Kirk-Othmer Encyclopedia of Chemical Technology.

AIR CONDITIONING

In the past 100 years, air conditioning has progressed from its beginnings in the refrigeration industry (see Refrigeration) to being an indispensable factor in society. Applications range from providing human comfort to controlling the conditions essential for the production of many chemical products.

The design of air conditioning systems is a highly specialized branch of engineering. A number of excellent information sources regarding air conditioning are available (1).

1. Basic Principles

Thermodynamic principles govern all air conditioning processes (see Heat exchange technology, heat transfer). Of particular importance are specific thermodynamic applications both to equipment performance which influences the energy consumption of a system and to the properties of moist air which determine air conditioning capacity. The concentration of moist air defines a system's load.

1.1. Thermodynamics

Many definitions and formulations exist for the laws of thermodynamics, a detailed treatment of which may be found in standard engineering texts (2). Definitions that apply best to air conditioning are as follows:

First law. This is the law of conservation of energy which states that the flow of energy into a system must equal the flow of energy out of the same system minus the energy that remains inside the system boundary. For an open system in which the energy flows are not time dependent and in which there is no accumulation of energy in the system, the first law may be written as

$$\sum_{\text{in}} \dot{Q} + \sum_{\text{in}} \dot{m}_i \left(h_i + Z_i + \frac{V_i^2}{2g} \right) = \sum_{\text{out}} \dot{W} + \sum_{\text{out}} \dot{m}_j \left(h_j + Z_j + \frac{V^2}{2g} \right)$$

where $\dot{Q}$ = rate of heat transfer to the system, $\dot{m}$ = mass flow rate, h = enthalpy of substance, Z = elevation of boundary above a horizontal reference, V = velocity of substance, g = gravitational acceleration, and W = work done by the system.

Open steady-flow systems, which include almost all air conditioning processes, follow this law. Examples include the energy flows in a cooling and dehumidifying coil or an evaporative cooling system.

Second Law. This law defines the maximum theoretical performance for air conditioning equipment and provides a means of identifying energy losses in a system. It states that no heat engine operating in a closed cycle may produce work when communicating with a single temperature source. Air conditioning is the result of a heat engine operating in reverse. This means that work is added to the system and there must always be at least two temperatures, a low temperature source from which heat is received and a high temperature sink to which heat is rejected.

The Carnot cycle is formulated directly from the second law of thermodynamics. It is a perfectly reversible, adiabatic cycle consisting of two constant entropy processes and two constant temperature processes. It defines the ultimate efficiency for any process operating between two temperatures. The coefficient of performance (COP) of the reverse Carnot cycle (refrigerator) is expressed as

$$\mathrm{COP} = \frac{\text{useful effect}}{\text{work input}} = \frac{T_1}{T_2 - T_1}$$

where T_1 = absolute temperature of the cold source and T_2 = absolute temperature of the hot sink.

In some applications, large quantities of waste or low cost heat are generated. The absorption cycle can be directly powered from such heat. It employs two intermediate heat sinks. Its theoretical coefficient of performance is described by

$$\mathrm{COP}_a = \frac{T_1\,(T_2 - T_{S1})}{T_2\,(T_{S2} - T_1)}$$

where T_{S1} = absolute temperature of one intermediate heat sink (condenser), and T_{S2} = absolutete temperature of the other intermediate heat sink (absorber).

Real processes always involve losses and irreversibilities and thus deviate from theory. Typical inefficiencies arise from temperature differences between the air stream and the heat exchange fluid, friction between moving parts, fluid pressure drops through heat exchangers and ducts, and pressure drops through pipes and valves. The fewer the inefficiencies, the more closely the process approaches the theoretical limit. Good texts on air conditioning (see general references or reference 1, provide a more detailed description of actual processes.

A simple cooling cycle serves to illustrate the concepts. Figure 1 shows a temperature–entropy plot for an actual refrigeration cycle. Gas at state 1 enters the compressor and its pressure and temperature are increased to state 2. There is a decrease in efficiency represented by the increase in entropy from state 1 to state 2 caused by friction, heat transfer, and other losses in the compressor. From state 2 to states 3 and 4 the gas is cooled and condensed by contact with a heat sink. Losses occur here because the refrigerant temperature must always be above the heat sink temperature for heat transfer to take place. The liquid refrigerant is commonly expanded adiabatically from state 4 to state 5 by a throttling device; thus there is a further loss in efficiency. Heat is added to the refrigerant from state 5 to state 1 and the cycle is repeated. The loss in this process again results from the temperature difference between the heat source and the refrigerant. Process A–B–C–D represents the Carnot cycle. Because the area inside the cycle boundary represents the work added, it is evident that the actual refrigeration cycle requires more work and thus has a considerably lower COP than the ideal cycle.

As illustrated both by the second law of thermodynamics and the example in Figure 1, the temperature difference between the heat source and sink needs to be minimized in order to increase the efficiency of the process. This means rejecting heat to the sink having the lowest possible temperature while obtaining heat from the source having the highest. Increased efficiency results from using the largest heat exchangers consistent with economy to minimize temperature differences between the working fluid and the source and sink. Lack of maintenance, especially in regard to heat exchangers, significantly increases the temperature differentials and the energy consumption. Other considerations resulting from the second law include minimizing fluid pressure losses by using the largest practical air ducts and fluid piping and utilizing the most efficient mechanical devices obtainable.

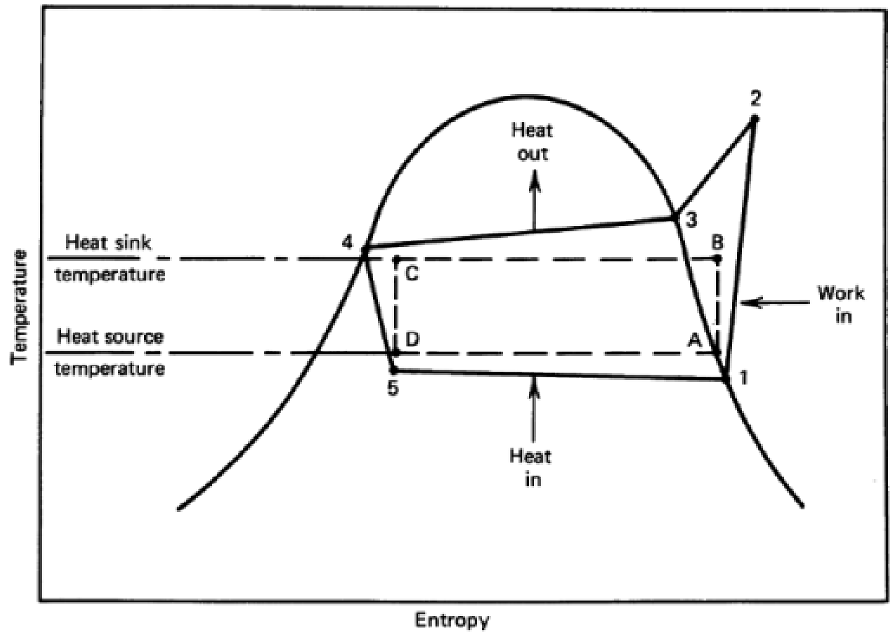

Fig. 1. Real refrigeration (—) and Carnot (– – –) cycles.

1.2. Psychrometrics

Psychrometrics is the branch of thermodynamics that deals specifically with moist air, a binary mixture of dry air and water vapor. The properties of moist air are frequently presented on psychrometric charts such as that shown in Figure 2 for the normal air conditioning range at atmospheric pressure. Similar charts exist for temperatures below 0°C and above 50°C as well as for other barometric pressures. All mass properties are related to the mass of the dry air.

The following quantities are found on a psychrometric chart:

1.2.1. Dry-bulb Temperature (DB) (Abscissa)

DBT is the temperature of a gas or mixture of gases indicated by an accurate thermometer after correction for radiation effect.

1.2.2. Dew-point Temperature (DPT)

DPT is the temperature at which the condensation of water vapor in a space begins for a given state of humidity and pressure as the temperature is reduced. It is the temperature corresponding to saturation (100% rh) for a given absolute humidity at constant pressure.

