# CHAPTER 13

# AIRCRAFT

**E**NVIRONMENTAL control system (ECS) is a generic term used in the aircraft industry for the systems and equipment associated with ventilation, heating, cooling, humidity/contamination control, and pressurization in the occupied compartments, cargo compartments, and electronic equipment bays. The term ECS often encompasses other functions such as windshield defog, airfoil anti-ice, oxygen systems, and other pneumatic demands. The regulatory or design requirements of these related functions are not covered in this chapter.

## 1. DESIGN CONDITIONS

Design conditions for aircraft applications differ in several ways from other HVAC applications. Commercial transport aircraft often operate in a physical environment that is otherwise not survivable for humans. In flight, the ambient air may be extremely cold and dry, and can contain high levels of ozone. On the ground, the ambient air may be hot, humid, and contain many pollutants such as particulate matter, aerosols, and hydrocarbons. These conditions change quickly from ground operations to flight. A hot-day, high-humidity ground condition usually dictates the thermal capacity of the air-conditioning equipment, and flight conditions determine the supply air compressor's capacity. Maximum heating requirements can be determined by either cold-day ground or flight operations.

In addition to essential safety requirements, the ECS should provide a comfortable cabin environment for the passengers and crew. This presents a unique challenge because of the high-density seating of the passengers. Furthermore, aircraft systems must be lightweight, accessible for quick inspection and servicing, highly reliable, able to withstand aircraft vibratory and maneuver loads, and able to compensate for various possible system failures.

### Ambient Temperature, Humidity, and Pressure

Figure 1 shows typical design ambient temperature profiles for hot, standard, and cold days. The ambient temperatures used for the design of a particular aircraft may be higher or lower than those shown in Figure 1, depending on the regions in which the aircraft is to be operated. The design ambient moisture content at various altitudes as recommended for commercial aircraft is shown in Figure 2. However, operation at moisture levels exceeding 200 gr/lb of dry air is possible in some regions. The variation in ambient pressure with altitude is shown in Figure 3. Refer to the psychrometric chart for higher altitudes for cabin humidity calculations. Figure 4 shows a psychrometric chart for 8000 ft altitude.

### Heating/Air Conditioning Load Determination

The cooling and heating loads for a particular aircraft model are determined by a heat transfer study of the several elements that comprise the air-conditioning load. Heat transfer involves the following factors:

• Convection between the boundary layer and the outer aircraft skin

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The preparation of this chapter is assigned to TC 9.3, Transportation Air Conditioning.
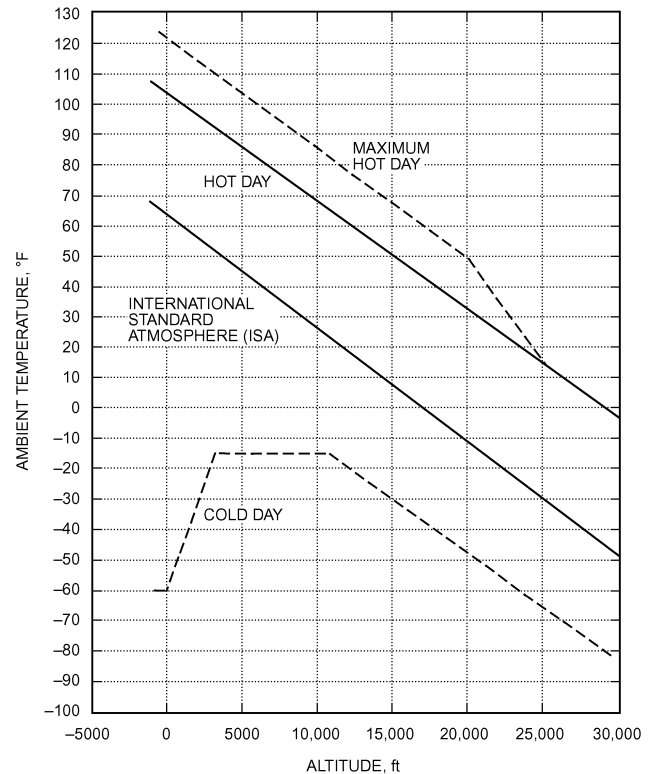


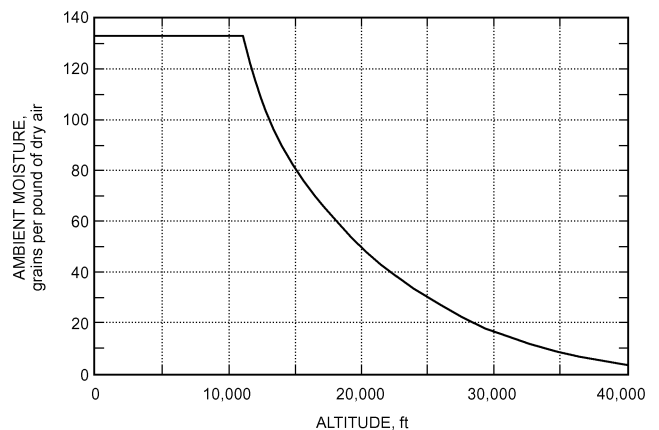**Fig. 1 Ambient Temperature Profiles**
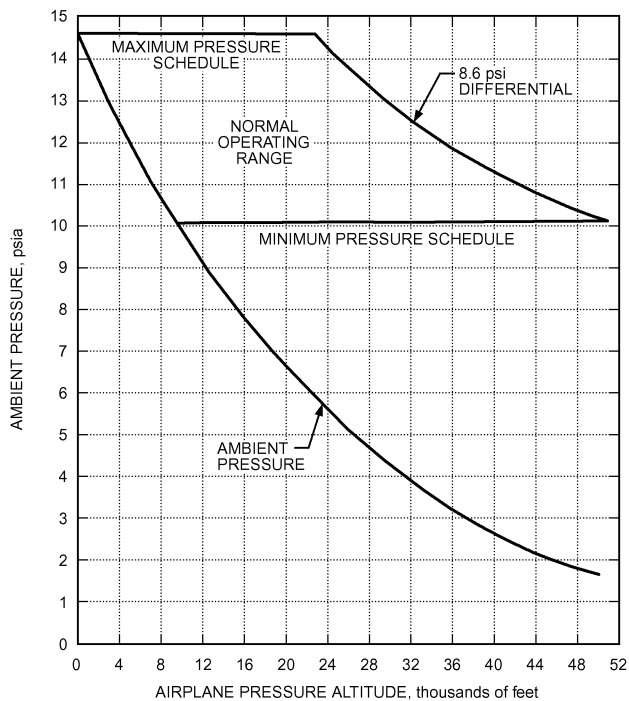


**Fig. 2 Design Humidity Ratio**

**Fig. 3    Cabin Pressure Versus Altitude**

- Radiation between the outer aircraft skin and the external environment
- Solar radiation through windows, on the fuselage, and reflected from the ground.
- Conduction through cabin walls and the aircraft structure
- Convection between the interior cabin surface and the cabin air
- Convection and radiation between the cabin and occupants
- Convection and radiation from internal sources of heat (e.g., electrical equipment)
- Latent heat from vapor cycle systems

