CHAPTER 12

INDUSTRIAL AIR CONDITIONING

INDUSTRIAL facilities such as manufacturing plants, laboratories, data processing rooms, and nuclear power plants are designed for processes and environmental conditions that include proper temperature, humidity, air motion, air quality, and cleanliness. Generated airborne contaminants must be collected and treated before being discharged from the building or recirculated.

Many industrial buildings require large quantities of energy, both in manufacturing and maintaining building environmental conditions. Energy can be saved by proper use of insulation and ventilation, and by recovery of waste heat.

For worker efficiency, the building environment should be comfortable and healthful, and should minimize fatigue and facilitate communications. The HVAC systems should control temperature and humidity, have low noise levels, control health-threatening fumes, and provide spot cooling to prevent heat stress.

GENERAL REQUIREMENTS

Typical temperatures, relative humidities, and specific filtration requirements for storage, manufacture, and processing of various commodities are listed in Table 1. Requirements for a specific application may differ from those in the table. Improvements in processes and increased knowledge may cause further variations; thus, systems should be flexible to accommodate future requirements.

Inside temperature, humidity, cleanliness, and allowable variations should be established by agreement with the owner. A compromise between the requirements for product or process conditions and those for comfort may optimize quality and production costs.

An environment that allows a worker to perform assigned duties without fatigue from the effects of temperature and humidity results in better continuous performance. It may also improve morale and reduce absenteeism.

PROCESS AND PRODUCT REQUIREMENTS

A product or process may require control of one or more of the following factors.

Rate of Chemical Reaction

Some processes require temperature and humidity control to regulate chemical reactions. In rayon manufacturing, for example, pulp sheets are conditioned, cut to size, and mercerized. The temperature directly controls the rate of reaction, and the relative humidity maintains the solution at a constant strength and rate of evaporation.

In drying varnish, oxidizing depends on temperature. Desirable temperatures vary with the type of varnish. High relative humidity retards surface oxidation and allows internal gases to escape as chemical oxidizers cure the varnish from within. Thus, a bubble-free surface is maintained with a homogeneous film throughout.

Rate of Crystallization

The cooling rate determines the size of crystals formed from a saturated solution. Both temperature and relative humidity affect the cooling rate and change the solution density by evaporation.

In coating pans for pills, a heavy sugar solution is added to the tumbling mass. As water evaporates, sugar crystals cover each pill. Moving the correct quantity of air over the pills at the correct temperature and relative humidity forms a smooth opaque coating. If cooling and drying are too slow, the coating will be rough, translucent, and have an unsatisfactory appearance. If the cooling and drying are too fast, the coating will chip through to the interior.

Rate of Biochemical Reaction

Fermentation requires both temperature and humidity control to regulate the rate of biochemical reactions. Many fermentation vessels are jacketed to maintain consistent internal temperatures. Fermentors are held at different temperatures depending on the process involved. In brewing, typical fermentor temperatures range from 7 to 11°C. Because of vessel jacketing, tight control of room temperature may not be required. Usually, space temperatures should be held as close as practical to the process temperature inside the fermentation vessel.

Designing such spaces should take into account gases and other by-products generated by fermentation. Typically, carbon dioxide is the most prevalent by-product of fermentation in brewing and presents the greatest potential hazard if a fermentor overpressurizes the seal. Adequate ventilation should be provided in case carbon dioxide escapes the process.

In biopharmaceutical processes, hazardous organisms can escape a fermentor; design of spaces using those fermentors should allow containment. Heat gains from steam-sparged vessels should also be accounted for in such spaces.

Product Accuracy and Uniformity

Air temperature and cleanliness affect quality in manufacturing precision instruments, lenses, and tools. When manufacturing tolerances are within 5 μm, close temperature control prevents expansion and contraction of the material; constant temperature is more important than the temperature level. Usually, conditions are selected for personnel comfort and to prevent a film of moisture on the surface. A high-efficiency particulate air (HEPA) or ultralow-penetration air (ULPA) filter may be required.

Product Formability

Manufacturing pharmaceutical tablets requires close control of humidity for optimum tablet formation.

Moisture Regain

Air temperature and relative humidity markedly influence production rate and product mass, strength, appearance, and quality in manufacturing or processing hygroscopic materials such as textiles,

The preparation of this chapter is assigned to TC 9.2, Industrial Air Conditioning.

Table 1 Temperatures and Humidities for Industrial Air Conditioning

Process	Dry Bulb, °C	rh, %
ABRASIVE		
Manufacture	26	50
CERAMICS		
Refractory	43 to 66	50 to 90
Molding room	27	60 to 70
Clay storage	16 to 27	35 to 65
Decalcomania production	24 to 27	48
Decorating room	24 to 27	48

Use high-efficiency filtration in decorating room. To minimize the danger of silicosis in other areas, a dust-collecting system or medium-efficiency particulate air filtration may be required.

Process	Dry Bulb, °C	rh, %
DISTILLING		
General manufacturing	16 to 24	45 to 60
Aging	18 to 22	50 to 60

Low humidity and dust control are important where grains are ground. Use high-efficiency filtration for all areas to prevent mold spore and bacteria growth. Use ultrahigh-efficiency filtration where bulk flash pasteurization is performed.