1.2.3. Enthalpy

Enthalpy is the thermodynamic property of a substance defined as the sum of its internal energy plus the quantity Pv/J, where P = pressure of the substance, v = its specific volume, and J = the mechanical equivalent of heat. Enthalpy is also known as total heat and heat content.

1.2.4. Humidity Ratio (Ordinate)

The humidity ratio is the weight of water vapor in the air per unit weight of dry air.

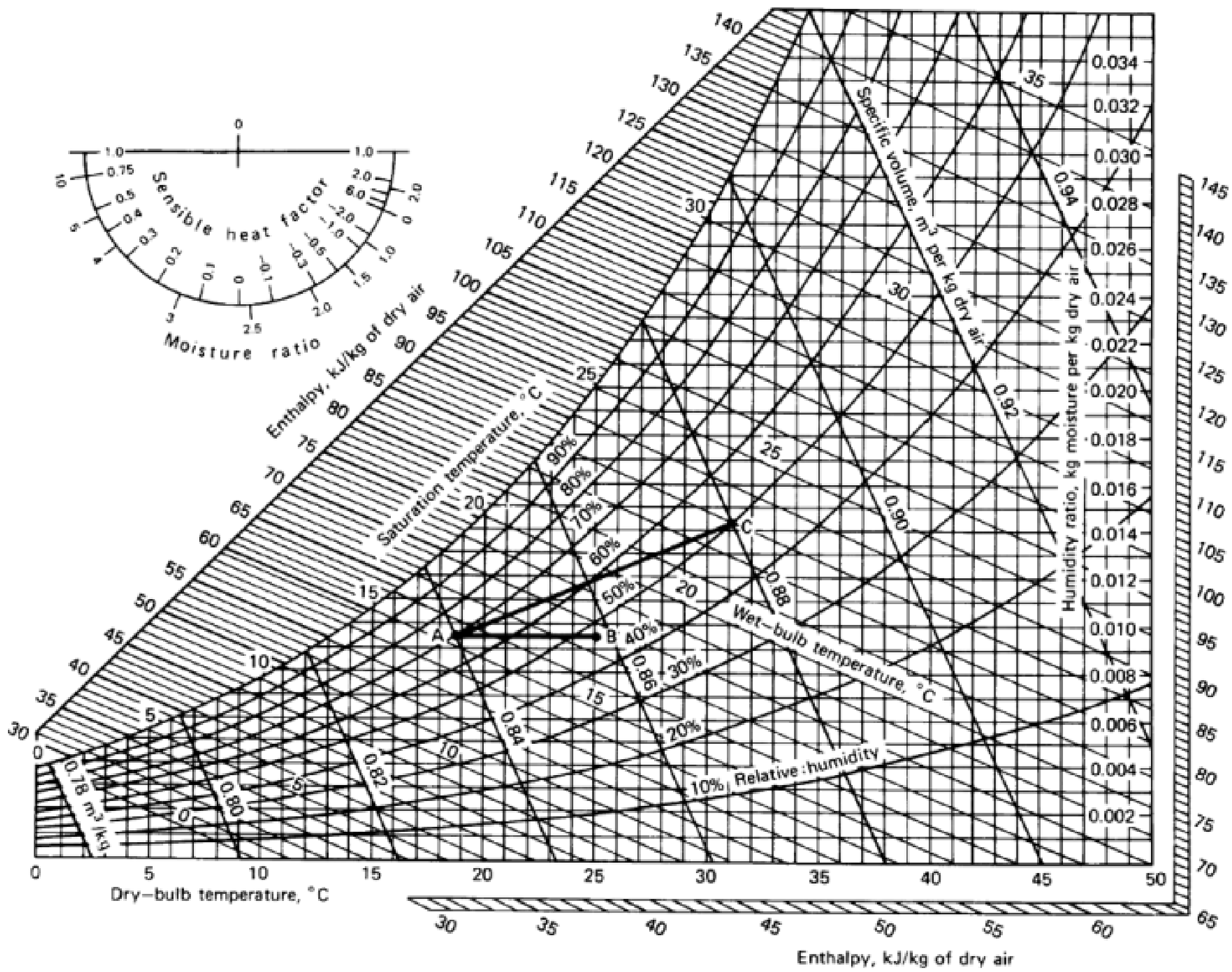

Fig. 2. Psychrometric chart at atmospheric pressure, 101.3 kPa (1 atm)(3). To convert kJ to kcal, divide by 4.184.(Courtesy of Business News Publishing Co.)

1.2.5. Relative Humidity (rh)

Relative humidity is the ratio of the mole fraction of water vapor present in the air to the mole fraction of water vapor present in saturated air at the same temperature and barometric pressure; it approximately equals the ratio of the partial pressure (or density) of the water vapor in the air to the saturation pressure (or density) of water vapor at the same temperature.

1.2.6. Saturation Temperature

The temperature at which the water vapor in moist air is in equilibrium with liquid water.

1.2.7. Sensible Heat Factor

The ratio of the change in sensible (constant moisture content) cooling enthalpy to the change in total cooling enthalpy.

1.2.8. Specific Volume

The volume of air per unit mass.

1.2.9. Wet-bulb Temperature

The equilibrium temperature which air attains if adiabatically saturated by water from a condensed phase.

The psychrometric chart may be used to determine the change in properties of air required for a condition or a process. For example, point A on Figure 2 has a dry-bulb temperature of 18.8°C and a relative humidity of 70%. Further, the air has a wet-bulb temperature of 15.2°C, an enthalpy of 61 kJ/kg (14.6 kcal/kg), an absolute humidity of 0.0095 kg/kg, and a specific volume of 0.84 m^3/kg. Sensible heating (no moisture addition) may be represented by the line from point A to point B. This causes the relative humidity to decrease to 48% and the enthalpy to increase to 68 kJ/kg (16.3 kcal/kg). The amount of energy required to raise the dry-bulb temperature from 18.8°C to 25°C is 7 kJ/kg (1.7 kcal/kg) of dry air. If the air mass or flow rate were known, the total energy required could be determined. Cooling and dehumidifying is represented by the line from point C to point A. This increases the relative humidity and requires the removal of 26 kJ/kg (6.2 kcal/kg) of dry air. The amount of moisture removed is 0.0047 kg/kg of dry air. Constructing a line parallel to A–C but through point 0 on the nomograph in the upper left of Figure 2 reveals that the sensible heat factor is 0.5. Other air conditioning processes, except those involving substantial pressure changes, can be plotted on a psychrometric chart although the process may not always be a straight line.

2. Design Conditions

Fundamental to the design of any air conditioning system is the determination of the operating conditions of temperature and humidity. Worker comfort must also be considered.

2.1. Process Requirements

Typical inside dry-bulb temperatures and relative humidities used for preparing, processing, and manufacturing various products, and for storing both raw and finished goods, are listed in Table 1. In some instances, the conditions have been compromised for the sake of worker comfort and do not represent the optimum for the product. In others, the conditions listed have no effect on the product or process other than to increase worker efficiency.

Table 1. Typical Industrial Inside-Design Conditions[a]

Industry	Process	Dry-bulb temperature, °C	Rh, %
abrasives	manufacture	24–27	45–50
bakery	dough mixer	24–27	40–50
	fermenting	24–28	70–75
	proof box	33–36	80–85
	bread cooler	21–27	80–85
	cold room	4–7	
	make-up room	26–28	65–70
	cake mixing	35–41	
	crackers and biscuits	15–18	50
	wrapping	15–18	60–65
	storage:		
	dried ingredients	21	55–65
	fresh ingredients	0–7	80–85
	flour	21–24	50–65
	shortening	7–21	55–60