### Ambient Air Temperature in Flight

During flight, very cold ambient air adjacent to the outer surface of the aircraft increases in temperature through ram effects, and may be calculated from the following equations:

$$T_{AW} = T_\infty + r(T_T - T_\infty)$$

$$T_T = T_\infty \left( 1 + \frac{k-1}{2}M^2 \right)$$

or

$$T_{AW} = T_\infty \left( 1 + r\frac{k-1}{2}M^2 \right)$$

$$r = \text{Pr}^{1/3}$$

where

Pr = Prandtl number for air (e.g., Pr = 0.73 at 432°R
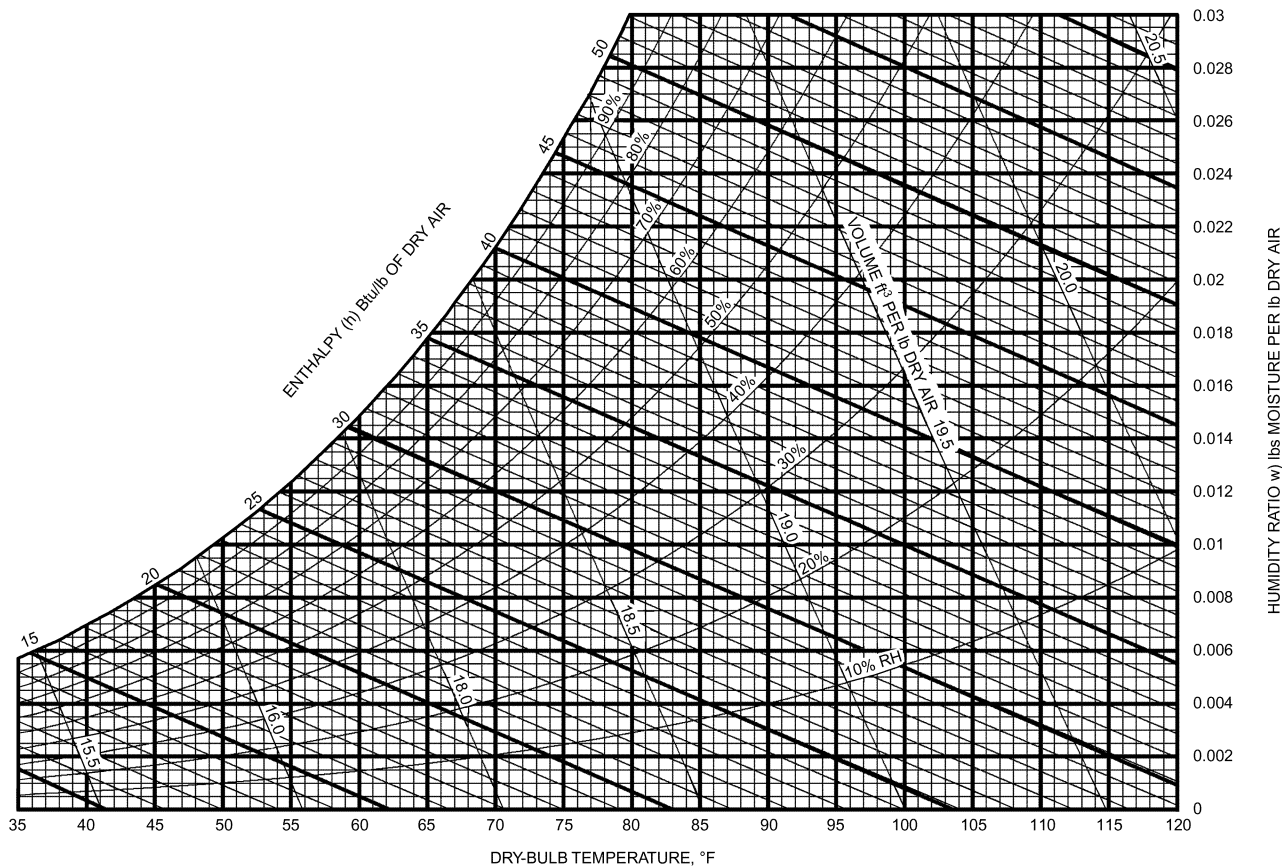$T_\infty$ = ambient static temperature, °R



**Fig. 4    Psychrometric Chart for Cabin Altitude of 8000 ft**

$T_T$ = ambient total temperature, °R
$k$ = ratio of specific heat; for air, $k = 1.4$
$M$ = airplane Mach number
$r$ = recovery factor for turbulent boundary layer (i.e., fraction of total temperature recovered in boundary layer as air molecules rest on the surface)
$T_{AW}$ = recovery temperature (or adiabatic wall temperature), °R

**Example 1.** The International Civil Aviation Organization (ICAO) cold day at 30,000 to 40,000 ft altitude has a static temperature of –85°F (375°R) and a Prandtl number of 0.739. If an airplane is traveling at 0.8 Mach, what would the external temperature be at the airplane's skin?

**Solution:** Iteration is usually required. First guess for $r \approx 0.9$:

$$\text{Pr} = 0.728 \text{ at } 0.9(423 - 375) + 375 = 418°R$$
$$r = \text{Pr}^{1/3} = (0.728)^{1/3} = 0.8996$$

$$T_T = T_\infty \left(1 + \frac{k-1}{2}M^2\right) = 375\left(1 + \frac{1.4-1}{2}[0.8]^2\right) = 423°R$$

$$T_{AW} = T_\infty + r(T_T - T_\infty) = 375 + 0.8996(423 - 375)$$
$$= 418.2°R \quad (-41.5°F)$$

## Air Speed and Mach Number

The airplane airspeed is related to the airplane Mach number by the local speed of sound:

$$u_\infty = M\sqrt{kRT_\infty}$$

*where*

$k$ = ratio of specific heats; 1.4 for air
$R$ = gas constant; 1716 ft²/s²·°R
$M$ = airplane Mach number
$u_\infty$ = airplane airspeed, fps

## Ambient Pressure in Flight

The static pressure over most of the fuselage (the structure around the cabin) is essentially equal to the ambient pressure at the appropriate altitude.

$$P_s = P_{inf} + C_p \frac{1}{2}\rho_\infty u_\infty^2$$

*where*

$P_s$ = pressure surrounding the fuselage, lb/ft²
$C_p$ = pressure coefficient, dimensionless; approximately zero for passenger section of fuselage
$\rho_\infty$ = free-stream or ambient air density, slug/ft³

## External Heat Transfer Coefficient in Flight

The fact that the fuselage is essentially at free-stream static pressure implies that a flat-plate analogy can be used to determine the external heat transfer coefficient at any point on the fuselage:

$$h = \rho_w c_p u_\infty 0.185(\log_{10}\text{Re}_x)^{-2.584}\text{Pr}^{-2/3}$$

$$\text{(note: } 10^7 < \text{Re}_x < 10^9\text{)}$$

$$\text{Re}_x = \frac{\rho_w u_\infty x}{\mu}$$

$\rho_w, c_p, \mu, \text{Pr}$

$$\text{evaluated at } T^* = \frac{T_{AW} + T_\infty}{2} + 0.22(T_{AW} - T_\infty)$$

$$q = hA(T - T_{AW})$$

*where*

$h$ = external heat transfer coefficient, Btu/s·ft²·°F
$\text{Re}_x$ = local Reynolds number, dimensionless
$x$ = distance along the fuselage from nose to point of interest, ft
$c_p$ = constant-pressure specific heat; for air, 0.24 Btu/lb·°F
$\rho_w$ = ambient air (weight) density at film temperature $T^*$, lb/ft³
$\mu$ = absolute viscosity of air at $T^*$; $1.021 \times 10^{-9}(T^*)^{3/2}[734.7/(T^* + 216)]$ lb$_m$/ft·s
$A$ = outside surface area, ft²
$T$ = outer skin temperature, °R
$q$ = convective heat loss from outer skin, Btu/h
$u_\infty$ = airplane airspeed, ft/h

## External Heat Transfer Coefficient on Ground

The dominant means of convective heat transfer depends on wind speed, fuselage temperature, and other factors. The (free convection) heat transfer coefficient for a large, horizontal cylinder in still air is entirely buoyancy-driven and is represented as follows:

$$\text{Gr} = \frac{g(\beta)(\Delta T)d^3}{\nu^2}$$

for $10^9 \le \text{GrPr} \le 10^{12}$:

$$h_{free} = \frac{0.13k(\text{GrPr})^{1/3}}{d}$$

*where*

$g$ = gravitational acceleration, 32.2 ft/s²
$k$ = thermal conductivity of air, Btu·ft/h·ft²·°R
$\nu$ = kinematic viscosity, ft²/s
$d$ = fuselage diameter, ft
$h_{free}$ = free-convection heat transfer coefficient, Btu/h·ft²·°R
$\beta$ = expansion coefficient of air = $1/T_f$, where $T_f = (T_{skin} + T_\infty)/2$, °R
$\Delta T = T_{skin} - T_\infty$
$T_{skin}$ = skin temperature, °R
$T_\infty$ = ambient temperature, °R
$\text{Gr}$ = Grashof number
$\text{Pr}$ = Prandtl number

A relatively light breeze introduces a significant amount of heat loss from the same horizontal cylinder. The forced-convection heat transfer coefficient for a cylinder may be extrapolated from the following:

$$\text{Re} = \frac{Vd}{\nu}$$

for $4 \times 10^4 \le \text{Re} \le 4 \times 10^5$

$$h_{forced} = \frac{0.0266k(\text{Re})^{0.805}\text{Pr}^{1/3}}{d}$$

where $V$ is wind speed in ft/s, and $\nu$ is evaluated at $T_f = (T_{skin} + T_\infty)/2$.

