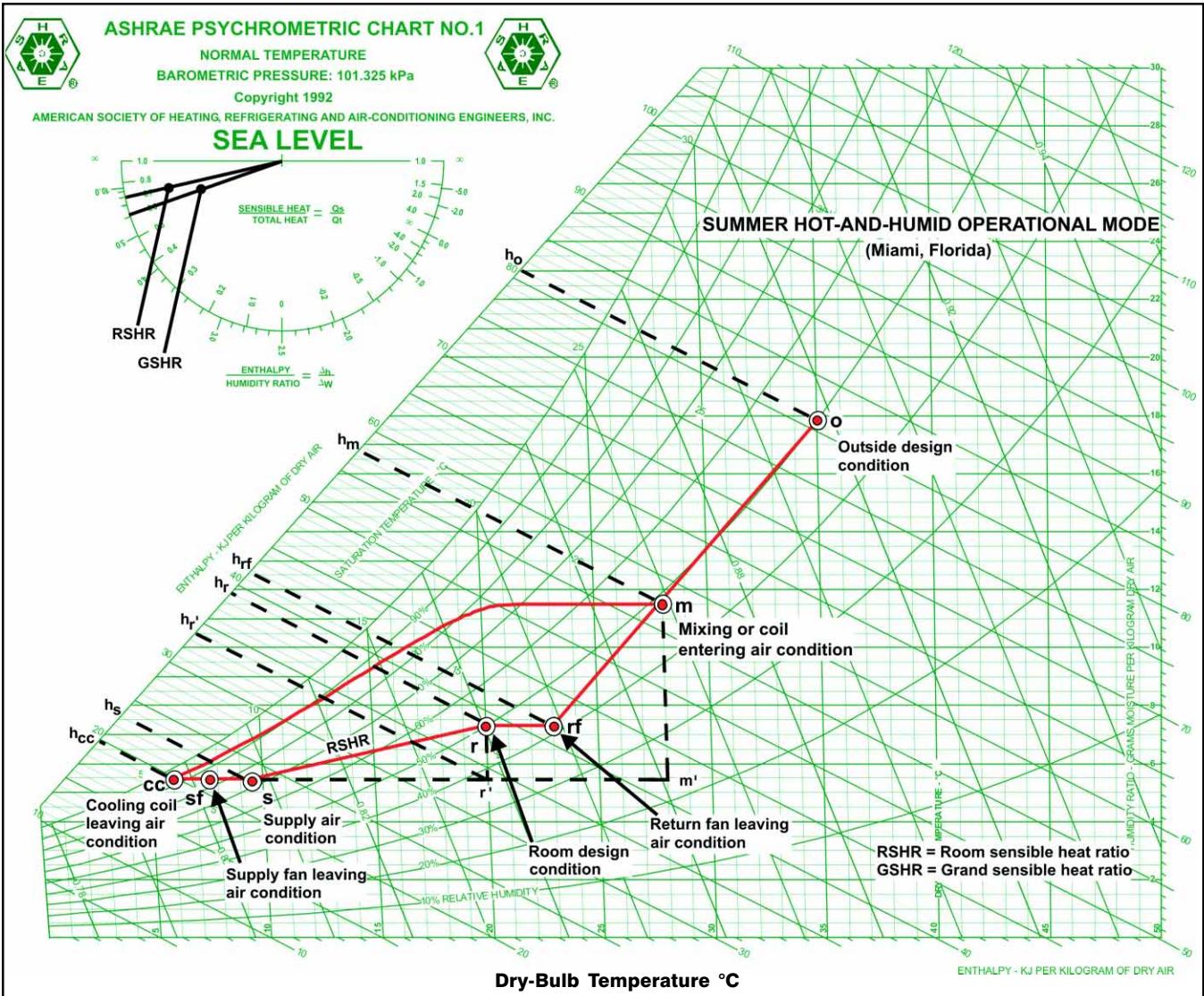


Figure 3: Psychrometric depiction of hot, humid summer air-conditioning system.

by the type of air-conditioning cycle they use. The main function of the psychrometric analysis of an air-conditioning system is to determine the volume flow rates of air to be pushed into the ducting system and the sizing of the major system components.