Process	Dry Bulb, °C	rh, %
ELECTRICAL PRODUCTS		
Electronics and X-ray		
Coil and transformer winding	22	15
Semiconductor assembly	20	40 to 50
Electrical instruments		
Manufacture and laboratory	21	50 to 55
Thermostat assembly and calibration	24	50 to 55
Humidistat assembly and calibration	24	50 to 55
Small mechanisms		
Close tolerance assembly	22*	40 to 45
Meter assembly and test	24	60 to 63
Switchgear		
Fuse and cutout assembly	23	50
Capacitor winding	23	50
Paper storage	23	50
Conductor wrapping with yarn	24	65 to 70
Lightning arrester assembly	20	20 to 40
Thermal circuit breakers assembly and test	24	30 to 60
High-voltage transformer repair	26	5
Water wheel generators		
Thrust runner lapping	21	30 to 50
Rectifiers		
Processing selenium and copper oxide plates	23	30 to 40

*Temperature to be held constant.

Dust control is essential in these processes. Minimum control requires medium-efficiency filters. Degree of filtration depends on the type of function in the area. Smaller tolerances and miniature components suggest high-efficiency particulate air (HEPA) filters.

Process	Dry Bulb, °C	rh, %
FLOOR COVERING		
Linoleum		
Mechanical oxidizing of linseed oil*	32 to 38	
Printing	27	
Stoving process	70 to 120	

*Precise temperature control required.

Medium-efficiency particulate air filtration is recommended for the stoving process.

Process	Dry Bulb, °C	rh, %
FOUNDRIES*		
Core making	16 to 21	
Mold making		
Bench work	16 to 21	
Floor work	13 to 18	
Pouring	4	
Shakeout	4 to 10	
Cleaning room	13 to 18	

*Winter dressing room temperatures. Spot coolers are sometimes used in larger installations.

In mold making, provide exhaust hoods at transfer points with wet-collector dust removal system. Use 280 to 380 L/s per hood.

In shakeout room, provide exhaust hoods with wet-collector dust removal system. Exhaust 190 to 240 L/s in grate area. Room ventilators are generally not effective.

In cleaning room, provide exhaust hoods for grinders and cleaning equipment with dry cyclones or bag-type collectors. In core making, oven and adjacent cooling areas require fume exhaust hoods. Pouring rooms require two-speed powered roof ventilators. Design for minimum of 10 L/s of floor area at low speed. Shielding is required to control radiation from hot surfaces. Proper introduction of air minimizes preheat requirements.

Process	Dry Bulb, °C	rh, %
FUR		
Drying	43	
Shock treatment	−8 to −7	
Storage	4 to 10	55 to 65

Shock treatment or eradication of any insect infestations requires lowering the temperature to −8 to −7°C for 3 to 4 days, then raising it to 16 to 21°C for 2 days, then lowering it again for 2 days and raising it to the storage temperature.

Furs remain pliable, oxidation is reduced, and color and luster are preserved when stored at 4 to 10°C.

Humidity control is required to prevent mold growth (which is prevalent with humidities above 80%) and hair splitting (which is common with humidities lower than 55%).

Process	Dry Bulb, °C	rh, %
GUM		
Manufacturing	25	33
Rolling	20	63
Stripping	22	53
Breaking	23	47
Wrapping	23	58

Process	Dry Bulb, °C	rh, %
LEATHER		
Drying	20 to 52	75
Storage, winter room temperature	10 to 16	40 to 60

After leather is moistened in preparation for rolling and stretching, it is placed in an atmosphere of room temperature and 95% relative humidity.

Leather is usually stored in warehouses without temperature and humidity control. However, it is necessary to keep humidity sufficiently low to prevent mildew. Medium-efficiency particulate air filtration is recommended for fine finish.

Process	Dry Bulb, °C	rh, %
LENSES (OPTICAL)		
Fusing	24	45
Grinding	27	80

Table 1 Temperatures and Humidities for Industrial Air Conditioning (*Continued*)

Process	Dry Bulb, °C	rh, %
MATCHES		
Manufacture	22 to 23	50
Drying	21 to 24	60
Storage	16 to 17	50

Water evaporates with the setting of the glue. The amount of water evaporated is 8 to 9 kg per million matches. The match machine turns out about 750,000 matches per hour.

Process	Dry Bulb, °C	rh, %
PAINT APPLICATION		
Lacquers: Baking	150 to 180	
Oil paints: Paint spraying	16 to 32	80

The required air filtration efficiency depends on the painting process. On fine finishes, such as car bodies, high-efficiency particulate air filters are required for the outdoor air supply. Other products may require only low- or medium-efficiency filters.

Makeup air must be preheated. Spray booths must have 0.5 m/s face velocity if spraying is performed by humans; lower air quantities can be used if robots perform spraying. Ovens must have air exhausted to maintain fumes below explosive concentration. Equipment must be explosion-proof. Exhaust must be cleaned by filtration and solvents reclaimed or scrubbed.

Process	Dry Bulb, °C	rh, %
PHOTO STUDIO		
Dressing room	22 to 23	40 to 50
Studio (camera room)	22 to 23	40 to 50
Film darkroom	21 to 22	45 to 55
Print darkroom	21 to 22	45 to 55
Drying room	32 to 38	35 to 45
Finishing room	22 to 24	40 to 55
Storage room (black and white film and paper)	22 to 24	40 to 60
Storage room (color film and paper)	40 to 50	40 to 50
Motion picture studio	22	40 to 55

The above data pertain to average conditions. In some color processes, elevated temperatures as high as 40°C are used, and a higher room temperature is required.