Table 1. ***Continued***

Industry	Process	Dry-bulb temperature, °C	Rh, %
	sugar	27	35
	water	0–2	
	wax paper	21–27	40–50
brewery	storage:		
	hops	−1 – 0	55–60
	grain	27	60
	liquid yeast	0–1	75
	lager	0–2	75
	ale	4–7	75
	fermenting cellar:		
	lager	4–7	75
	ale	13	75
	racking cellar	0–2	75
candy (chocolate)	candy centers	27–29	40–50
	hand-dipping room	15–18	50–55
	enrobing room	24–27	55–60
	enrobing:		
	loading end	27	50
	enrober	32	13
	stringing	21	40–50
	tunnel	4–7	dp–40
	packing	18	55
	pan specialty room	21–24	45
	general storage	18–21	40–50
candy (hard)	manufacturing	24–27	30–40
	mixing and cooling	24–27	40–45
	tunnel	13	dp–55
	packing	18–24	40–45
	storage	18–24	45–50
	drying: jellies, gums	49–65	15
	cold room: marshmallow	24–27	45–50
chewing gum	manufacturing	25	33
	rolling	20	63
	stripping	22	53
	breaking	23	47
	wrapping	23	58
ceramics	refractory	43–65	50–90
	molding room	27	60–70
	clay storage	15–27	35–65
	decal and decorating	24–27	45–50
cereal	packaging	24–27	45–50
cosmetics	manufacturing	18–21	
distilling	storage:		
	grain	15	35–40
	liquid yeast	0–1	
	manufacturing	15–24	45–60
	aging	18–22	50–60
electrical products	electronic and x ray: coils and transmission winding	22	15
	tube assembly	20	40
	electrical installations: manufacturing and laboratory	21	50–55
	thermostat assembly and calibration	24	50–55

Table 1. ***Continued***

Industry	Process	Dry-bulb temperature, °C	Rh, %
	humidistat assembly and calibration	24	50–55
	close-tolerance assembly	22	40–45
	meter assembly test	23–24	60–63
	switchgear:		
	fuse and cut-out assembly	23	50
	capacitor winding	23	50
	paper storage	23	50
	conductor wrapping	24	65–70
	lightning arrestor	20	20–40
	circuit breaker: assembly and test	24	30–60
	rectifiers: process selenium and copper oxide plates	23	30–40
furs	drying	43	
	shock treatment	−8	
	storage	4–10	55–65
	cutting	comfort	
	vinyl-laminating room	13	15
leather	drying:		
	vegetable-tanned	21	75
	chrome-tanned	49	75
	storage	10–15	40–60
lenses (optical)	fusing	comfort	
	grinding	27	80
matches	manufacturing	22–23	50
	drying	21–24	40
	storage	15–17	50
munitions	metal percussion elements:		
	drying parts	88	
	drying paints	43	
	black-powder drying	52	
	condition and load powder-type fuse	21	40
	load tracer pellets	27	40
pharmaceutical	powder storage:		
	before manufacturing	21–27	30–35
	after manufacturing	24–27	15–35
	milling room	27	35
	tablet compressing	21–27	40
	tablet coating	27	35
	effervescent: tablet and powder	32	15
	hypodermic tablet	24–27	30
	colloids	21	30–50
	cough syrup	27	40
	glandular products	26–27	5–10
	ampule manufacturing	27	35
	gelatin capsule	78	40–50
	capsule storage	24	35–40
	microanalysis	comfort	
	biological manufacturing	27	35
	liver extract	21–27	20–30
	serums; animal room	comfort	
photo material	drying	−7 to 52	40–80

Table 1. *Continued*

Industry	Process	Dry-bulb temperature, °C	Rh, %
	cutting and packing	18–24	40–70
	storage: film base, film paper, coated paper	21–24	40–65
	safety film	15–27	45–50
	nitrate film	4–10	40–50
plastic	manufacturing:		
	thermosetting compounds	27	25–30
	cellophane	24–27	45–65
plywood	hot press: resin	32	60
	cold press	32	15–25
precision machining	spectrographic analysis	comfort	
gear matching and assembly storage:	24–27	35–40	
	gasket	38	50
	cement and glue	18	40
	machines:		
	gauging, assembly	comfort	
	adjusting precision	comfort	
	parts	comfort	
	honing	24–27	35–45
printing	multicolor lithographing:		
	pressroom	24–27	46–48
	stockroom	23–27	49–51
	sheet and web printing	comfort	
	storage, folding, etc	comfort	
refrigeration equipment	valve manufacturing	24	40
compressor assembly	21–24	30–45	
	refrigerator assembly	comfort	
	testing	18–28	47
rubber-dipped goods	manufacturing	32	
cementing	27	25–30	
	surgical articles	24–32	25–30
	storage before manufacturing	15–24	40–50
	laboratory (ASTM standard)	23	50
textiles	cotton:		
	opening, picking	21–24	55–70
	carding	28–30	50–55
	drawing and roving	27	55–60
	ring spinning:		
	conventional	27–29	60–70
	long-draft	27–29	
	frame spinning	27–29	55–60
	spooling, warping	26–27	60–65
	weaving	26–27	70–85
	cloth room	24	65–70
	combing	24	55–65
	linen:		
	carding, spinning	24–27	60
	weaving	27	80
	woolens:		
	picking	27–29	60
	carding	27–29	65–70

Table 1. ***Continued***

Industry	Process	Dry-bulb temperature, °C	Rh, %
	spinning	27–29	50–60
	dressing	24–27	60
	weaving:		
	light goods	27–29	55–70
	heavy goods	27–29	60–65
	drawing	24	50–60
	worsteds:		
	carding, combing, and gilling	27–29	60–70
	storage	21–29	75–80
	drawing	27–29	50–70
	cap spinning	27–29	50–55
	spooling, winding	24–27	55–60
	weaving	27	50–60
	finishing	24–27	60
	silk:		
	preparation and dressing	27	60–65
	weaving, spinning	27	65–70
	throwing	27	60
	rayon:		
	spinning	27–32	50–60
	throwing	27	55–60
	weaving:		
	regenerated	27	50–60
	acetate	27	55–60
	spun rayon	27	80
	picking	24–27	50–60
	carding, roving, drawing	27–32	50–60
	knitting: viscose or cuprammonium	27–29	65
	synthetic-fiber preparation and weaving:		
	viscose	27	60
	celanese	27	70
	nylon	27	50–60
tobacco	cigar and cigarette manufacturing	21–24	55–65
	softening	32	85–88
	stemming, stripping	24–29	75
	storage and preparation	26	70
	conditioning	24	75
	packing and shipping	24	60

[a] Listed conditions are typical; final design conditions are established by customer requirements.

Specific inside design conditions are required in industrial applications for one or more of the following reasons:

A constant temperature is required for close-tolerance measuring, gauging, machining, or grinding operations, to prevent expansion and contraction of machine parts, machined products, and measuring devices. In this instance a constant temperature is normally more important than the temperature level. Relative humidity is secondary in importance but should not go above 45% to minimize formation of a surface moisture film.

Some nonhygroscopic materials such as metals, glass, and plastics, have the ability to capture water molecules within microscopic surface crevices, thus forming an invisible, noncontinuous surface film. The density of the film increases as the relative humidity increases. Thus, relative humidity must be held below the critical point at which metals may etch or at which the electrical resistance of insulating materials is significantly decreased.

Where highly polished surfaces are manufactured or stored for short intervals between different phases of processing, relative humidity and temperature are both maintained constant to minimize surface moisture films. If these surfaces are shipped or stored for extended intervals, protective coverings or coatings may be required.

The temperature and humidity should be maintained at comfort conditions consistent with the operator's expected level of activity in order to minimize perspiration. Constant temperature and humidity may also be required in machine rooms to prevent the etching or corrosion of machine parts. If perspiration causes only minor damage to the product and results in few rejects, then inside design conditions at 27°C and 40% rh are satisfactory. Where even small amounts of perspiration cause extreme damage to precision-machined parts and result in a high amount of rejects, inside design conditions of 21°C and 40% rh are recommended.

Control of relative humidity is needed to maintain the strength, pliability, and moisture regain of hygroscopic materials such as textiles and paper. Humidity control may also be required in some applications to reduce the effect of static electricity. Temperature and/or relative humidity may also have to be controlled in order to regulate the rate of chemical or biochemical reactions, such as the drying of varnishes, the application of sugar coatings, the preparation of synthetic fibers and other chemical compounds, or the fermentation of yeast.

2.2. Human Comfort

ASHRAE has extensively researched the effect of air conditioning on human comfort. The more practical results are summarized below; reference 4 contains a complete discussion.

Thermal comfort may be defined as "that condition of mind in which satisfaction is expressed with the thermal environment" (4). It is thus defined by a statistically valid sample of people under very specific and controlled conditions. No single environment is satisfactory for everybody, even if all wear identical clothing and perform the same activity. The comfort zone specified in ASHRAE Standard 55 (5) is based on 90% acceptance, or 10% dissatisfied.