There are generally four extreme climatic conditions that may involve an air-conditioning system. In summer operation, for example, the dry-bulb temperature of the outdoor air is always high, but the humidity ratio may be either high or low. In hot, humid climates (e.g., Miami), the air-conditioning system is typically composed of a cooling coil with a surface temperature below the dew-point temperature (Figure 2). That way, the system can achieve cooling and dehumidification. In hot, dry climates (e.g., Phoenix), evaporative coolers typically are used.

Winter conditions may have similar extremes, with the dry-bulb and dew-point temperatures both being low. In extremely

cold conditions (e.g., Minneapolis), the environment typically is very dry. In this case, the air-conditioning system usually is composed of a heating coil and a humidifying device, with the former being located upstream of the latter.

The humidifying device may be a spray washer composed of a spray chamber in which a number of spray nozzles and risers are installed. Spray washers are typically used in industrial applications where the device performs the dual function of air humidification and cleaning. The washer may have one or more banks of spray nozzles that have the capacity of injecting 1 to 2 gpm (0.6 to 0.13 L/s) of atomized water per nozzle into the airstream. Adequate atomization of the water can be achieved by operating at pumping pressures ranging from 20 to 40 psi (138 to 276 kPa).<sup>7</sup> Washers typically use baffles at the inlet air section to distribute the air uniformly throughout the chamber. At the exit section, moisture eliminators prevent carryover water from exiting the chamber into the