Conversely, ideal storage conditions for color materials necessitate refrigerated or deep-freeze temperatures to ensure quality and color balance when long storage times are anticipated.

Heat liberated during printing, enlarging, and drying processes is removed through an independent exhaust system, which also serves the lamp houses and dryer hoods. All areas except finished film storage require a minimum of medium-efficiency particulate air filters.

Process	Dry Bulb, °C	rh, %
PLASTICS		
Manufacturing areas		
Thermosetting molding compounds	27	25 to 30
Cellophane wrapping	24 to 27	45 to 65

In manufacturing areas where plastic is exposed in the liquid state or molded, high-efficiency particulate air filters may be required. Dust collection and fume control are essential.

Process	Dry Bulb, °C	rh, %
PLYWOOD		
Hot pressing (resin)	32	60
Cold pressing	32	15 to 25
RUBBER-DIPPED GOODS		
Manufacture	32	
Cementing	27	25 to 30*
Dipping surgical articles	24 to 27	25 to 30*
Storage prior to manufacture	16 to 24	40 to 50*
Testing laboratory	23	50*

*Dew point of air must be below evaporation temperature of solvent.

Solvents used in manufacturing processes are often explosive and toxic, requiring positive ventilation. Volume manufacturers usually install a solvent-recovery system for area exhaust systems.

Process	Dry Bulb, °C	rh, %
TEA		
Packaging	18	65

Ideal moisture content is 5 to 6% for quality and mass. Low-limit moisture content for quality is 4%.

Process	Dry Bulb, °C	rh, %
TOBACCO		
Cigar and cigarette making	21 to 24	55 to 65*
Softening	32	85 to 88
Stemming and stripping	24 to 29	70 to 75
Packing and shipping	23 to 24	65
Filler tobacco casing and conditioning	24	75
Filter tobacco storage and preparation	25	70
Wrapper tobacco storage and conditioning	24	75

*Relative humidity fairly constant with range as set by cigarette machine.

Before stripping, tobacco undergoes a softening operation.

paper, wood, leather, and tobacco. Moisture in vegetable and animal materials (and some minerals) reaches equilibrium with the moisture in the surrounding air by **regain** (the percentage of absorbed moisture in a material compared to that material's bone-dry mass). For example, if a material sample with a mass of 2.5 kg has a mass of only 2.25 kg after thorough drying under standard conditions of 105 to 110°C, the mass of absorbed moisture is 0.25 kg, 10% of the sample's bone-dry mass. Therefore, the regain is 10%.

Table 2 lists typical regain values for materials at 24°C in equilibrium at various relative humidities. Temperature change affects the rate of absorption or drying, which generally varies with the thickness, density, and nature of the material. Sudden temperature changes cause slight change in regain even with fixed relative humidity, but the major change occurs as a function of relative humidity.

Hygroscopic materials deliver sensible heat to the air in an amount equal to the latent heat of the absorbed moisture. The amount of heat liberated should be added to the cooling load if it is significant, but it is usually quite small. Manufacturing economy requires regain to be maintained at a level suitable for rapid and satisfactory manipulation. Uniform relative humidity allows high-speed machinery to operate efficiently.

Some materials may be exposed to the required humidity during manufacturing or processing, others may be treated separately after conditioning and drying. Conditioning removes or adds hygroscopic moisture. Drying removes both hygroscopic moisture and free moisture in excess of that in equilibrium. Drying and conditioning can be combined to remove moisture and accurately regulate the final moisture content in products such as tobacco and textiles. Conditioning or drying is frequently a continuous process in which the material is conveyed through a tunnel and subjected to controlled atmospheric conditions. For more detail, see Chapter 22 of the 2000 *ASHRAE Handbook—HVAC Systems and Equipment*.

Corrosion, Rust, and Abrasion

In manufacturing metal products, temperature and relative humidity need to be kept sufficiently low to prevent hands from sweating, thus protecting the finished article from fingerprints,