**Example 2.** One approximation of the fuselage is a cylinder in cross-flow. The fuselage is 12 ft in diameter and 120 ft long, in a 14 fps crosswind and a film temperature of 575°R. The surface temperature varies with the paint color and the degree of solar heating. For instance, a typical white paint could be 30°F higher than the ambient air temperature, so the heat transfer from the fuselage would be

Free convection:

$$\text{Gr} = \frac{g(\beta)(\Delta T)d^3}{\nu^2} = \frac{32.2(0.00174)(30)(12)^3}{(1.9 \times 10^{-4})^2} = 8.05 \times 10^{10}$$

for $10^9 \le \text{GrPr} \le 10^{12}$.

$$h_{free} = \frac{0.13k(GrPr)^{1/3}}{d} = \frac{0.13(0.016)[8.05 \times 10^{10}(0.704)]^{1/3}}{12}$$

$$= 0.67 \text{ Btu/h·ft}^2\text{·°F}$$

Forced convection:

$$Re = \frac{Vd}{\nu} = \frac{14(12)}{1.9 \times 10^{-4}} = 8.84 \times 10^5$$

for $4 \times 10^4 \le Re \le 4 \times 10^5$. Note that, although this Reynolds number is beyond the recommended range, the extrapolation has about a 10% error (underprediction) when compared to other more complicated methods.

Comparison of heat transfer coefficients shows that, in this situation, heat transfer is dominated by forced convection, so the free-convection aspect can be ignored.

### External Radiation

The section of airplane fuselage that surrounds the cabin radiates primarily to the sky. At sea level, the sky temperature is about 30°F cooler than the surrounding air temperature (depending on humidity and other factors). As the airplane climbs, there is a decreasing amount of air above to radiate to, so the difference between air temperature and sky temperature increases. For example, at a cruising altitude of 30,000 to 35,000 ft, the sky temperature is about 100°F cooler than the air temperature (free-stream static). The limiting condition, of course, is outer space, where the sky temperature is the cosmic background radiation (CBR). The sky temperature in this case is only about 6°R. The heat loss to the sky by radiation is

$$qR = A\sigma(\varepsilon)\left(T^4 - T_{sky}^4\right)$$

*where*

- $q_R$ = radiation heat loss from outer skin, Btu/h
- $A$ = outside surface area, ft$^2$
- $T$ = outer skin temperature, °R
- $\sigma$ = Stephan-Boltzmann constant, $1.712 \times 10^{-9}$ Btu/h·ft$^2$·R$^4$
- $\varepsilon$ = emissivity of surface, paint, etc.
- $T_{sky}$ = sky temperature, °R

Solar radiation on the ground is covered in detail elsewhere (e.g., Chapter 36); however, during cruising, the incident solar radiation should be adjusted for altitude. The column of air between the sun and the airplane varies with time of day (angle) and altitude. Standard sea-level solar flux, for a given latitude and time of day, can be adjusted for altitude using Beer's law:

$$I_{SL} = I_o e^{-na_{ms}}$$

$$I_y = I_o e^{-na_{ms}m}$$

$$C_y = I_y/I_{SL}$$

$$q_s = A\alpha(C_y)I$$

*where*

- $I$ = solar radiation to a surface at sea level after accounting for latitude and time of day, Btu/h·ft$^2$
- $I_o$ = solar constant, 429.5 Btu/h·ft$^2$
- $I_y$ = normal solar flux at altitude, Btu/h·ft$^2$
- $I_{SL}$ = normal solar flux at sea level, Btu/h·ft$^2$
- $C_y$ = correction factor for altitude
- $n$ = turbidity factor: 2.0 for clear air, 4 to 5 for smog
- $m$ = relative thickness of air mass, $P_y/P_{SL}$ = (altitude pressure)/(sea level barometric pressure)
- $a_{ms}$ = molecular scattering coefficient = 0.128-0.054 $\log_{10}(m)$
- $\alpha$ = solar absorptivity of surface, window, paint, etc.
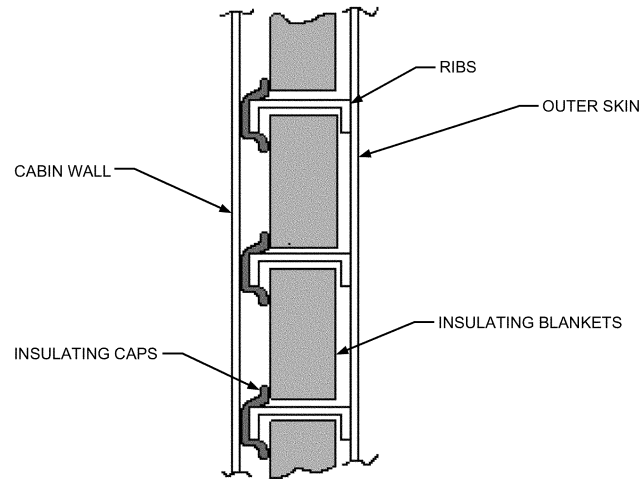- $A$ = outside surface area, ft$^2$



**Fig. 5  Example of Aircraft Insulation Arrangement**

### Conduction

The conductive path from the air in the cabin to the surrounding environment is generally described as several heat transfer elements in series and in parallel with each other. The structure is typically quite conductive (e.g., aluminum), and must be insulated to avoid a direct heat path from inside to outside. The structure typically has an outer skin supported by circumferential and longitudinal ribs. The members require a structurally efficient attachment, which often is also thermally efficient, so that the entire structure is essentially at the same temperature. As a result, the effective "fin" area may be much larger than the simple outside surface area of the fuselage. Figure 5 shows an example of an aircraft insulation arrangement.

For occupant comfort, the cabin wall temperature should not be drastically different from the air temperature within the cabin, because the passengers frequently are in contact with this and other interior surfaces. The insulation accommodates this requirement as well as noise reduction, which on occasion is the dominant requirement.

### Stack Pressure across Cabin Wall

The cold outer skin during flight generates buoyancy-driven flow between the cabin and the cavity formed by the cabin wall and the outer skin. Because this cavity is normally filled with insulation blankets, it may be relatively porous to airflow. The outer skin is frequently below the cabin dew point (and below freezing), so water condenses on the structure and ice may build up with time. The amount of flow in and out of the cavity depends on the leakage area of the cabin wall. Leakage commonly occurs through panel joints and gaps surrounding penetrations, as well as around doors, where additional structure and mechanisms may provide addition thermal conductivity and air passages to the outer skin. A certain amount of flow in and out of the cavity is unavoidable because of normal pressurization and depressurization of the cabin during descent and climb. The driving pressure, or stack pressure, is simply the density difference between the connected volumes:

$$\Delta P_{stack} = (\rho_{cavity1} - \rho_{cavity2})gh$$

$$= \frac{P_{cabin}\left(\dfrac{1}{T_{cavity1}} - \dfrac{1}{T_{cavity2}}\right)gy}{R}$$

*where*

- $y$ = cavity height, ft
- $T$ = temperature, °R

$\rho$ = air density, slug/ft$^3$
$g$ = gravitational constant = 32.3 ft/s$^2$
$R$ = gas constant, 1716 ft$^2$/s$^2 \cdot °R$
$\Delta P$ = stack pressure, lb/ft$^2$
$P_{cabin}$ = absolute cabin pressure, lb/ft$^2$

## Metabolic Heat from Occupants

A thorough treatment of metabolic heat from humans is covered in Chapter 9 of the 2017 *ASHRAE Handbook—Fundamentals*. Because an airplane cabin is frequently at higher altitudes, the balance between sensible and latent heat changes slightly from that given in that chapter. To correct for altitude, the following approach is recommended. First, examining the heat transfer coefficient:

For low air velocity ($V < 40$ fpm), flow is dominated by natural convection:

$$h = \frac{k}{d}C(\text{Gr Pr})^m = \frac{k}{d}C\left(\frac{\rho^2 g\beta(\Delta T)d^3\text{Pr}}{\mu^2}\right)^m \rightarrow h \propto \rho^{2m}$$