Recent experiments (4) have shown that there are no significant age or gender-related differences in thermal environment preference when all other factors such as weight of clothing and activity level are the same. Whereas people often accept thermal environments outside of their comfort range, there is no evidence that they adapt to these other conditions. Their environmental preference does not change. Similarly there is no evidence that there is any seasonal or circadian rhythm influence on a person's thermal preference.

Local areas of thermal discomfort, ie, one part of the body warmer or cooler than preferred, may cause a person to be uncomfortable when the overall temperature and humidity would normally produce a sensation of thermal comfort. Some causes of this are nonuniform thermal radiation, such as hot or cold windows, walls, panels, floors, and ceilings. Experiments show that people are more sensitive to the asymmetry caused by a warm overhead surface than by a cold vertical surface. However, the percentage of people dissatisfied begins to rise rapidly once the radiant surface temperature rises more than a few degrees above the air temperature. Comfort charts are normally based on an environment where the mean radiant temperature is the same as the air temperature. This means that if there are significant surfaces such as radiant ceilings or large windows outside the range of the air temperature, the conditions for comfort may have to be adjusted. Drafts, normally felt by the local cooling effect of the air moving past the body, are another cause of local thermal discomfort. They are one of the most annoying factors in offices and often result in complaints and demands for higher ambient temperatures. Drafts can come from improperly designed air distribution systems as well as from localized surfaces such as cold windows or walls.

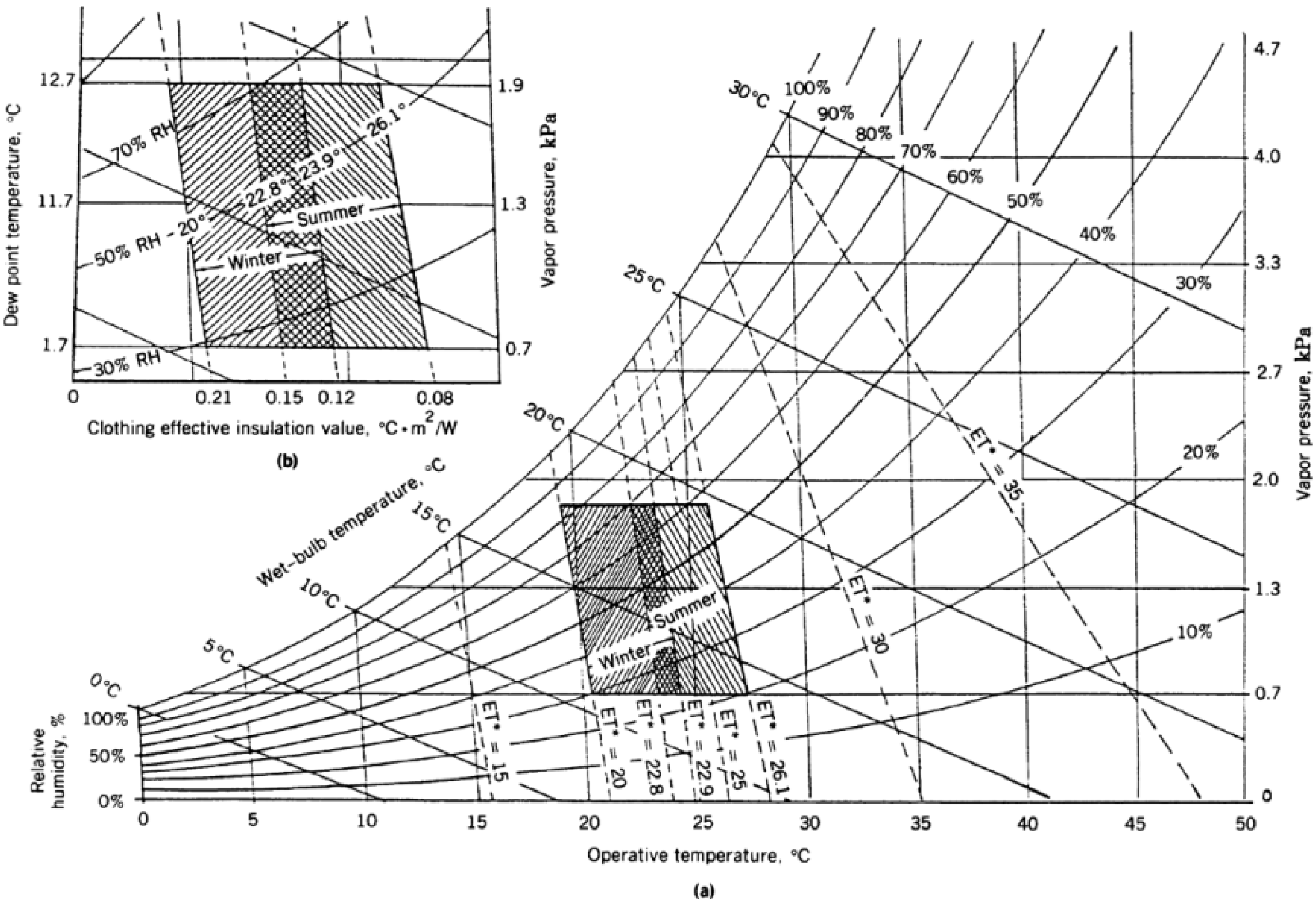

Fig. 3. Comfort zones at 6%of population predicted dissatisfied from ref. 4. RH lines are valid only when the air temperature equals the average temperature of the surfaces. (**a**) Operative temperature range where ET* is effective temperature as defined in text. (**b**) Comfort zone detail. To convert kPa to mm Hg, multiply by 7.5.

Figure 3 shows the winter and summer comfort zones plotted on the coordinates of the ASHRAE psychrometric chart. These zones should provide acceptable conditions for room occupants wearing typical indoor clothing who are at or near sedentary activity. Figure 3 applies generally to altitudes from sea level to 2150 m and to the common case for indoor thermal environments where the temperature of the surfaces (t_r) approximately equals air temperature (t_a) and the air velocity is less than 0.25 m/s. A wide range of environmental applications is covered by ASHRAE Comfort Standard 55 (5). Offices, homes, schools, shops, theaters, and many other applications are covered by this specification.

Effective temperature (ET*) is a single number representing those combinations of temperature and humidity which are equivalent in terms of comfort. It is defined as the dry-bulb temperature of the environment at 50% relative humidity. Standard effective temperature loci for normally clothed, sedentary persons are plotted on Figure 3. The sensation of comfort depends in part upon the wetness of one's skin. Thus, as a person becomes more active the effective temperature lines become more horizontal and the influence of relative humidity is more pronounced.