Table 2 Regain of Hygroscopic Materials*

Classification	Material	Description	Relative Humidity 10	20	30	40	50	60	70	80	90
Natural textile fibers	Cotton	Sea island—roving	2.5	3.7	4.6	5.5	6.6	7.9	9.5	11.5	14.1
	Cotton	American—cloth	2.6	3.7	4.4	5.2	5.9	6.8	8.1	10.0	14.3
	Cotton	Absorbent	4.8	9.0	12.5	15.7	18.5	20.8	22.8	24.3	25.8
	Wool	Australian merino—skein	4.7	7.0	8.9	10.8	12.8	14.9	17.2	19.9	23.4
	Silk	Raw chevennes—skein	3.2	5.5	6.9	8.0	8.9	10.2	11.9	14.3	18.3
	Linen	Table cloth	1.9	2.9	3.6	4.3	5.1	6.1	7.0	8.4	10.2
	Linen	Dry spun—yarn	3.6	5.4	6.5	7.3	8.1	8.9	9.8	11.2	13.8
	Jute	Average of several grades	3.1	5.2	6.9	8.5	10.2	12.2	14.4	17.1	20.2
	Hemp	Manila and sisal rope	2.7	4.7	6.0	7.2	8.5	9.9	11.6	13.6	15.7
Rayons	Viscose nitrocellulose	Average skein	4.0	5.7	6.8	7.9	9.2	10.8	12.4	14.2	16.0
	Cuprammonium cellulose acetate		0.8	1.1	1.4	1.9	2.4	3.0	3.6	4.3	5.3
Paper	M.F. newsprint	Wood pulp—24% ash	2.1	3.2	4.0	4.7	5.3	6.1	7.2	8.7	10.6
	H.M.F. writing	Wood pulp—3% ash	3.0	4.2	5.2	6.2	7.2	8.3	9.9	11.9	14.2
	White bond	Rag—1% ash	2.4	3.7	4.7	5.5	6.5	7.5	8.8	10.8	13.2
	Comm. ledger	75% rag—1% ash	3.2	4.2	5.0	5.6	6.2	6.9	8.1	10.3	13.9
	Kraft wrapping	Coniferous	3.2	4.6	5.7	6.6	7.6	8.9	10.5	12.6	14.9
Miscellaneous organic materials	Leather	Sole oak—tanned	5.0	8.5	11.2	13.6	16.0	18.3	20.6	24.0	29.2
	Catgut	Racquet strings	4.6	7.2	8.6	10.2	12.0	14.3	17.3	19.8	21.7
	Glue	Hide	3.4	4.8	5.8	6.6	7.6	9.0	10.7	11.8	12.5
	Rubber	Solid tires	0.11	0.21	0.32	0.44	0.54	0.66	0.76	0.88	0.99
	Wood	Timber (average)	3.0	4.4	5.9	7.6	9.3	11.3	14.0	17.5	22.0
	Soap	White	1.9	3.8	5.7	7.6	10.0	12.9	16.1	19.8	23.8
	Tobacco	Cigarette	5.4	8.6	11.0	13.3	16.0	19.5	25.0	33.5	50.0
Miscellaneous inorganic materials	Asbestos fiber	Finely divided	0.16	0.24	0.26	0.32	0.41	0.51	0.62	0.73	0.84
	Silica gel		5.7	9.8	12.7	15.2	17.2	18.8	20.2	21.5	22.6
	Domestic coke		0.20	0.40	0.61	0.81	1.03	1.24	1.46	1.67	1.89
	Activated charcoal	Steam activated	7.1	14.3	22.8	26.2	28.3	29.2	30.0	31.1	32.7
	Sulfuric acid		33.0	41.0	47.5	52.5	57.0	61.5	67.0	73.5	82.5

*Moisture content expressed in percent of dry mass of the substance at various relative humidities, temperature 24°C.

tarnish, and/or etching. Salt and acid in perspiration can cause corrosion and rust in a few hours. Manufacture of polished surfaces and of steel-belted radial tires usually requires medium-efficiency to HEPA filtering to prevent surface abrasion.

Air Cleanliness

Each application must be evaluated to determine the filtration needed to counter the adverse effects on the product or process of dust particles, airborne bacteria, smoke, spores, pollen, and radioactive particles. These effects include chemically altering production material, spoiling perishable goods, and clogging small openings in precision machinery. See Chapter 24 of the 2000 *ASHRAE Handbook—HVAC Systems and Equipment* for details.

Static Electricity

Humidity can reduce static electricity in processing light materials such as textile fibers and paper and where potentially explosive atmospheres or materials are present. Static electricity is often detrimental to processing and extremely dangerous in explosive atmospheres. Static electric charges are minimized when relative humidity is above 35%. Room relative humidity may need to be maintained at 65% or higher because machinery heat raises the machine ambient temperature well above the room temperature at which the relative humidity is normally measured.

EMPLOYEE REQUIREMENTS

Space conditions required by health and safety standards to avoid excess exposure to high temperatures and airborne contaminants are often established by the American Conference of Governmental Industrial Hygienists (ACGIH 2001). In the United States, the National Institute of Occupational Safety and Health (NIOSH) does research and recommends guidelines for workplace environments. The Occupational Safety and Health Administration (OSHA) sets standards based on these guidelines, with enforcement usually assigned to a corresponding state agency.

Standards for safe levels of contaminants in the work environment or in air exhausted from facilities do not cover everything that may be encountered. Minimum safety standards and design criteria are available from U.S. Department of Health agencies such as the National Institute of Health, National Cancer Institute, and Public Health Service. The U.S. Department of Energy and Nuclear Regulatory Commission establish standards for radioactive substances.

Thermal Control Levels

Industrial plants are usually designed for an internal temperature of 16 to 32°C and a maximum of 60% rh. Tighter controls are often dictated by the specific operations and processes located in the building. The ACGIH has established guidelines to evaluate high temperature and humidity levels in terms of heat stress (Dukes-Dobos and Henschel 1971). See Chapter 8 of the 2001 *ASHRAE Handbook—Fundamentals* for a more detailed analysis of work rate, air velocity, rest, and the effects of radiant heat.

Temperature control becomes tighter and more specific if personnel comfort rather than avoidance of heat stress becomes the criterion. Nearly sedentary workers prefer a winter temperature of 22°C and a summer temperature of 26°C at a maximum of 60% rh. Workers at a high rate of activity prefer 18°C; they are less sensitive to temperature changes and can be cooled by increasing the air velocity. ASHRAE *Standard* 55 provides more detailed information.

Contamination Control Levels

Toxic and/or hazardous materials are present in many industrial plants and laboratories. Gases and vapors are found near acid baths and tanks holding process chemicals. Plating operations, spraying, mixing, abrasive cleaning, and other processes generate dust, fumes, and mists. Many animal and laboratory procedures (e.g., grinding, blending, sonication, weighing) generate aerosols. Air-conditioning and ventilation systems must minimize exposure to these materials. When airborne, these materials greatly expand their range and potential for affecting more employees. Chapter 12 of the 2001 *ASHRAE Handbook—Fundamentals*, OSHA requirements, and ACGIH (2001) give guidance on the health impact of various materials.