For a cylindrical approximation of an adult at rest, Gr = $10^7$, so $C = 0.59$ and $m = 1/4$, which leads to

$$h_{alt} = h_{SL}\left(\frac{\rho_{alt}}{\rho_{SL}}\right)^{2(1/4)} = h_{SL}\left(\frac{P_{alt}}{P_{SL}}\right)^{0.5}$$

For higher air velocity ($40 < V < 800$ fpm), flow is dominated by forced convection:

$$h = \frac{k}{d}C(\text{Re})^n\text{Pr}^{1/3} = \frac{k}{d}C\left(\frac{\rho Vd}{\mu}\right)^n \text{Pr}^{1/3} \rightarrow h \propto \rho^n$$

For a cylindrical approximation of an adult at rest, Re > 4000, so $C = 0.193$ and $n = 0.618$, which leads to

$$h_{alt} = h_{SL}\left(\frac{\rho_{alt}}{\rho_{SL}}\right)^{0.618} = h_{SL}\left(\frac{P_{alt}}{P_{SL}}\right)^{0.618}$$

These two correction factors have been combined (see Equation [37] in Chapter 9 of the 2017 *ASHRAE Handbook—Fundamentals*) to produce a simpler relationship that applies to the full velocity range ($0 < V < 800$ fpm):

$$h_{alt} \approx h_{SL}\left(\frac{P_{alt}}{P_{SL}}\right)^{0.55}$$

Next, examining the evaporation or mass transfer from the occupants, the evaporative heat transfer coefficient varies inversely with the ambient pressure (see Equation [38] in Chapter 9 of the 2017 *ASHRAE Handbook—Fundamentals*):

$$h_e = (LR)(h)$$

$$h_{e,alt} = LR_{alt}h_{SL}\left(\frac{P_{alt}}{P_{SL}}\right)^{0.55} \quad \text{and} \quad h_{SL} = \frac{h_{e,SL}}{LR_{SL}}$$

$$h_{e,alt} = LR_{alt}h_{SL}\left(\frac{h_{e,SL}}{LR_{SL}}\right)\left(\frac{P_{alt}}{P_{SL}}\right)^{0.55}$$

Substitute

$$LR_{alt} = \frac{R_{air}h_{fg}(144)\left(\dfrac{D_v}{\alpha}\right)^{2/3}}{P_{alt}c_{p,air}R_w}$$

$$LR_{SL} = \frac{R_{air}h_{fg}(144)\left(\dfrac{D_v}{\alpha}\right)^{2/3}}{P_{SL}c_{p,air}R_w}$$

(a conversion of pressure by 144 is shown here because LR is customarily in units of °F/psi)

$$h_{e,alt} \approx h_{e,SL}\left(\frac{P_{SL}}{P_{alt}}\right)^{0.45}$$

*where*

LR = Lewis relation, °F/psi
$h$ = heat transfer coefficient, Btu/h·ft$^2$·°F
$h_{SL}$ = heat transfer coefficient at sea level, Btu/h·ft$^2$·°F
$h_e$ = evaporative heat transfer coefficient, Btu/h·ft$^2$·psi
$h_{e,alt}$ = evaporative heat transfer coefficient at altitude, Btu/h·ft$^2$·psi
$h_{e,SL}$ = evaporative heat transfer coefficient at sea level, Btu/h·ft$^2$·psi
$P_{alt}$ = cabin pressure at altitude, lb/ft$^2$
$P_{SL}$ = pressure at sea level; 2116 lb/ft$^2$
$R_{air}$ = gas constant for air; 1716 ft$^2$/s$^2$·°R
$h_{fg}$ = evaporation enthalpy at human skin temperature, 1037 Btu/lb
$D_v$ = mass diffusivity of water vapor in air; 0.99 ft$^2$/h
$\alpha$ = diffusivity; 0.8366 ft$^2$/h
$c_{p,air}$ = specific heat of air; 0.24 Btu/lb·°F
$R_w$ = gas constant for water vapor; approximately 2758 ft$^2$/s$^2$·°R

About 70% of the metabolic heat is lost through convection/radiation (245 Btu/h sensible or 98 Btu/h convection, $h = 0.55$, plus 147 Btu/h radiation, $h_r = 0.83$) and 30% through evaporation (105 Btu/h latent) while seated at rest at sea level (see Table 1). At 8000 ft cabin altitude, in still air, the sensible heat would drop to $(0.47/0.55)98 = 84$ Btu/h convection, the radiation would remain at 147 Btu/h, and the latent heat would rise to $(129/113)105 = 120$ Btu/h for a total of 351 Btu/h. This would indicate a slightly higher temperature for comfort, or a net effect of a slightly cooler sensation at altitude, compared to the 350 Btu/h total required.

## Internal Heat Sources

When considering heat sources in the cabin, there are several parallels to commercial and residential HVAC. Many heat sources such as appliances (refrigerators, conventional ovens, microwave ovens), lighting, and entertainment (TV, stereo), may be in the cabin. In addition, the electronics and equipment associated with the

**Table 1   Heat and Mass Transfer Coefficients for Human Body Versus Altitude**

| Altitude, ft | Pressure, lb/ft$^2$ | Convection $h$, Btu/h·ft$^2$·°F | | Evaporation $h_e$, Btu/h·ft$^2$·psi | |
|---|---|---|---|---|---|
| | | $V < 40$ | $40 < V < 800$ | $V < 40$ | $40 < V < 800$ |
| 0 | 2116 | 0.55 | $0.061V^{0.6}$ | 113 | $12.5V^{0.6}$ |
| 1000 | 2041 | 0.54 | $0.060V^{0.6}$ | 115 | $12.7V^{0.6}$ |
| 2000 | 1968 | 0.53 | $0.059V^{0.6}$ | 117 | $12.9V^{0.6}$ |
| 3000 | 1897 | 0.52 | $0.057V^{0.6}$ | 119 | $13.1V^{0.6}$ |
| 4000 | 1828 | 0.51 | $0.056V^{0.6}$ | 121 | $13.4V^{0.6}$ |
| 5000 | 1761 | 0.50 | $0.055V^{0.6}$ | 123 | $13.6V^{0.6}$ |
| 6000 | 1696 | 0.49 | $0.054V^{0.6}$ | 125 | $13.8V^{0.6}$ |
| 7000 | 1633 | 0.48 | $0.053V^{0.6}$ | 127 | $14.0V^{0.6}$ |
| 8000 | 1572 | 0.47 | $0.052V^{0.6}$ | 129 | $14.3V^{0.6}$ |

operation of a commercial aircraft put demands on the airplane's environmental control system.

**Cooling Requirements.** The sizing criteria for air conditioning are usually ground operation on a hot, humid day with the aircraft fully loaded and the doors closed. A second consideration is cooldown of an empty, heat-soaked aircraft before passenger loading; a cooldown time of less than 30 min is usually desired. A cabin temperature of between 75 and 80°F is typically specified for these hot-day ground design conditions. During cruise, the system should maintain a cabin temperature of 75°F with a full passenger load. The cooling load is entirely sensible in most cases when air-cycle machines are used. When a vapor-cycle recirculation system is used, latent heat is added.

**Heating Requirements.** Heating requirements are based on a partially loaded aircraft on a very cold day. Cabin temperature warm-up for a cold-soaked aircraft is desired to be within 30 min as well. A cabin temperature of 70°F is typically specified for cold-day ground-operating conditions. During cruise, the system should able to maintain a cabin temperature of 75°F with a 20% passenger load, a cargo compartment temperature above 40°F, and cargo floor temperatures above 32°F to prevent freezing of cargo.

## Temperature Control

Whenever a section of the cabin or flight deck has capability for independent supply temperature control, it is termed a **zone**. Commercial aircraft (over 19 passengers) can have as few as two zones (cockpit and cabin) and as many as seven. These crew and passenger zones are individually temperature-controlled to a crew-selected temperature for each zone, ranging from 65 to 85°F. Some systems have limited temperature control in the passenger zones that can be adjusted by the flight attendants. The selected zone temperature is controlled to within 2°F of the sensed temperature, and temperature uniformity in the zone should be within 5°F. Separate temperature controls can be provided for cargo compartments.