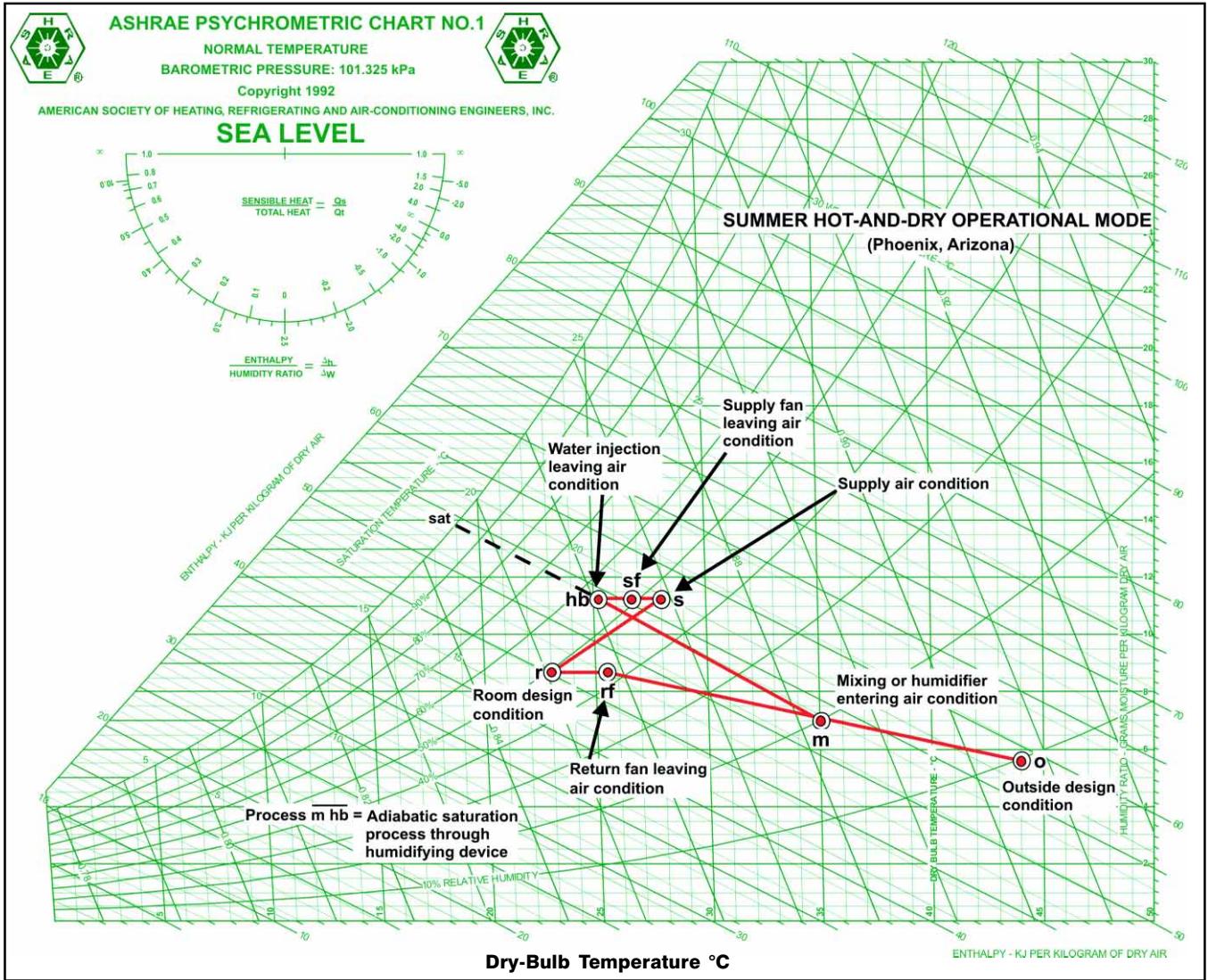


Figure 4: Psychrometric depiction of a hot, dry summer air-conditioning system.

conditioned space.

In cases where the outdoor air is cool but humid (e.g., Seattle), there may not be a need to humidify the air, and the air-conditioning system typically is composed of a heating coil only. However, because the humidity ratio at low temperatures is low even though the relative humidity may be high, some humidification may be required when the dew point is low during the winter.

In addition to these four extreme climatic conditions, the air-conditioning system may need to operate in the fall and spring. This mixed-mode operation usually requires switching between heating and cooling based on the value of the outdoor temperature. However, because of the potential energy waste associated with this mode of operation, the system usually is set to operate only if the outdoor temperature goes outside of a pre-specified wide band (to minimize the frequency of cycling between the heating and cooling modes).

To provide the reader with an idea of the psychrometric analy-

ses that need to be performed on an air-conditioning system, only three of the previous systems (hot, humid; hot, dry; and cold, dry) will be described in more detail. The cool, humid mode of operation is identical to the cold, dry mode (except in the absence of the humidifying device).

**Summer Hot, Humid Mode.** Figure 2 shows a basic air-conditioning system capable of both summer and winter mode operations. Figure 3 shows the psychrometric representation of a hot, humid summer mode operation applicable to Miami. In this mode, outdoor air at State “o” is adiabatically mixed with recirculated air from the room after passing through the ceiling plenum, the return duct, and the return fan (State “rf”) to form the mixed air condition “m,” which is also the entering state to the cooling coil. Air is then cooled and dehumidified until it exits the coil at State “cc.” After that, air is reheated, due to passing over the supply fan and through the supply ducts, to State “s,” the supply condition. The space sensible, latent, and total loads can, respectively, be expressed as:

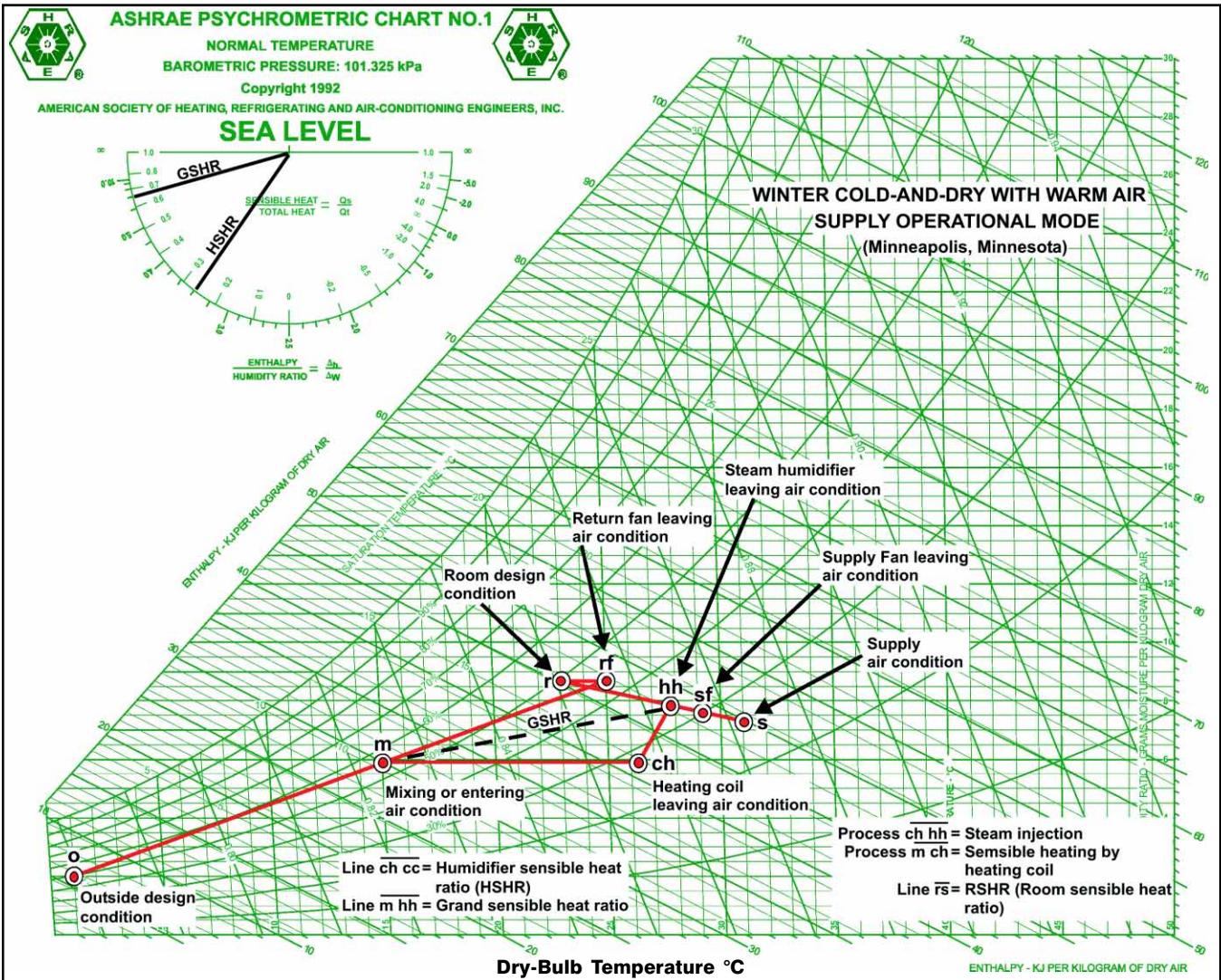


Figure 5: Psychrometric depiction of a cold, dry winter air-conditioning system.

$$\dot{Q}_{R,S} = \dot{m}_s (h_r' - h_s)$$

$$\dot{Q}_{R,L} = \dot{m}_s (h_r - h_r')$$

$$\dot{Q}_{RT} = \dot{m}_s (h_r - h_s)$$

$$\dot{Q}_{G,L} = \dot{m}_s (h_m - h_m')$$

$$\dot{Q}_{G,T} = \dot{m}_s (h_m - h_{cc})$$

where,  $\dot{Q}$  represents the load quantities and the enthalpies have subscripts corresponding to the respective points identified on the psychrometric chart. Any one of these equations can be used to compute the supply mass flow rate. The supply volume flow rate, however, is computed with the knowledge of the specific volume at the supply condition  $v_s$ . This is expressed as:

$$\dot{V}_s = \dot{m}_s v_s$$

The space (room) sensible heat ratio (RSHR) is graphically represented by line “rs” on the psychrometric chart. As for the cooling coil (or grand) loads, the following equations apply:

$$\dot{Q}_{G,S} = \dot{m}_s (h_m' - h_{cc})$$

Again, the subscripts of the enthalpy quantities correspond to state points identified on the chart. The above equations can be used to size the cooling coil. The grand (or cooling coil) sensible heat ratio (GSHR) is graphically represented by line “m cc.” The relative humidity of the air exiting the cooling coil is a function of the coil design, fin spacing, coil surface area, and coil face velocity, among other factors. For a coil with 10 or more fins per inch and four rows of coil, the relative humidity of the leaving air is approximately 93%. For six- and eight-row coils with fin spacing of 10 or more per inch, the exiting relative humidities are 96% and 98%, respectively.<sup>8</sup>