Concentrations of gaseous flammable substances must also be kept below explosive limits. Acceptable concentrations of these substances are a maximum of 25% of the lower explosive limit. Chapter 12 of the 2001 *ASHRAE Handbook—Fundamentals* provides data on flammable limits and their means of control.

Instruments are available to measure concentrations of common gases and vapors, but specific monitoring requirements and methods must be developed for uncommon ones.

DESIGN CONSIDERATIONS

Required environmental conditions for equipment, process and personnel comfort must be known before selecting HVAC equipment. The engineer and owner jointly establish design criteria, including the space-by-space environment in the facilities, process heat loads and exhaust requirements, heat and cooling energy recovery, load factors and equipment diversity, lighting, cleanliness, etc. Consideration should be given to the method of separating dirty processes from areas that require progressively cleaner air.

Insulation should be evaluated for initial cost and operating and energy cost savings. When high levels of moisture are required within the building, the air-conditioning and structural envelope must prevent unwanted condensation and ensure a high-quality product. Condensation can be prevented by eliminating thermal short circuits, installing proper insulation, and using vapor barriers. See Chapters 23 and 24 of the 2001 *ASHRAE Handbook—Fundamentals* for further details.

Personnel engaged in some industrial processes may be subject to a wide range of activity levels for which a broad range of temperatures and humidities are desirable. Chapter 8 of the 2001 *ASHRAE Handbook—Fundamentals* addresses recommended indoor conditions for a variety of activity levels.

If layout and construction drawings are not available, a complete survey of existing premises and a checklist for proposed facilities are necessary (Table 3).

New industrial buildings are typically single-story with a flat roof and ample height to distribute air and utilities without interfering with process operations. Fluorescent fixtures are commonly mounted at heights up to 4 m, high output fluorescent fixtures up to 6 m, and high pressure sodium or metal halide fixtures above 6 m. Lighting design considers light quality, diffusion, room size, mounting height, and economics. Illumination levels should conform to recommendations of the Illuminating Engineering Society of North America.

Air-conditioning systems can be located on the roof of the building. Air intakes should not be located too close to loading docks or other sources of contamination. (See the section on Air Filtration Systems.) HVAC system installation must be coordinated with other systems and equipment that compete for space at the top of the building, such as fire sprinklers, lighting, cranes, structural elements, etc.

Operations in the building must also be considered: some require close control of temperature, humidity, and/or contaminants. A schedule of operations is helpful in determining heating and cooling loads.

Table 3 Facilities Checklist

Construction

1. Single or multistory
2. Type and location of doors, windows, crack lengths
3. Structural design live loads
4. Floor construction
5. Exposed wall materials
6. Roof materials and color
7. Insulation type and thicknesses
8. Location of existing exhaust equipment
9. Building orientation

Use of Building

1. Product needs
2. Surface cleanliness; acceptable airborne contamination level
3. Process equipment: type, location, and exhaust requirements
4. Personnel needs, temperature levels, required activity levels, and special workplace requirements
5. Floor area occupied by machines and materials
6. Clearance above floor required for material-handling equipment, piping, lights, or air distribution systems
7. Unusual occurrences and their frequency, such as large cold or hot masses of material moved inside
8. Frequency and length of time doors open for loading or unloading
9. Lighting, location, type, and capacity
10. Acoustical levels
11. Machinery loads, such as electric motors (size, diversity), large latent loads, or radiant loads from furnaces and ovens
12. Potential for temperature stratification

Design Conditions

1. Design temperatures—indoor and outdoor dry and wet bulb
2. Altitude
3. Wind velocity
4. Makeup air required
5. Indoor temperature and allowable variance
6. Indoor relative humidity and allowable variance
7. Indoor air quality definition and allowable variance
8. Outdoor temperature occurrence frequencies
9. Operational periods: one, two, or three
10. Waste heat availability and energy conservation
11. Pressurization required
12. Mass loads from the energy release of productive materials

Code and Insurance Requirements

1. State and local code requirements for ventilation rates, etc.
2. Occupational health and safety requirements
3. Insuring agency requirements

Utilities Available and Required

1. Gas, oil, compressed air (pressure), electricity (characteristics), steam (pressure), water (pressure), wastewater, interior and site drainage
2. Rate structures for each utility
3. Potable water

LOAD CALCULATIONS

Table 1 and specific product chapters of this Handbook discuss product requirements. Chapter 29 of the 2001 *ASHRAE Handbook—Fundamentals* provides appropriate heating and cooling load calculation techniques.

Solar and Transmission

The roof load is usually the largest solar load on the envelope. Solar loads on walls are often insignificant particularly because modern factory buildings tend to be windowless. Insulating building walls and roof almost always benefits HVAC cost and performance.

Internal Heat Generation

Internal heat generated by equipment and processes, as well as products, lighting, people and utilities, may satisfy heating load requirements. Understanding equipment operating schedules allows an appropriate diversity factor to be applied to the actual power consumption. Using connected loads may greatly oversize the system. Processes tend to be operated continuously but may be shut down on weekends or at night. Heating to some minimal level without equipment and/or process load should be considered.