Temperature control may also be the predominant driver of ventilation requirements. The interior of the fuselage has several electronic/electrical heat sources that are required for the aircraft's operation, as well as heat loads from ambient and from occupants and their activities. These increasing heat loads are accommodated by reducing supply temperatures:

$$T_{supply} = T_{cabin} - \frac{q_{sources}}{c_p \dot{w}}$$

where

$q_{sources}$ = all heat into cabin, Btu/h
$\dot{w}$ = air weight flow, lb/h
$c_p$ = specific heat; 0.24 Btu/lb·°F for air
$T$ = temperature, °F

Supply temperatures in each of the zones have practical limits, such as the freezing temperature of water (humidity), when either the heat loads are too large or the mass flow is too low.

## Air Velocity

The passenger cabin is most similar to buildings with very high occupant densities, such as theaters or lecture halls. In these situations, the air-conditioning system is typically in cooling mode (i.e., the supply diffuser temperature is cooler than the room temperature). The ducting and diffuser networks are best described as cold-air systems, in which the duct velocities are higher, duct temperatures lower, and the fraction of recirculated air smaller (about 50% of the mixture) than in buildings (which use up to 95%). The cold-air diffuser is also in much closer proximity to the occupants in an aircraft cabin. The design challenge is to deliver cool air to the passengers without uncomfortable drafts.
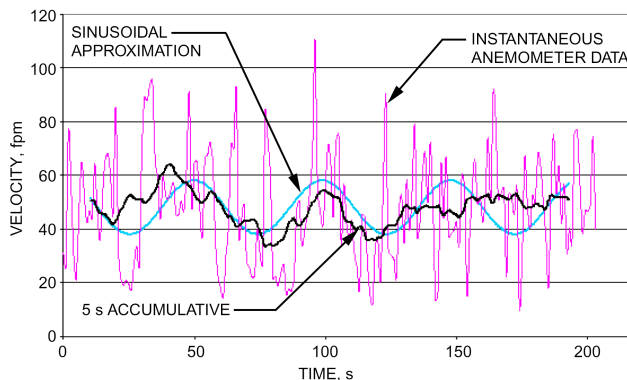


**Fig. 6   Transient Air Velocity Measured in Seated Area of Aircraft Cabin**

The velocity characteristics of an airplane cabin are uniquely affected by transitional flow behavior. The supply diffuser Reynolds number is typically between 3000 and 5000. Turbulence induced by the diffuser affects the perceived draftiness. Figure 6 shows the unsteady velocity variations measured in an aircraft cabin.

At any instant in time, the velocity field in the cabin will change, but an overall pattern develops for the time-averaged velocity. An example of this comes from computational fluid dynamics (CFD) modeling of a passenger cabin. Ventilation air enters the cabin near the center and blows outward in two directions. Air leaves near the floor on both sides, as shown in Figure 7.

Several comfort indices are used to evaluate air velocity, such as predicted percent dissatisfied (PPD) or predicted mean vote (PMV). Draft-sensitive areas of the body such as the ankles or neck receive special attention during air distribution system design. The velocity requirements are described in detail in Chapter 9 of the 2017 *ASHRAE Handbook—Fundamentals* and ASHRAE *Standard* 55.

## Ventilation

Air drawn from the compressor section of the jet engine is called **bleed air** (also known as outside air, fresh air, outdoor air, or ambient air). When air is provided by sources other than the engine, it is not bleed air in the strict sense, because it is no longer bled from the engines. The current FAA requirement is to provide 0.55 lb/min of bleed/outdoor air per person. Because this requirement is expressed as a weight flow, the bleed air ventilation rate as a volumetric flow varies with cabin pressure and temperature. Cabin altitude is a convenient way of expressing cabin pressure by referencing the cabin pressure to a standard atmosphere. The required 0.55 lb/min is equivalent to about 7 cfm/person at sea level and 75°F. Based on ASHRAE research, ASHRAE *Standard* 161 established a ventilation rate for aircraft passengers at 7.5 cfm per passenger. This rate was based in part on the consideration that not all spaces in the enclosed area achieve 100% ventilation effectiveness. At other cabin pressures or altitudes, flow volumes can be found with the following equation:

$$Q_{FR} = \frac{\dot{w}}{\rho} = \frac{\dot{w}}{\left(\dfrac{P_c g}{RT_c}\right)} = \frac{\dot{w}RT_c}{P_c g}$$

where

$\dot{w}$ = 0.55 lb/min
$R$ = 1716 ft$^2$/s$^2$·°R
$g$ = 32.2 ft/s$^2$
$T_c$ = cabin temperature; 70°F = 529.67°R
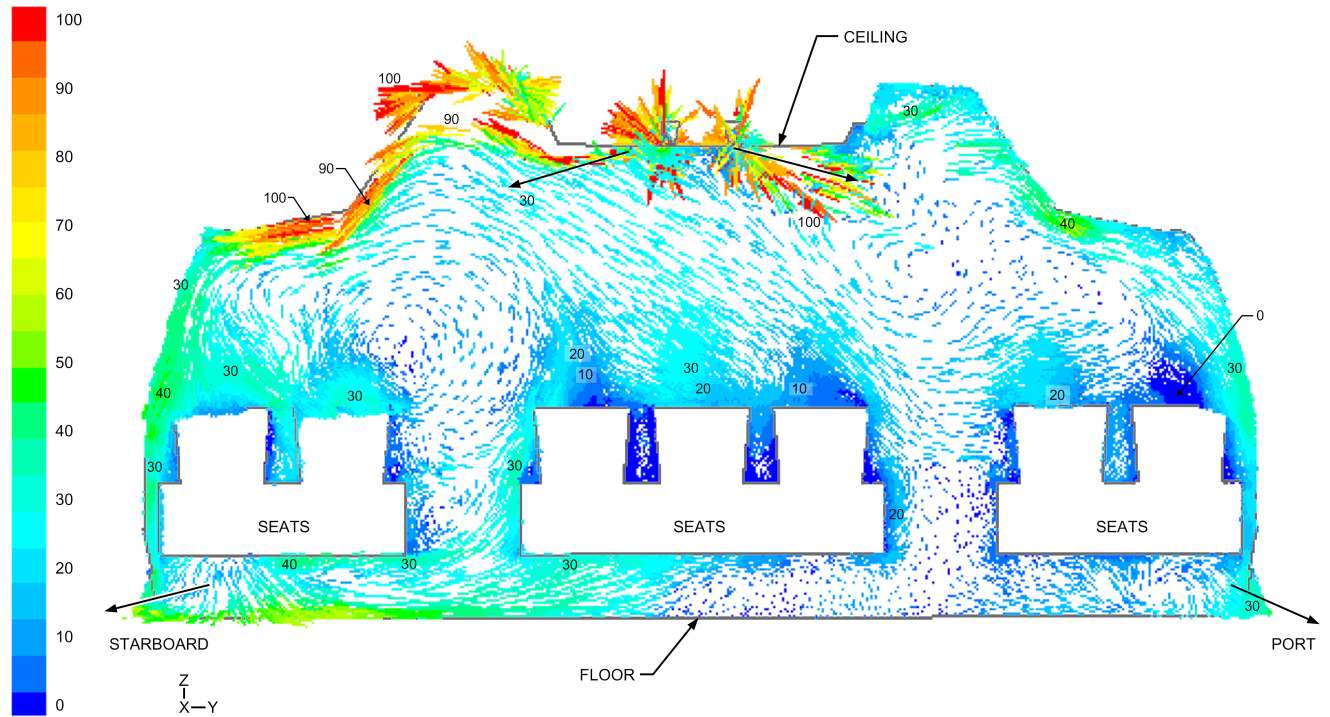$P_c$ = cabin pressure from Table 2, lb/ft$^2$

**Fig. 7   Cabin Air Velocities from CFD, fpm**
(Lin et al. 2005)

In many aircraft, the bleed/outdoor air flow is augmented by filtered or recirculated air. There are currently no regulatory requirements on the amount of recirculated air that enters the cabin, but it is customary to provide about 10 cfm per person of recirculated air in addition to the bleed air required by regulation, for a total of about 20 cfm per person at 8000 ft cabin altitude.