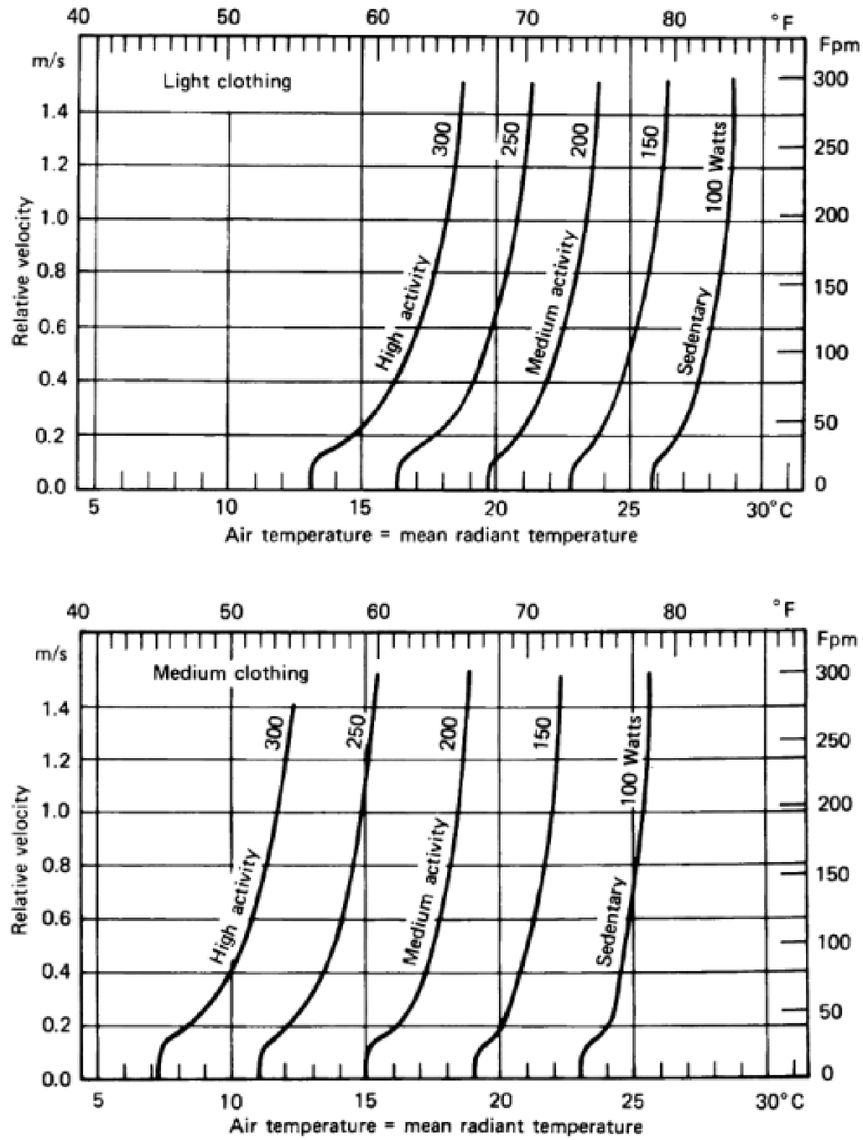

Fig. 4. Comfort lines, ambient air temperature equals mean radiant temperature (4). To convert watts to kcal/min, multiply by 0.143.

When air movement, clothing, or activity are not as specified in the definition of ET*, Figure 4, derived from an equation developed by Fanger (6), may be used. Knowledge of the energy expended during the course of routine physical activities is also necessary, since the production of body heat increases in proportion to exercise intensity. Table 2 presents probable metabolic rates (or the energy cost) for various activities. However, for higher activity levels, the values given could be in error by as much as 50%. Engineering calculations should allow for this. The activity level of most people is a combination of activities or work–rest periods. A weighted average metabolic rate is generally satisfactory, provided that activities alternate several times per hour.

Table 2. Metabolic Rate at Different Activities

Activity	Metabolic rate, W[a]
resting	
seated, quiet	100
standing, relaxed	120
walking	
on the level: 0.9 m/s (2 mph)	200
1.35 m/s (3 mph)	260
1.8 m/s (4 mph)	380
miscellaneous occupations	
bakery, eg, cleaning tins, packing boxes	140–200
brewery, eg, filling bottles, loading beer boxes onto belt	120–240
foundry work	
using a pneumatic hammer	300–340
tending furnaces	500–700
general laboratory work	140–180
machine work	
light, eg, electrical industry	200–240
heavy, eg, steel work	350–450
shop assistant	200
teacher	160
vehicle driving	
car	150
heavy vehicle	320
domestic work	
house cleaning	200–340
cooking	160–200
washing by hand and ironing	200–360
office work	
typing	120–140
miscellaneous office work	110–130
drafting	110–130
leisure activities	
calisthenics exercise	300–400
dancing, social	240–440
tennis, singles	360–460
squash, singles	500–720
golf, swinging and walking	140–260
golf, swinging and golf cart	140–180

[a] Ranges are given for those activities which may vary considerably from one place of work or leisure to another, or when performed by different people. Some occupational and leisure time activities are difficult to evaluate because of differences in exercise intensity and body position. To convert W to kcal/h, divide by 1.162.

2.3. Equipment Size Requirements

Determining the proper size of air conditioning and heating equipment requires detailed study and calculation. A comprehensive statement of requirements and allowable variations must be supplied so that the best comfort conditioning system choice can be made. With such information it is possible to estimate not only equipment size, but also yearly energy requirements using any of several comprehensive computer (7) or manual methods. Different systems can be designed and compared to ensure that the owner has a cost-effective yet energy-efficient system.

An analysis of the building structure must be conducted to determine the effects of heat gain from the sun. This analysis includes building orientation, type of construction, surrounding vegetation and structures, and reflective surfaces. People, lighting, machinery loads, and heat gains from chemical processes are evaluated as well as hooded (ventilated) processes, and lengths of operation. Outdoor air required both for ventilation to remove odors and contaminants, and for replacement of air exhausted through hoods must be conditioned. ASHRAE Standard 62 (8) provides recommendations for minimum outdoor air requirements; local codes should be investigated. A building often requires cooling at low outdoor temperatures as a result of high internal heat gains. Interior portions of many buildings require cooling during occupied hours throughout the year. The use of outdoor air, when its temperature and dew point are suitable (economizer cycle), is an efficient means of air conditioning. Care must be taken, however, in applying economizer cycles to areas where close humidity control is required because additional humidification or dehumidification may be needed.

The following information is customarily required for thorough design of new air conditioning systems or renovation of existing systems.

3. Air Conditioning and Humidification Systems

Air conditioning may involve heating or cooling air, humidifying or drying it, and the control of chemical impurities to maintain the desired space conditions. Proper controls and energy conserving practices are also important to air conditioning and humidification.

3.1. Typical Air Conditioning Systems

Two broad categories of air conditioning systems exist, unitary and applied. Unitary systems are self-contained units that are “off the shelf.” They use electricity for cooling, and may use electricity, natural gas, fuel oil, or propane for heating. Heat rejected during the cooling cycle is dissipated to the outdoors. Multiple unitary systems may be employed to provide greater overall reliability and to permit individual control of various sections of a plant. A typical unit for rooftop mounting is shown in Figure 5. It contains means for heating, ventilating, and cooling.

More flexibility is obtained with applied equipment (Fig. 6), which is normally used to condition a relatively large area of a plant. This is usually part of a “field erected” system. In applied systems, outdoor air for ventilation or cooling (economizer cycle) is drawn through a preconditioning or preheat coil and mixed with air returned from the conditioned space. Dampers regulate the relative amounts of outdoor and recycled air for temperature control. The air is filtered before passing into the conditioning section which contains cooling and dehumidifying coils, air washers for humidity control, and heating coils. Bypass of return air may be included for temperature control. The refrigerating effect is provided in one of several ways. Well water may be employed if available in sufficient quality and quantity and at a suitable temperature. More commonly, refrigerating machines or “chillers” are used. In small systems, reciprocating compressors are employed and the refrigerant may be directly admitted to the cooling coil. In larger applications, water is chilled and circulated through the central station unit. For applications in excess of 350 kW (1.2×10^6 Btu/h), reciprocating compressors may be replaced by centrifugal systems. Most systems are electrically powered; however, steam or gas turbines are used occasionally. Absorption chillers are frequently used when a suitable supply of “waste” heat is available. Low pressure steam, hot water, and process streams may provide the motive force. Solar heated water is also finding application (9) (see Solar energy).

3.2. Humidification

For winter operation, or for special process requirements, humidification may be required (see Simultaneous heat and mass transfer). Humidification can be effected by an air washer which employs direct water sprays (see Evaporation). Regulation is maintained by cycling the water sprays or by temperature control of the air

- Temperature and/or humidity to be maintained
  - Allowable seasonal variations
  - Permissible control tolerance
- Outdoor conditions to be assumed for design extremes under which the plant must operate
- Architectural plans and details of building construction (if original plans are not available, the building must be measured carefully and details of construc-tion must be determined by inspection)
  - Orientation of the building
  - Neighboring structures
  - Special zoning requirements based on load concentrations, and differences in conditions required for various processes
  - Glass areas
    - Type of glass
    - Shading devices
    - Reveals and overhangs
- Sensible heat gains
  - Power equipment
    - Usage factor
    - Percent loaded
    - Hours used
    - Rated power requirement
  - Lighting
    - Usage factor
    - Hours used
    - Auxiliaries
    - Rated power requirement
  - Miscellaneous, eg, ovens, exposed steam pipes, use of exhaust hoods
  - Temperature of product entering space
    - Product temperature above space temperature (resulting in a heat gain to the space)
    - Product temperature below space temperature (producing a credit to sensible-heat gain or a heating requirement)
- Latent heat gains
  - Evaporation from wet surfaces due to process
  - Migration of water vapor through building materials (especially important in low dew-point application)
  - Water vapor from moist product
- Sensible and latent heat gains
  - People
    - Degree of activity
    - Time of occupancy
    - Number
  - Gas burning equipment
    - Usage factor
    - Heating value of gas
    - Use of hoods
  - Equipment of evaporating water
    - Usage factor
    - Capacity
    - Energy required to operate
  - Chemical and biological reactions
  - Infiltration of air
    - Frequency of door opening
    - Window cracks
    - Porosity of building structure
  - Steam or water released