The latent load in most industrial facilities is minimal, with people and outside air being the primary contributors. Some processes and products do generate a latent load. They need to be understood because this latent load can dominate the HVAC system design. Moisture condensation on cold surfaces must be managed when the latent load becomes very large.

Stratification Effect

The cooling load may be dramatically reduced in a work space that takes advantage of temperature stratification. A stagnant blanket of warm air directly under the roof will have little effect on occupants or equipment as long as it remains undisturbed. Heat sources near the stagnant air will have little effect on the cooling load. When the ceiling or roof is high, 20 to 60% of the heat energy rises out of the cooling zone, depending on building construction and the temperature of heat sources.

Supply and return air ducts should be installed as low as practical to avoid mixing the warm boundary layers. The location of supply air diffusers generally establishes the stratified air boundary. Spaces with a low occupant-to-floor-area ratio adapt well to using low quantities of supply air with spot cooling for personnel.

Makeup Air

Makeup air provides ventilation and building pressurization. It must be filtered and conditioned to blend with return air and then distributed to the conditioned space. The quantity of makeup air must exceed that of the exhaust air to positively pressurize the building. Makeup air quantity may be varied to accommodate an exhaust system with intermittently operating elements. Heat and cooling recovery from the exhaust airstream can substantially reduce the outside air load.

Processes that require an extensive amount of exhaust air should ideally be placed in an area of the plant provided with minimal heating and no refrigerated air conditioning. Ventilation air may be required to reduce the quantity of health-threatening fumes, airborne bacteria, or radioactive particles. Minimum ventilation rates must meet the requirements of ASHRAE *Standard* 62.

Economizers can take advantage of ambient conditions and possibly satisfy HVAC loads without added heating or cooling.

Fan Heat

Heat from air-moving fans warms as well as pressurizes the air. This heat is not felt by the occupants but does add to the cooling load. The discharge air temperature of a draw-through cooling arrangement requires cooler air to the fan to accommodate the temperature increase of air passing through the fan. The increase is more significant in systems with higher discharge air pressures.

SYSTEM AND EQUIPMENT SELECTION

Industrial air-conditioning equipment includes heating and cooling sources, air-handling and air-conditioning apparatus, filters, and an air distribution system. Components should be selected and the system designed for long life with low maintenance and operating costs to provide low life-cycle cost.

Systems may consist of the following:

- Heating-only in cool climates, where ventilation air provides comfort for workers
- Air washer systems, where high humidities are desired and where the climate requires cooling
- Heating and evaporative cooling, where the climate is dry
- Heating and mechanical cooling, where temperature and humidity control are required and other means of cooling are insufficient

All systems include air filtration appropriate to the contaminant control required.

Careful evaluation should determine zones that require control, especially in large, high-bay areas where the occupied zone is a small portion of space volume. ASHRAE *Standard* 55 defines the occupied zones as 75 to 1830 mm high and more than 610 mm from the walls.

HEATING SYSTEMS

Floor Heating

Floor heating is often desirable in industrial buildings, particularly in large, high-bay buildings, garages, and assembly areas where workers must be near the floor, or where large or fluctuating outside air loads make maintaining ambient temperature difficult.

Floors may be tempered to 18 to 21°C by embedded hydronic systems, electrical resistance cables, or warm air ducts as an auxiliary to the main heating system. Heating elements may be buried deep in the floor (150 to 450 mm) to allow slab warm-up at off-peak times, thus using the floor mass as heat storage to save energy during periods of high use.

Floor heating may be the primary or sole heating means, but floor temperatures above 29°C are uncomfortable, so such use should be limited to small, well-insulated spaces.

Unit and Ducted Heaters

Gas, oil, electric, hot-water, or steam-fired unit heaters with propeller fans or blowers are used for spot heating areas or are arranged in multiples for heating an entire building. Temperatures can be varied by individual thermostatic control. Unit heaters should be located so that the discharge (throw) will reach the floor adjacent to and parallel with the outside wall, and spaced to produce a ring of warm air moving peripherally around the building. In industrial buildings with heat-producing processes, heat tends to stratify in high-bay areas. In large buildings, additional heaters should be placed in the interior so that their discharge reaches the floor to reduce stratification. Downward-discharge unit heaters in high bays and large areas may have a revolving discharge. Gas- and oil-fired unit heaters should not be used where corrosive vapors are present.

Ducted heaters include large direct- or indirect-fired heaters, door heaters, and heating and ventilating units. They usually have centrifugal fans. Direct-fired gas heaters, in which the gas burns in the air being supplied to the space, may be used for makeup air heating because they are self-venting.

Unit heaters and makeup air heaters commonly temper outside air that enters buildings through open doors. Mixing quickly brings the space temperature back to the desired setting after the door is closed. The makeup air heater should be applied as a door heater in buildings where the doors are large and open for extended periods, such as doors for large trucks or railroad cars. Unit heaters are also needed in buildings that have considerable leakage or a sizeable negative pressure. These units help pressurize the door area, mix the incoming cold air, temper it, and quickly bring the area back to the desired temperature after the door is closed.

Door heating units that resemble a vestibule operate with airflow down across the opening and recirculated from the bottom, which help reduce cold drafts across the floor. These units are effective on high-usage doors under 3 m tall. Additional information on heating is given in Chapter 31 of the 2000 *ASHRAE Handbook—HVAC Systems and Equipment*.