**Ventilation Effectiveness.** ASHRAE *Standards* 62.1-2018 and 161-2018 address ventilation effectiveness (VE), a measure of mixing within the volume relative to a perfectly mixed system (*Standard* 62.1 uses the term **zone air distribution effectiveness $E_z$** instead of VE). It is described with the following equations:

$$VE = \frac{c_{mixed} - c_{in}}{c_{local} - c_{in}}$$

where $c$ = contaminant concentration, or

$$VE = \frac{Q_{local}}{Q_{cabin}}$$

*where*

$c_{local}$ = local contaminant concentration by volume
$c_{in}$ = inlet contaminant concentration
$c_{mixed}$ = concentration if perfectly mixed
$Q_{cabin}$ = contaminant flow to cabin or zone, cfm
$Q_{local}$ = flow delivered to breathing zone, cfm

Contaminant concentrations in a perfectly mixed system are the same in the cabin volume as at the exit (floor grilles), and the concentration in the exit is based only on the ventilation rate and generation rate (including source and sink). Therefore, ventilation effectiveness indicates the degree of contaminant stratification with the volume. VE > 1 means that concentrations in the breathing zone are lower than in a perfectly mixed system; VE < 1 means they are higher.

There is a distinction between VE for bleed air and VE for total ventilation. For bleed air, the inlet concentration $c_{in}$ is the

**Table 2   FAA-Specified Bleed Airflow per Person**

| Cabin Pressure | | | Required Flow per Person |
|---|---|---|---|
| psia | lb/ft² | Altitude, ft | at 75°F, cfm |
| 14.696 | 2116 | 0 | 7.4 |
| 14.432 | 2078 | 500 | 7.5 |
| 14.173 | 2041 | 1000 | 7.7 |
| 13.917 | 2004 | 1500 | 7.8 |
| 13.664 | 1968 | 2000 | 8.0 |
| 13.416 | 1932 | 2500 | 8.1 |
| 13.171 | 1897 | 3000 | 8.3 |
| 12.930 | 1862 | 3500 | 8.4 |
| 12.692 | 1828 | 4000 | 8.6 |
| 12.458 | 1794 | 4500 | 8.7 |
| 12.228 | 1761 | 5000 | 8.9 |
| 12.001 | 1728 | 5500 | 9.1 |
| 11.777 | 1696 | 6000 | 9.2 |
| 11.557 | 1664 | 6500 | 9.4 |
| 11.340 | 1633 | 7000 | 9.6 |
| 11.126 | 1602 | 7500 | 9.8 |
| 10.916 | 1572 | 8000 | 10.0 |

concentration of gases in the supply air to the entire system (i.e., bleed air concentration). The local concentration will be larger than the inlet concentration only if the contaminant is generated within the cabin. For total ventilation, VE uses the $c_{in}$ at the nozzle (i.e., supply mixture concentration) and includes contaminants from the recirculation system. The practical use of this VE applies to particulate levels in the cabin, because the recirculated air is equivalent to bleed air in this regard.

Contaminant concentrations in the cabin can be converted to flows delivered to the breathing zone $Q_{local}$ using the following relationship:

$$Q_{local} = \frac{q_{gen}}{c_{local} - c_{in}}$$

Substitute

$$q_{gen} = Q_{supplied}(c_{mixed} - c_{in})$$

$$Q_{local} = Q_{supplied} \frac{c_{mixed} - c_{in}}{c_{local} - c_{in}}$$

where

$q_{gen}$ = CO$_2$ generation rate, 0.0105 scfm/person
$c_{local}$ = local CO$_2$ concentration by volume
$c_{in}$ = inlet CO$_2$ concentration
$Q_{supplied}$ = flow to cabin or zone, cfm
$Q_{local}$ = flow delivered to breathing zone, cfm

Some consideration can be given to distribution effectiveness (DE), where flows to higher-occupant-density sections of the cabin (e.g., coach) are used to set minimum flows to the cabin, and lower-density sections (e.g., first class) may subsequently be over-ventilated:

$$DE = \frac{Q_{zone}/n_{zone}}{Q_{cabin}/n_{cabin}}$$

where

$Q_{zone}/n_{zone}$ = flow per person in zone
$Q_{cabin}/n_{cabin}$ = average flow per person for entire cabin

Distribution effectiveness accounts for a system that provides a uniform flow per length of cabin yet has varying seating densities along the length. For bleed air distribution, this effectiveness is tempered somewhat by occupant diversity $D$ (see ASHRAE *Standard* 62.1), because underventilated zones feed into the same recirculation flow. For total flow (bleed + recirculated) and for systems without recirculation, however, occupant diversity does not apply.

System ventilation efficiency (SVE) is a measure of how well mixed the recirculated air is with the bleed air before it enters the cabin. The SVE can be determined from the concentration variations in the ducts leaving the mix manifold (see Figure 11), for instance. The SVE is similar to VE in formulation:

$$SVE = \frac{c_{all\ zones} - c_{amb}}{c_{zone} - c_{amb}}$$

where

$c_{all\ zones}$ = average concentration of all supply ducts
$c_{zone}$ = concentration in individual supply duct
$c_{amb}$ = ambient reference concentration = $C_{fr}$ (bleed air concentration)

## Dilution Ventilation and TLV

Contaminants that are present in the supply air and are also generated within the cabin require increasing dilution flows to avoid reaching Threshold Limit Values (TLVs®) (ACGIH). For example, suppose carbon monoxide is present in the atmosphere at 210 ppb and that each person generates 0.168 mL CO per minute, or $5.93 \times 10^{-6}$ cfm (Owens and Rossano 1969). The amount of bleed air required to stay below the EPA guideline of 9000 ppb will depend on the ambient CO levels, the human generation rate, and the CO contribution of the ventilation system:

$$Q_{req} = \frac{q_{gen}}{C_{TLV} - \Delta C_{system} - C_{fr}} = \frac{q_{gen}}{C_{TLV} - C_{supply}}$$

where

$C_{TLV}$ = allowable concentration
$\Delta C_{system}$ = concentration rise from system
$C_{supply}$ = concentration in supply (air entering cabin)
$C_{fr}$ = concentration in bleed air
$q_{gen}$ = CO generated per person

**Example 3.** If the ventilation system does not contribute carbon monoxide to the supply air, then the required ventilation rate to stay below the threshold is

$C_{TLV}$ = 9000 ppb = 0.000009

$q_{gen}$ = $5.93 \times 10^{-6}$ cfm

$\Delta C_{system}$ = 0

$C_{fr}$ = 210 ppb = $2.1 \times 10^{-7}$

$$Q_{req} = \frac{q_{gen}}{C_{TLV} - \Delta C_{system} - C_{fr}} = \frac{5.93 \times 10^{-6}}{0.000009 - 0 - 2.1 \times 10^{-7}}$$

$$= 0.67 \text{ cfm/person}$$

If, however, the ventilation system produces a 1000 ppb rise in carbon monoxide, then the required ventilation is

$C_{TLV}$ = 9000 ppb = 0.000009

$q_{gen}$ = $5.93 \times 10^{-6}$ cfm

$\Delta C_{system}$ = 1000 ppb = 0.000001

$C_{fr}$ = 210 ppb = $2.1 \times 10^{-7}$

$$Q_{req} = \frac{q_{gen}}{C_{TLV} - \Delta C_{system} - C_{fr}} = \frac{5.93 \times 10^{-6}}{0.000009 - 0.000001 - 2.1 \times 10^{-7}}$$

$$= 0.76 \text{ cfm/person}$$

It is important to note that, under certain circumstances, $q_{gen}$ and $\Delta C_{system}$ may change sign as contaminant sources become contaminant sinks. This simplified approach shown here is more conservative, and could overpredict contaminant levels in real situations.