- Ventilation air
  - For human occupancy
  - Toxic fume and smoke dilution
  - Odor dilution
  - Offsetting exhaust hood requirements
- Energy sources
  - Availability and cost
  - Options
- Heat recovery possibilities
  - Process streams
  - Ventilation
  - Equipment
  - Lighting
  - Air conditioning system
  - Refuse

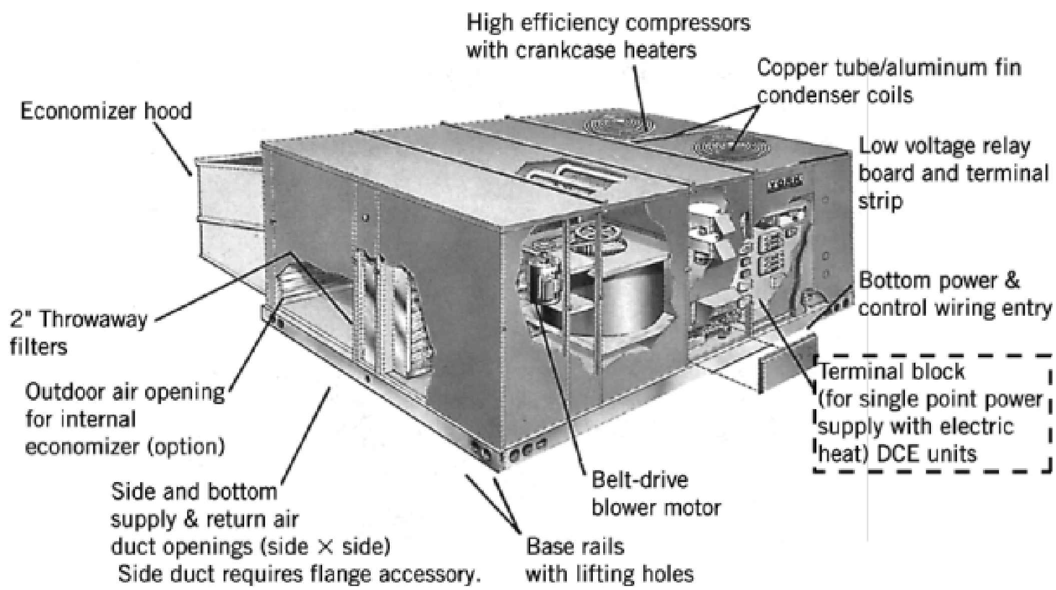

Fig. 5. Rooftop unitary system.(Courtesy of York International Corporation.)

or water. Where a large humidification capacity is required, an ejector which directly mixes air and water in a nozzle may be employed. Steam may be used to power the nozzle. Live low pressure steam can also be released directly into the air stream. Capillary-type humidifiers employ wetted porous media to provide extended air and water contact. Pan-type humidifiers are employed where the required capacity is small. A water filled pan is located on one side of the air duct. The water is heated electrically or by steam. The use of steam, however, necessitates additional boiler feed water treatment and may add odors to the air stream. Direct use of steam for humidification also requires careful attention to indoor air quality.

3.3. Dehumidification

Dehumidification may be accomplished in several ways (see Drying). Moderate changes in humidity can be made by exposing the air stream to a surface whose temperature is below the dew point of the air. The air is cooled

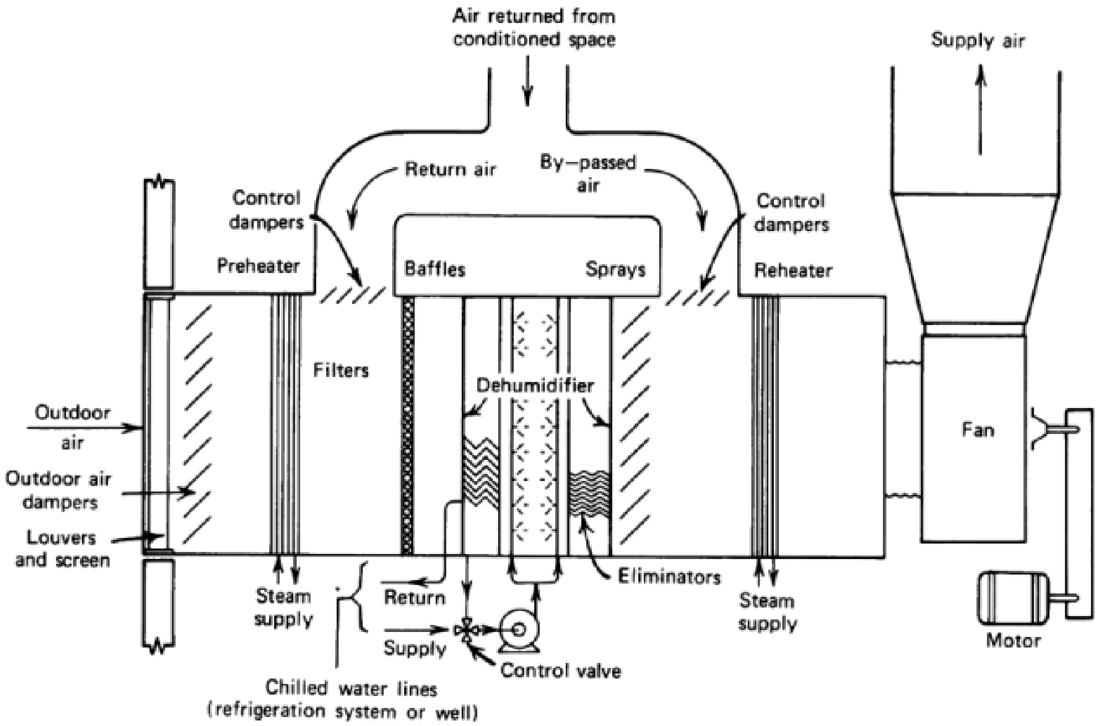

Fig. 6. Diagram of applied system.

and releases a portion of its moisture. Closed cycle air conditioning systems normally effect dehumidification also. The cooled air may require reheating to attain the desired dry-bulb temperature if there is insufficient sensible load in the space.

Another method of moderate dehumidification is by direct contact between the air and cold water using open circuit equipment. An air washer or capillary humidifier maintaining the water at a cold temperature is an example.

Some industrial processes produce predominately latent air conditioning loads. Others dictate very low humidities and when the dew point falls below 0°C, freezing becomes a major concern. Dehydration equipment, using solid sorbents such as silica gel and activated alumina, or liquid sorbents such as lithium chloride brine and triethylene glycol, may be used. The process is exothermic and may require cooling the exiting air stream to meet space requirements. Heat is also required for reactivation of the sorbent material.

Solid sorbent materials have the ability to adsorb water vapor until an equilibrium condition is attained. The total weight of water that can be adsorbed in a particular material is a function of the temperature of the material and of the relative humidity of the air (see Adsorption). To regenerate the sorbent, its temperature must be raised or the relative humidity lowered. The solid sorbents most commonly used are silica (qv), alumina (see Aluminum compounds), and molecular sieves (qv).

Liquid sorbent materials in aqueous solutions reduce the vapor pressure relative to that of pure water. Such a solution, if of proper strength, causes moisture to condense from the air even though the solution temperature is above the dew point of the air. Brines such as calcium chloride, lithium chloride, lithium bromide, and calcium bromide may be used singly or in combination. They are generally somewhat corrosive in nature. Triethylene glycol, and to a lesser extent diethylene glycol and ethylene glycol, are also used (see Glycols). Brines should not have a solidification curve too near the working range; they must be odorless, relatively noncorrosive, chemically stable, and reasonable in cost. The most serious hazards of application are corrosion and carry-over from equipment into the room. Regeneration of the brine is generally accomplished by boiling the excess water out of the brine and exhausting it to another air stream. The solution is then recooled to a temperature suitable for dehumidification. Equipment is available to make this process continuous.