**Summer Hot, Dry Mode.** A psychrometric depiction of the processes involved in this mode of operation is shown in Figure 4. As indicated earlier, the air-conditioning equipment in

this case is simply composed of a humidifying device where atomized water is introduced into the airstream. Outdoor air at State “o” is typically mixed with return air from the conditioned space after passing through the return ducts and over the return fan (State “rf”) to form the mixed state “m.” The evaporative cooling process that results from the spray equipment usually follows a constant wet-bulb temperature line, with the air exiting at State “hh.” After that, the air passes over the supply fan and through the supply ducts until it enters the conditioned space at State “s.” The humidifying effectiveness,  $\eta_H$ , can be expressed either in terms of a temperature deficit ratio or a humidity deficit ratio as:

$$\eta_H = \frac{T_m - T_{hh}}{T_m - T_{sat}}$$

$$\eta_H = \frac{W_{hh} - W_m}{W_{sat} - W_m}$$

Special care has to be exercised in analyzing room and grand loads in this mode as the sensible and latent components have opposite signs. For example, the evaporative cooling process used results in a decrease in the air temperature (sensible cooling), whereas it increases the humidity ratio (latent heating). The process results in a very small change in the air enthalpy (almost zero) as the adiabatic saturation process through the humidifying device follows a constant wet-bulb temperature line.

**Winter Cold, Dry Mode.** Two scenarios are possible in a winter system. One involves the supply of heated air, and the other involves the supply of unheated air to the conditioned space. The latter mode is applicable in cases when the outdoor temperature is not so cold that the fan and duct heating may be enough to provide for comfort level temperatures. Because of the similarities between these scenarios, we will only consider the former scenario for further analysis.

As mentioned earlier, for the cold, dry mode there is a need to humidify the airstream. *Figure 5* shows the basic cycle represented on the psychrometric chart for this operational mode. Outside air at State “o” is mixed with recirculated air from the room after passing over the return fan (State “rf”) producing the mixed state “m.” Air at this state passes over a heating coil and leaves at State “ch.” After the sensible heating process “m ch,” air enters the humidifying device where both the dry-bulb temperature and humidity ratio of the airstream are increased, producing state “hh” at the exit of the device. In the humidifying device, either steam or atomized hot water is injected. Air then passes over the supply fan and through the supply ducts to the conditioned space at the supply condition “s.”

The amount of heating required by the heating coil typically needs to be coordinated with the heating performed by the humidifying device due to steam or hot water injection. The optimum amount of heating performed by both devices may be hard to pinpoint in an exact way, but a careful choice of the state of air leaving the heating coil may go a long way

towards minimizing unnecessary use of heating energy.

The sensible heat ratio for the humidifying device is represented by line “ch hh.” The grand sensible heat ratio (GSHR) of the overall system is represented by line “m hh.”

## Conclusions

This article presents an overview of psychrometric processes and systems as applied to different operational modes. Proper execution of this stage is crucial in accurately computing the volume flow rates of air through the air-conditioning ducts. This phase, in an air-conditioning design process, follows the load calculation phase. While the latter phase produces quantities that represent the sensible and latent loads imposed on the conditioned space, the former phase (psychrometric analysis) is capable of incorporating the effects of introducing fresh outside air into the space for ventilation purposes.

Cooling or heating equipment sizing has to take into account not only the load imposed on the conditioned space, but also the outside load. By specifying the amount of outside air to be introduced for a specified set of outdoor and indoor conditions, psychrometric analysis enables the HVAC designer to compute the load imposed on the conditioning equipment (grand load).

The analysis is inherently capable of distinguishing between the sensible and latent load quantities of outside and conditioned space (room) air, thus providing an insightful picture of how to handle the existing moisture.

Psychrometric analysis also enables the designer to account for other smaller loads that may be imposed on the system such as ducts and fans in equipment sizing. By identifying the different state points of the air as it passes through the duct system and over the supply and return fans, the volume flow rates of air computed by the analysis become necessarily inclusive of the effects of the ducts and fans in equipment sizing.

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