## Air Exchange

High occupant density ventilation systems have higher air exchange rates than most buildings (i.e., offices). The typical airplane may have an air exchange rate of 10 to 20 air changes per hour (ach), whereas an office might have 1 ach. The air is not replaced in a mixed system at every air exchange. Actually, the ratio $Q/V$ (air exchange rate) is more like the inverse of decay time constant $\tau$. An airplane cabin can be approximated as a partially mixed volume (a volume with ventilation effectiveness) as long as the contaminant sources are uniformly distributed throughout the volume. For a well-mixed volume, contaminant in equals contaminant out plus contaminant accumulated in the volume, or

$$Qc_{in} = Qc_{out} + V \frac{dc}{dt}$$

Accounting for ventilation effectiveness, the concentration leaving the volume $c_{out}$ is related to the concentration within the volume $c$ and the concentration entering the volume $c_{in}$ by the ventilation effectiveness VE:

$$VE = \frac{c_{mixed} - c_{amb}}{c_{local} - c_{amb}} = \frac{c_{out} - c_{amb}}{c_{local} - c_{amb}} \rightarrow c_{out} = c_{in} + VE(c - c_{in})$$

Substituting,

$$Qc_{in} = Q[c_m + VE(c - c_{in})] + V \frac{dc}{dt}$$

which leads to

$$c = c_{in} - (c_{in} - c_o)e^{-\frac{Q(VE)}{V}t}$$

Although air exchange rates are occasionally used as requirements on the ventilation system, in the case of cabin ventilation, there is no basis for setting one. Air exchange rate can be a surrogate (only for similarly sized volumes) for temperature uniformity, air quality, or smoke clearance. The flow-per-person specification is preferred, because it can be related to the predominant pollutant source more directly. Air exchange rates therefore indirectly provide valid ventilation comparisons between airplanes of similar volume and seating density. However, comparisons with buildings are misleading: occupant densities could be 30 times higher in aircraft, and bioeffluent doses (defined here as the time integral of the concentration of occupant-generated contaminants) for the same ventilation rate per person are greater in aircraft passenger cabins, depending upon occupancy times (see the section on Air Quality).

## Filtration

Most airplane manufacturers have provisions for recirculated air filtration. Common practice is to install high-efficiency particulate air (HEPA) filters. The current industry standard for new build production aircraft is EU class H13 according to EN *Standard* 1822-1 and ISO *Standard* 29463-1 class 35H (i.e., 99.95% minimum removal efficiency by sodium flame test) (Eurovent 4/4, BS3928). This is equivalent to 99.97% minimum removal efficiency of approximately 0.3 μm when tested according to Institute of Environmental Sciences and Technology *Recommended Practice* RP-CC001.5 (IEST 1997).

Filters are required to have sufficient particulate capacity to remain effective between normal maintenance intervals. The life of the filter is related to the recirculation system pressure drop, system operating pressure, and the recirculation fan curve. As the filter becomes loaded, pressure drop increases. When added to the system losses, the effect is a reduction in flow, as shown in Figure 8.

It is important to change the filters at least as often as recommended by the manufacturer to maintain flow capacity.

Carbon/HEPA filters are available on the recirculation system for some aircraft models. Performance is not fully characterized. Filters must be tested and certified for each aircraft design. Currently available designs are intended to replace standard HEPA filters. The system designer must verify with the filter manufacturer the service life of the filter for the intended application. Most systems have no filtration of the engine bleed air supply as standard equipment, although some technologies (e.g., combined VOC/ozone converters
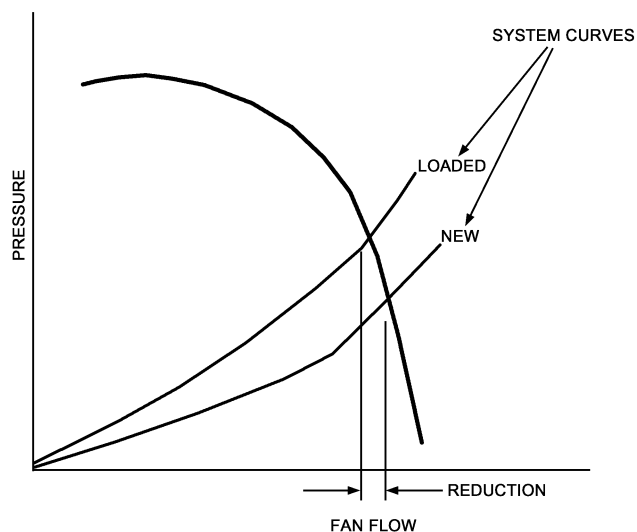


**Fig. 8 Flow Reduction Caused by Filter Loading**

and bleed air centrifugal cleaners) are sometimes offered as optional equipment.

## Pressurization/Oxygen

Cabin pressurization achieves the required partial pressures of oxygen for the crew and passengers during high-altitude flight. At altitudes above 8000 ft, the occupied cabin must be pressurized to an equivalent altitude of 8000 ft or less to allow normal physiological functions without supplemental oxygen. The maximum pressure difference between the cabin and outside environment is limited by aircraft structural design limits. The differential pressure control provides a cabin pressure based on the flight altitude of the aircraft. A typical cabin altitude schedule is shown in Figure 3. Additional provisions that are separate from normal cabin pressure controls must be provided for positive- and negative-pressure relief to protect the aircraft structure.

A DOT-sponsored study (DOT 1989) concluded that current pressurization criteria and regulations are generally adequate to protect the traveling public. The study also noted that the normal maximum rates of change of cabin pressure (approximately 500 ft/min in increasing altitude and 300 ft/min in decreasing altitude) do not pose a problem for the typical passenger.

However, pressurization of the cabin to equivalent altitudes of up to 8000 ft, as well as changes in the normal rates of pressure during climb and descent, may create discomfort for some people, such as those suffering from upper respiratory or sinus infections, obstructive pulmonary diseases, anemia, or certain cardiovascular conditions. In those cases, supplemental oxygen may be recommended. Children and infants sometimes experience discomfort or pain because of pressure changes during climb and descent. Injury to the middle ear has occurred to susceptible people, but is rare.

During a sudden cabin depressurization in flight, passengers and crew are provided with overhead masks supplying supplemental oxygen. Passengers with respiratory diseases can bring portable oxygen containers on board.

Humans at rest breathe at a rate of approximately 0.32 cfm while consuming oxygen at a rate of 0.014 cfm at 8000 ft. The percent oxygen makeup of the supply air remains at approximately 21% at cruise altitude. A person receiving 10 cfm of outside air and 10 cfm of recirculation air would therefore receive approximately 4.2 cfm of oxygen. The level drops to 4.186 cfm as it leaves the cabin. Consequently, the content of oxygen in cabin air is little affected by breathing (i.e., it drops 0.33%). Although the percentage of oxygen in cabin air remains virtually unchanged (20.93%) at all normal flight altitudes, the partial pressure of oxygen decreases with increasing altitude, which decreases the amount of oxygen held by the blood's hemoglobin. The increase in cabin altitude may cause low-grade hypoxia (reduced tissue oxygen levels) in some people. However, the National Academy of Sciences (NAS 1986, 2002) concluded that pressurization of the cabin to an equivalent altitude of 5000 to 8000 ft is physiologically safe for healthy individuals: no supplemental oxygen is needed to maintain sufficient arterial oxygen saturation.

## System Description

The outdoor air supplied to the airplane cabin is usually provided by the compressor stages of the engine, and cooled by air-conditioning packs located under the wing center section. An air-conditioning pack uses the compressed ambient air as the refrigerant in air-cycle cooling.

Air is supplied and exhausted from the cabin on a continuous basis. As shown in Figure 9, air enters the passenger cabin from supply nozzles that run the length of the cabin. Exhaust air leaves the cabin through return air grilles located in the sidewalls near the floor, running the length of the cabin on both sides. Exhaust air is continuously extracted from below the cabin floor by recirculation

fans that return part of the air to the distribution system. The remaining exhaust air passes to an outflow valve, which directs the air overboard. The cabin ventilation system is designed to deliver air uniformly along the length of the cabin.

### Pneumatic System

The pneumatic system, or **engine bleed air system**, extracts a small amount of the gas turbine engine compressor air to ventilate and pressurize the aircraft compartments. A schematic of a typical system is shown in Figure 10. During climb and cruise, bleed air is usually taken from the mid-stage engine bleed port for minimum-horsepower extraction (bleed penalty). During idle descent it is taken from the high-stage engine bleed port, where maximum available pressure is required to maintain cabin pressure and ventilation. The auxiliary power unit (APU) is also capable of providing the pneumatic system with compressed air on the ground and in flight. Bleed air is pressure-controlled to meet the requirements of the system using it, and it is usually cooled to limit bleed manifold temperatures to meet fuel safety requirements. In fan jets, engine fan air is extracted for use as a heat sink for bleed air using an air-to-air heat exchanger called a precooler; for turboprop engines, ram air is used, which usually requires an ejector or fan for static operation. Other components include bleed-shutoff and modulating valves, a fan-air-modulating valve, sensors, controllers, and ozone converters. The pneumatic system is also used intermittently for airfoil and engine cowl anti-icing, engine start, and several other pneumatic functions.