Infrared Heaters

High-intensity gas, oil, or electric infrared heaters transfer heat directly to the occupants, equipment, and floor in the space without appreciably warming the air, though some air heating occurs by convection from objects heated by the infrared heaters. These heaters are classified as near- or far-infrared heaters, depending on how close the wavelengths they emit are to visible light. Near-infrared heaters emit a substantial amount of visible light.

Both vented and unvented gas-fired infrared heaters are available as individual radiant panels, or as a continuous radiant pipe with burners 4.5 to 9 m apart and an exhaust vent fan at the end of the pipe. Unvented heaters require exhaust ventilation to remove flue products from the building and prevent moisture from collecting on the walls and ceiling. Insulation reduces the ventilation requirement.

Infrared heaters are common in the following applications:

- High-bay buildings, where heaters are usually mounted 3 to 9 m above the floor, along outside walls, and tilted to direct maximum radiation to the floor. If the building is poorly insulated, the controlling thermostat should be shielded to avoid influence from the radiant effect of the walls and the cold walls.
- Semi-open and outside areas, where people can be comfortably heated directly and objects can be heated to avoid condensation.
- Loading docks, where snow and ice can be controlled by strategic placement of near-infrared heaters.

Additional information on both electric and gas infrared heating is given in Chapter 15 of the 2000 *ASHRAE Handbook—HVAC Systems and Equipment*.

COOLING SYSTEMS

Common cooling systems include refrigeration equipment, evaporative coolers, and high-velocity ventilation air.

For manufacturing operations, particularly in heavy industry where mechanical cooling cannot be economically justified, evaporative cooling systems often provide good working conditions. If the operation requires heavy physical work, spot cooling by ventilation, evaporative coolers, or refrigerated air can be used. To minimize summer discomfort, high outside ventilation rates may be adequate in some hot-process areas. A mechanical air supply with good distribution is needed in all these operations.

Refrigerated Cooling Systems

The most commonly used refrigerated cooling systems are roof-mounted, direct-expansion packaged units. Larger systems may use chilled water distributed to air-handling units.

Central system condenser water rejects heat through a cooling tower. Refrigerated heat recovery is particularly advantageous in buildings with simultaneous need to heat exterior spaces and cool interior spaces.

Mechanical cooling equipment should be selected in multiple units. This enables the equipment to match its response to fluctuations in the load and to allow maintenance during off-peak operation periods. Packaged refrigeration equipment commonly uses positive-displacement (reciprocating, scroll, or screw) compressors with air-cooled condensers. When equipment is on the roof, the condensing temperature may be affected by warm ambient air, often 5 to 10 K higher than design outside air temperature. ASHRAE *Standard* 15 provides rules for the type and quantity of refrigerant in direct air-to-refrigerant exchangers.

For processes that require dew points below 10°C (e.g., pharmaceutical processing), desiccant-based systems should be considered.

Evaporative Cooling Systems

Evaporative cooling systems may be direct or indirect evaporative coolers or air washers. Evaporative coolers have water sprayed directly on wet surfaces through which air passes. Any excess water is drained off. An air washer recirculates water, and the air flows through a heavily misted area. Water atomized in the airstream evaporates, cooling the air. Refrigerated water simultaneously cools and dehumidifies the air. For spaces that require an air washer and high relative humidities (e.g., tobacco and textile processing areas), heat provided to the sump should provide sufficient energy for humidification beyond that from heat recovered in the return airstream.

Evaporative cooling conserves energy, particularly in mild weather. Air washers may control both temperature and humidity using refrigerated spray water and reheat coils. Temperature and humidity of the exit airstream may be controlled by varying the temperature of the chilled water and reheat coil and by varying the quantity of air passing through the heat coil with a dew point thermostat.

Ensure that accumulation of dust or lint does not clog the nozzles or evaporating pads of evaporative cooling systems. It may be necessary to filter air entering the evaporative cooler. Chemical treatment of the water may be necessary to prevent mineral build-up or biological growth on the pads or in the pans.

AIR FILTRATION SYSTEMS

Air filtration systems remove contaminants from the building supply or exhaust airstream. Supply air filtration at the equipment intake removes particulate contamination that may foul heat exchange surfaces, contaminant products, or present a health hazard to people, animals, or plants. Gaseous contaminants must sometimes be removed to prevent exposing personnel to odors or health-threatening fumes. Return air with a significant potential for carrying contaminants should be recirculated only if it can be filtered enough to minimize personnel exposure. Return air should be exhausted if monitoring and contaminant control cannot be ensured.

The supply filtration system usually includes collection media or a filter, a media-retaining device or filter frame, and a filter housing or plenum. The filter medium is the most important part of the system. A mat of randomly distributed small-diameter fibers is commonly used. For more on filtration systems, see Chapter 24 of the 2000 *ASHRAE Handbook—HVAC Systems and Equipment*.

Exhaust Air Filtration Systems

Exhaust air systems are either (1) general systems that remove air from large spaces or (2) local systems that capture aerosols, heat, or gases at specific locations in a room and transport them so they can be collected, inactivated, and safely discharged to the atmosphere. Air in a general system usually requires minimal or no treatment before being discharged to the atmosphere. Air from local exhaust systems can sometimes be safely discharged to the atmosphere, but may require contaminant removal before being discharged. All emitted air must meet appropriate air quality standards. Chapters 28 and 29 of this volume and Chapter 25 of the 2000 *ASHRAE Handbook—HVAC Systems and Equipment* have more information on industrial ventilation and exhaust systems.