3.4. Chemical Neutralization

Spray-type air washers are used extensively for removal or neutralization of noxious components from large volumes of air, particularly exhaust air streams. Appropriate reagents are sprayed into the washer to purify the air by neutralization, eg, sodium hydroxide solution is used if the air contains acidic gases. The solution must be continuously reconcentrated and any precipitated salts removed. The contact efficiency of such washers is high, and the simple construction provides easy maintenance and constant efficiency (see Air pollution control methods).

3.5. Evaporative Cooling

Evaporative air cooling equipment deposits water directly into the air stream through evaporation (see Heat exchange technology, heat transfer; Simultaneous heat and mass transfer). These systems are employed where the application has a high sensible heat load and requires final design relative humidities of 50% or greater, or where the entering air's relative humidity is very low. Evaporative cooling and humidification are often accomplished by the same equipment, depending on the relative temperatures of the air and water.

There are several basic types of evaporative cooling devices. Among them are spray air washers, cell washers, and wetted media air coolers. Intimate contact between the spray water and the flowing air causes heat and mass transfer between the air and the water. Cell washers obtain intimate air–water contact by passing the air through cells packed with glass, metal, or fiber screens. Wetted media coolers contain evaporative pads, made usually of aspen wood fibers, and a water circulating pump to lift the sump water to a distributing system from which it runs down through the pads and back into the sump. Washers are commonly available from 1 to 118 m^3/s (2000–250,000 ft^3/min) capacity depending on the type; however, there is no limit to sizes that can be constructed. Air velocity, air dry-bulb, air wet-bulb, water spray density, spray pressure, and other design factors must be considered for each application.

Continued satisfactory performance of any evaporative cooling device depends largely on a regular cleaning and inspection schedule. The frequency of this maintenance varies with operating conditions; however, a weekly inspection is common practice. A spray system requires the most attention: partially clogged nozzles are indicated by a rise in spray pressure; eroded orifices by a fall in pressure. Strainers can minimize these problems. For continuous operation a bypass around the strainer or duplex strainers is required. Air washer tanks should be drained and dirt deposits removed at regular intervals. Eliminators and baffles should be inspected periodically and repainted to prevent damage by corrosion. A small amount of water, depending on the hardness of the makeup water, should be bled-off to maintain an acceptable concentration of solids according to recommendations of a water treatment specialist (see Water, industrial water treatment). In the case of cell-type washers, a differential pressure gage to measure the air flow resistance across the cells can be used to determine the need to clean the media. In all washers, proper water treatment must be maintained to prevent the growth of bacteria, fungi, and other microorganisms.

3.6. Air Conditioning Control

When sized to meet design conditions, a heating or cooling system normally operates over a wide range of temperatures and loads; thus proper control becomes important. Controls may range from a single thermostat to complex computer systems. The general references provide several texts on these subjects. The system must be adjusted and maintained in order to provide operation for many years. The simplest control system which will produce the necessary results is best. The design professional should have the information noted in the sections on air conditioning equipment requirements for all anticipated operating conditions. For energy efficiency the specifications should contain wide tolerances.

3.7. Energy Conservation

The design of systems that conserve energy requires knowledge of the building, its operating schedule, and the systems to be installed (see Energy management). The following approaches lead to reduced energy consumption:

3.7.1. Use Equipment Only When Needed

Start morning warm-up no earlier than necessary and do not use outside air for ventilation until the building is occupied. Use minimum amounts of outdoor air according to reference 8. Supply heat at night only to maintain a temperature above 13°C.

3.7.2. Supply Heating and Cooling from the Most Efficient Source

3.7.2.1. Sequence Heating and Cooling. Do not supply both at the same time. The zoning and system selection should eliminate or at least minimize simultaneous heating and cooling.

3.7.2.2. Provide Only the Heating or Cooling Actually Needed. Generally, the supply temperature of hot and cold air, or water, should be reset according to actual need. This is especially important on systems or zones that allow simultaneous heating and cooling.

4. Uses of Air Conditioning in Industry

Many industrial processes require accurate environmental control. Examples include: chemical reactions and processes that are affected by atmospheric conditions; biochemical reactions; quality, uniformity, and standardization of certain products; factors such as rate of crystallization and size of crystals; product moisture content or regain; deliquescence, lumping, and caking of hygroscopic materials; expansion and contraction of machines and products; physical, chemical, and biological cleanliness; effects of static electricity; odors and fumes; conditions in storage and packaging; quality of painted and lacquered finishes; simulation of stratosphere or space conditions; and productivity and comfort of workers. Controlled atmospheric conditions are especially important to the textile, pharmaceutical, food processing, explosives, and photographic materials industries. Analytical laboratories, clean rooms, and computer control rooms also require air conditioned environments.

4.1. Synthetic Fibers

In the synthetic textile industry, air conditioning is used to achieve uniform quality and viscosity for spinning; to control the rate of reaction and coagulation; to control toxic fumes and evaporation from acid baths; to prevent stretching during the winding of wet threads; to control regain; and to prevent crystal formation on threads and machines. Because of toxic fumes in some rayon processes, air conditioning with a large amount of outdoor air and extensive exhaust is a hygienic necessity. In the mechanical handling of the finished synthetic yarns, in throwing, weaving, and knitting operations, air conditioning is necessary for quality and production control (see Textiles).

4.2. Pharmaceuticals and Biologicals

Air conditioning is an important processing requirement in the production of many pharmaceutical materials, as in the manufacture of pills and capsules and in the packaging of the finished product to maintain constancy in formula, quality, and dosage. It helps to achieve constant production rates, cleanliness, and purity of product; to prevent lumping, caking, and sticking; to reduce diffusion of material into the air; to remove noxious fumes and gases; and to produce the desired polish on coated pills (see Pharmaceuticals).

4.3. Rubber

In the rubber industry, air conditioning provides uniform performance in drying and shortens the drying period, controls oxidation, eliminates blisters in dipping operations, preserves tensile strength, minimizes explosion hazards from static electricity, and reduces the concentration of toxic fumes (see Rubber compounding).

4.4. Photographic Materials

Air conditioning is an essential element in the processing of photographic materials to control the moisture regain of film and minimize static discharge, thus reducing fire hazard and preventing fogging and streaking. Air conditioning assures dust-free air and provides ideal conditions for packaging and storage, thereby reducing production losses. Careful control of temperature, humidity, cleanliness, and ventilation is practical and essential (see Photography).

4.5. Explosives

The munitions industry employs air conditioning to control uniformity in the manufacture and loading of various explosive mixtures, to control drying and moisture content, to minimize static discharges, to reduce the hazards of fire and explosion, to remove and neutralize toxic fumes, to remove and recover dust or solvents from manufacturing or loading processes, and to provide proper atmospheric conditions for the storage of raw materials or finished product (see Explosives).

4.6. Breweries

Air conditioning and the extensive use of refrigeration are necessary to provide controlled temperature in wort cooling, fermentation, storage, and final packaging of the finished beer. Sanitation and removal of carbon dioxide are important aspects of this application (see Beer).

4.7. Food Processing

Air conditioning, including drying and freezing, has many applications in food processing. Examples are food dehydration, blast freezing, smoke houses, storage facilities, canned and dried foods, frozen foods, meat-packing, chewing gum manufacturing, concentrated fruit juices, and hard and chocolate candy (see Food processing).

4.8. Metal Industry

Air Air conditioning plays an important part in cupola and blast furnaces and in Bessemer converters. It is used to supply air of proper moisture content and to increase worker comfort, eg, in crane cabs, pulpits, or other individual “hot” operating spots. This is accomplished by individual or group spot-cooling. For powder metallurgy, a low temperature is needed in metal fitting and humidity control is required in metal finishing to eliminate perspiration stains, etching, and rust (see Metal treatments; Metallurgy, powder metallurgy).

4.9. Ceramics

The drying of ceramic products before firing is controlled by air conditioning to standardize form and dimension, establish uniform drying at a controlled rate, and prevent strains that may otherwise cause cracking and crazing during firing (see Ceramics).