In exhaust air emission control, fabric-bag filters, glass-fiber filters, venturi scrubbers, and electrostatic precipitators all collect particles. Packed-bed or sieve towers can absorb toxic gases. Activated carbon columns or beds, often with oxidizing agents, are frequently used to absorb toxic or odorous organics and radioactive gases.

Outside air intakes should be carefully located to avoid recirculating contaminated exhaust air. Wind direction, building shape, and location of effluent source strongly influence concentration patterns.

Air patterns from wind flowing over buildings are discussed in Chapter 16 of the 2001 *ASHRAE Handbook—Fundamentals*. The leading edge of the roof interrupts smooth airflow, resulting in reduced air pressure at the roof and on the lee side. Exhaust air must be discharged through either a vertical stack terminating above the building turbulent air boundary or a shorter stack with a high enough discharge velocity to project the effluent through the air boundary into the undisturbed air passing over the building. The high discharge prevents fume damage to both the roof and roof-mounted equipment, and keeps fumes away from building air intakes. A high vertical stack is the safest, simplest solution to fume dispersal.

Contamination Control

In addition to maintaining thermal conditions, air-conditioning systems should control contaminant levels to provide a safe and healthy environment, good housekeeping, and quality control for the processes. Contaminants may be gases, fumes, mists, or airborne particulate matter; they may be produced by a process in the building or contained in the outside air.

Contamination can be controlled by preventing the release of aerosols or gases into the room and by diluting room air contaminants. If the process cannot be enclosed, it is best to capture aerosols and gases near their source with a local exhaust system that includes a hood or enclosure, ducts, fan, motor, and exhaust stack.

Dilution controls contamination in many applications but may not provide uniform safety for personnel. High local concentrations of contaminants can exist despite a high overall dilution rate.

EXHAUST SYSTEMS

An exhaust system draws a contaminant away from its source and removes it from the space. An exhaust hood surrounding the point of generation contains the contaminant as much as is practical. The contaminant is transported through ductwork from the space, cleaned as required, and exhausted to the atmosphere. The inlet air quantity of the hood is established by the velocities required to contain the contaminant. Chapter 30 has more information on local exhaust systems.

Design values for average and minimum face velocities are a function of the characteristics of the most hazardous material the hood is expected to handle. Minimum values may be prescribed in codes for exhaust systems. Contaminants with greater mass may require higher face velocities for control. Design face velocities should be set carefully: too high a velocity can be as hazardous as one too low. Refer to ACGIH (2001), and ASHRAE *Standard* 110 for more information.

Properly sized ductwork keeps the contaminants flowing. This requires very high velocities for heavy materials. Selection of materials and construction of exhaust ductwork and fans depend on the nature of the contaminant, ambient temperature, lengths and arrangement of ducts, method of hood fan operation, and flame and smoke spread ratings.

Exhaust systems remove gases, vapors, or smokes from acids, alkalis, solvents, and oils. The following should be minimized:

- **Corrosion.** Commonly used reagents in laboratories include hydrochloric, sulfuric, and nitric acids (singly or in combination) and ammonium hydroxide. Commonly used organic chemicals include acetone, benzene, ether, petroleum, chloroform, carbon tetrachloride, and acetic acid.
- **Dissolution.** Coatings and plastics are subject to dissolving, particularly by solvent and oil fumes.
- **Melting.** Certain plastics and coatings at elevated hood operating temperatures can melt.

Low temperatures that cause condensation in ferrous metal ducts increase chemical destruction. Ducts are less subject to attack when runs are short and direct to the terminal discharge point. The longer the runs, the longer the period of exposure to fumes and the greater the condensation. Horizontal runs allow moisture to remain longer than on vertical surfaces. Intermittent fan operation can contribute to longer periods of wetness than continuous operation. High loading of condensables in exhaust systems should be avoided by installing condensers or scrubbers as close to the source as possible.

OPERATION AND MAINTENANCE

All designs should allow ample room to clean, service, and replace any component quickly so that design conditions are affected as little as possible. Maintenance of refrigeration and heat rejection equipment is essential for proper performance without energy waste. Maintenance includes changing system filters periodically. Industrial applications are dirty, so proper selection of filters, careful installation to avoid air bypassing the filter, and prudent filter changing to prevent overloading and blowout are required. Dirt that lodges on the tips of forward-curved fan blades reduces air-handling capacity appreciably. Fan and motor bearings require lubrication, and fan belts need periodic inspection. Direct- and indirect-fired heaters should be inspected annually. Steam and hot-water heaters have fewer maintenance requirements than comparable equipment with gas or oil burners.

For system compatibility, water treatment is essential. Air washers and cooling towers should not be operated unless the water is properly treated.

HEAT RECOVERY AND ENERGY CONSERVATION

Process industry presents unique opportunities to recover heat from the exhaust airstream for use in preconditioning makeup air. Extreme care must be taken to ensure compatibility of heat exchanger components and materials with contaminants often found in exhaust streams. For example, brewery spaces are held between 1.7 and 10°C. Exhaust air passes over a heat recovery wheel to precondition outside makeup air, which in turn controls the level of carbon dioxide contamination. Coated aluminum heat recovery wheels can be subject to premature failure because of caustic cleaning materials conveyed in the exhaust system.

Additional consideration should be given to the assessment of risk associated with the heat recovery strategy. Frequently, downtime in large industrial facilities can exceed millions of dollars per hour. Costs associated with failure of a heat recovery device can easily overcome savings in energy costs if the result is a facility shutdown.

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