4.10. Laboratories

A wide range of temperatures from -110 to $120°C$, humidities from 5 to 95%, pressures from near vacuum to many atmospheres, as well as other special ambient conditions, are not unusual for test chambers and in some instances even for complete laboratories. Requirements may be either to maintain constant conditions or to alternate high and low temperatures in conjunction with high and low humidities. Test facilities may be designed to test specifications and standards of materials and products as well as to determine environmental standards. Simulation of conditions outside the earth's atmosphere is required for testing aerospace vehicles, eg, the radiation of the sun is approximated by banks of high energy lamps on one wall; other surfaces are maintained at a temperature of $-180°C$ or below to simulate the coldness of space.

5. Economic Evaluation of Air Conditioning Systems

The total economic picture, including life cycle costs and energy expenditures, must be considered in selecting an efficient air conditioning system. For many systems, the ratio of annual energy usage to first cost ranges from 0.25 to 2. Thus, over its useful life, a system consumes many times its initial costs.

Comparing two or more complex alternatives is more difficult than examining equipment capacity or first cost. Characteristics of alternatives should be weighted for relative importance and measured on a common scale to allow proper evaluation. Many characteristics such as first cost, capacity, space requirement, and annual energy use can be measured objectively and used for system comparisons. Experience has shown that items such as maintenance expense, component life, and downtime can also be reliably estimated. Other factors, eg, system maintainability, flexibility, and comfort, are more arbitrary.

Life cycle cost analysis is the proper tool for evaluation of alternative systems (11, 12). The total cost of a system, including energy cost, maintenance cost, interest, cash flow, equipment replacement and/or salvage value, taxes, inflation, and energy cost escalation, can be estimated over the useful life of each alternative system. A list of life cycle cost items which may be considered for each system is presented in Tables 3 and 4. Reference 14 presents a cash flow analysis which also includes factors such as energy cost escalation.

Table 3. Owning and Operating Cost Data and Summary[a]

Owning costs	
Initial cost of system (amortized)	*Amortization factors*
equipment[b]	amortization period n (number of years during which initial cost is to be recovered)
control systems–complete	
wiring and piping costs attributable to system	
	interest rate, i
any increase in building construction cost attributable to system	capital recovery factor
equivalent uniform annual cost	
any decrease in building construction cost attributable to system	
Annual fixed charges	
installation costs	income taxes
miscellaneous	property taxes
	insurance
	rent

Table 3. ***Continued***

Owning costs	
Initial cost of system (amortized)	*Amortization factors*
	Total annual fixed charges
Operating costs	
Annual energy and fuel costs	ventilation
electric energy costs	preheaters
chiller or compressor	reheaters
pumps	supplementary heating (ie, oil preheating)
chilled water	
heating water	other
condenser or tower water	domestic water heating
well water	cooking and food service equipment
boiler auxiliaries (including fuel oil heaters)	air conditioning
absorption	
fans	chiller or compressor
condenser or tower	gas and diesel engine driven
inside air handling	gas turbine driven
exhaust	steam turbine driven
make-up air	miscellaneous
boiler auxiliaries and equipment room ventilation	water
condenser make-up water	
resistance heaters (primary or supplementary)	sewer charges
chemicals	
heat pump	miscellaneous
domestic water heating	*Total annual fuel and energy costs*
lighting	
cooking and food service equipment	*Wages of engineers and operators*
miscellaneous (elevators, escalators, computers, etc)	*Annual maintenance allowances*
replacement or servicing of oil, air, or water filters	
gas, oil, coal, or purchased steam costs on-site generation of the	
contracted maintenance service	
electrical power requirements	lubricating oil and grease
under electric energy costs	general housekeeping costs
heating	replacement of worn parts (labor and material)
direct heating	
	refrigerant
	Total annual maintenance allowance
Summary	
equivalent uniform annual cost	
total annual fixed charges	
total annual fuel and energy costs	
wages of engineers and operators	
total annual maintenance allowance	
Total Annual Owning and Operating Costs.	

[a] Ref. 13.
[b] See Table 4.

Table 4. Initial Costs[a]

energy and fuel service costs	cooling distribution equipment
fuel service, storage, handling, piping, and distribution costs	pumps, piping, piping insulation, condensate drains, etc
electrical service entrance and distribution equipment costs	terminal units, mixing boxes, diffusers, grilles, etc
total energy plant	air treatment and distribution equipment
heat producing equipment	air heaters, humidifiers, dehumidifiers, filters, etc
boilers and furnaces	
steam–water converters	fans, ducts, duct insulation, dampers, etc
heat pumps or resistance heaters	
make-up heaters	exhaust and return systems
heat producing equipment auxiliaries	system and controls automation
refrigeration equipment	terminal or zone controls
compressors, chillers, or absorption units	system program control
alarms and indicator system	
cooling towers, condensers, well water supplies	building construction and alteration
mechanical and electric space	
refrigeration equipment auxiliaries	chimneys and flues
heat distribution equipment	building insulation
pumps, reducing valves, piping, piping insulation, etc	solar radiation controls
acoustical and vibration treatment	
terminal units or devices	distribution shafts, machinery foundations, furring

[a] Ref. 13.

BIBLIOGRAPHY

"Air Conditioning" in *ECT* 1st ed., Vol. 1, pp. 238–252, by L. Macrow and U. A. Bowman, Carrier Corporation; in *ECT* 2nd ed., Vol. 1, pp. 481–501, by R. Elsea and R. C. Terwilliger, Jr., Carrier Corporation; in *ECT* 3rd ed., Vol. 1, pp. 598–624, by K. W. Cooper and R. A. Erth, York Division, Borg-Warner Corporation.

Cited Publications

1. *ASHRAE Handbooks*, American Society of Heating, Refrigeration, and Air Conditioning Engineers, Inc., Publications Department, Atlanta, Ga. four vols.: *Fundamentals, Equipment, Systems and Applications*, and *Refrigeration*. One volume is revised each year.
2. F. C. McQuiston and J. D. Parker, *Heating, Ventilating and Air Conditioning*, 3rd ed., John Wiley & Sons, Inc., New York, 1988.
3. W. F. Stoecker, *Using SI units in Heating, Air Conditioning, and Refrigeration*, rev. ed., Business News Publishing Co., 1976.
4. Ref. 1, *Fundamentals*, 1989, Chapter 8.
5. *ASHRAE Standards*, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc., Publications Department, Atlanta, Ga. Standard 55, 1981. Standards are upgraded on a regular basis.
6. Ref. 1, *Fundamentals*, 1989, p. 8.17.
7. *A Bibliography of Available Computer Programs in the Area of Heating, Ventilating, Air Conditioning and Refrigeration*, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc., 1986.
8. Ref. 5, Standard 62.
9. A. B. Newton, *ASHRAE J.* **34** (Feb. 1975).
10. Ref. 1, *Equipment*, 1988.
11. R. T. Ruegg, *Life-Cycle Cost Manual for the Federal Energy Management Program*, U.S. Department of Energy Federal Energy Management program, NTIS-PR-360, May 1982.
12. R. T. Ruegg and S. R. Petersen, *Comprehensive Guide for Least-cost Energy Decisions*, NBS Special Publication 709, January 1987.
13. Ref. 1, *Systems and Applications*, 1987.

14. Ref. 1, *Systems and Applications*, Chapt. 49, 1987.

General References

15. *ASHRAE Journal* (monthly) and *ASHRAE Transactions* (semiannually) American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, Ga.
16. *ASHRAE Transactions* (semiannually)
17. *Heating/Piping/Air Conditioning*, (monthly) Penton Publications, Inc., Cleveland, Ohio.
18. R. W. Haines, *HVAC System Design Handbook*, TAB Books, Blue Ridge Summit, Pa., 1988.
19. B. C. Langley, *Control Systems for Air Conditioning and Refrigeration*, Prentice Hall, Englewood Cliffs, N.J. 1985.
20. G. W. Gupton Jr., *HVAC Controls, Operation and Maintenance*, Fairmont Press, Lilburn, Ga., 1987.
21. R. W. Haines, *Control Systems for Heating, Ventilating and Air Conditioning*, Van Nostrand-Reinhold, New York, 4th ed., 1987.

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Evaporation; Beer; Textiles; Pharmaceuticals; Photography; Explosives; Food processing; Metal treatments; Metallurgy powder; Ceramics