Each engine has an identical bleed air system for redundancy and to equalize the compressor air bled from the engines. The equipment is sized to provide the necessary temperature and airflow for airfoil and cowl anti-icing, or cabin pressurization and air



**Fig. 9    Cabin Airflow Path**



| $\boxed{S}$ = STARTER | $\textcircled{F}$ = FAN | $\textcircled{I}$ = INTERMEDIATE STAGE | $\textcircled{H}$ = HIGH STAGE |

**Fig. 10    Engine/APU Bleed System**

conditioning with one system or engine inoperative. The bleed air used for airfoil anti-icing is controlled by valves feeding piccolo tubes extending along the wing leading edge. Similar arrangements may be used for anti-icing the engine cowl and tail section.

### Air Conditioning

Air-cycle refrigeration is the predominant means of air conditioning for commercial and military aircraft. The reverse-Brayton cycle or Brayton refrigeration cycle is used, as opposed to the Brayton power cycle that is used in gas turbine engines. The difference between the two cycles is that, in the power cycle, fuel in a combustion chamber adds heat, and in the refrigeration cycle, a ram-air heat exchanger removes heat. The familiar Rankine vapor cycle, which is used in building and automotive air conditioning and in domestic and commercial refrigeration, is used for military aircraft as well as galley cooling on larger commercial transports.

In an air cycle, compression of the ambient air by the gas turbine engine compressor provides the power input. The heat of compression is removed in a heat exchanger using ambient air as the heat sink. This cooled air is refrigerated by expansion across a turbine powered by the compressed bleed air. The turbine energy resulting from the isentropic expansion is absorbed by a second rotor, which is either a ram air fan, bleed air compressor, or both. This assembly is called an **air cycle machine (ACM)**.

The most common types of air-conditioning cycles for commercial transport aircraft are shown in Figure 11. All equipment in common use on commercial and military aircraft is open loop, although many commercial aircraft systems include various means of recirculating cabin air to minimize engine bleed air use without sacrificing cabin comfort. The basic differences between the systems are the type of air cycle machine used and its means of water separation. Hybrid ACM/vapor cycle systems are discussed in Chapter 27 of the 2018 *ASHRAE Handbook—Refrigeration*.

The most common of these air cycle machines in use are the bootstrap ACM consisting of a turbine and compressor; the three-wheel ACM consisting of a turbine, compressor, and fan; and the four-wheel ACM consisting of two turbines, a compressor, and a fan. The bootstrap ACM is most commonly used for military applications, although many older commercial aircraft models use the bootstrap cycle. The three-wheel ACM (simple bootstrap cycle) is used on most of the newer commercial aircraft, including commuter aircraft and business aircraft. The four-wheel ACM (condensing cycle) was first applied in 777 aircraft.

The compartment supply temperature may be controlled by mixing ram-cooled bleed air with the refrigerated air to satisfy the range of heating and cooling. Other more sophisticated means of temperature control are often used; these include ram air modulation, various bypass schemes in the air-conditioning pack, and downstream controls that add heat for individual zone temperature control.

The bleed airflow is controlled by a valve at the inlet of the air-conditioning pack. The flow control valve regulates flow to the cabin for ventilation and repressurization during descent. Most aircraft use two or three air cycle packs operating in parallel to compensate for failures during flight and to allow the aircraft to be dispatched with certain failures. However, many business and commuter aircraft use a single pack. High-altitude aircraft that have a single pack also have emergency pressurization equipment that uses ram-cooled bleed air.

If the engine ingests water, or if the air cycle drops significantly below the dew point, some water separation devices are installed to avoid water spray in the cabin. Low- or high-pressure water separation may be used. A **low-pressure water separator**, located downstream from the cooling turbine, has a cloth lining that coalesces fine water particles entrained in the turbine discharge air into droplets. The droplets are collected, drained, and sprayed into the ram airstream using a bleed-air-powered ejector; this process
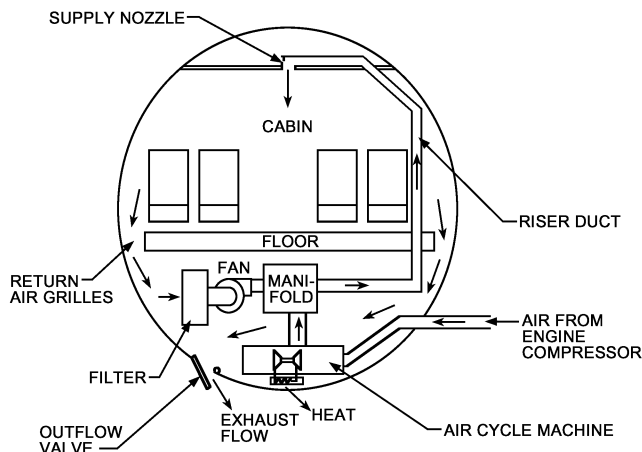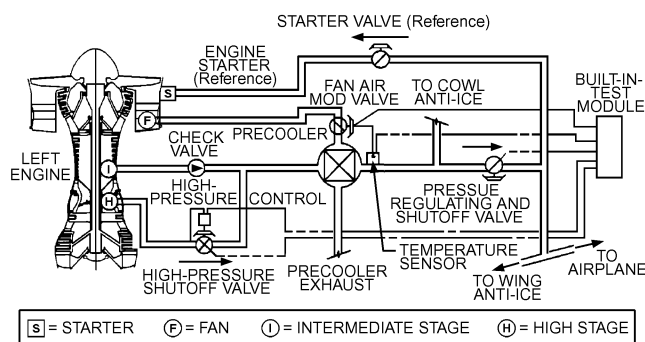
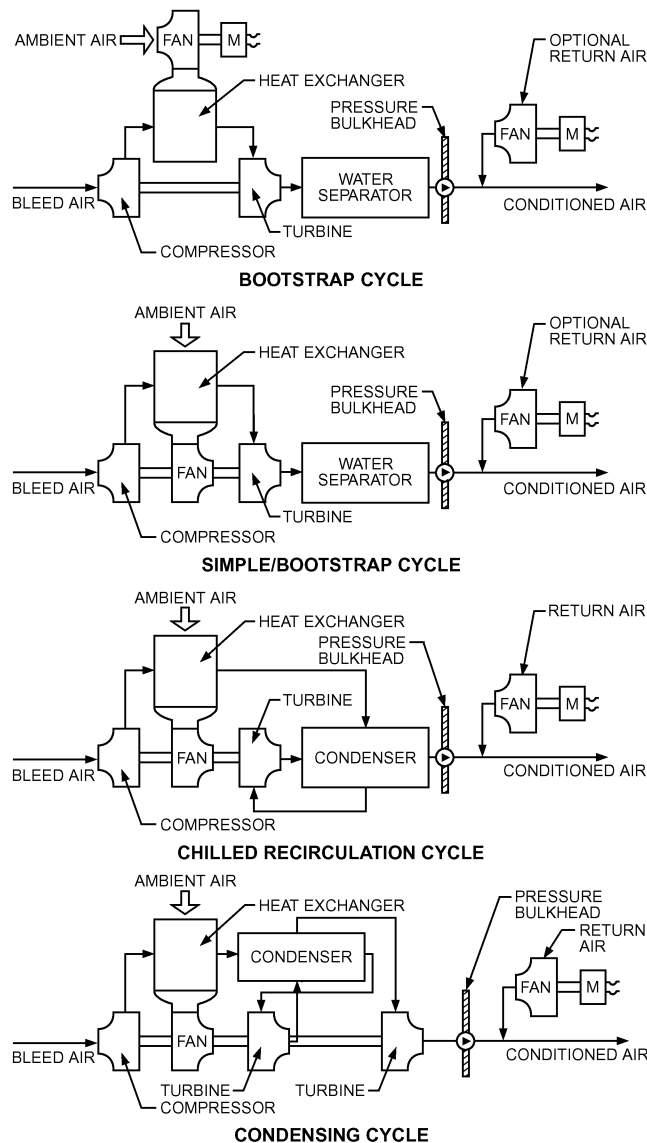**Fig. 11   Some Aircraft Refrigeration Cycles**



**Fig. 12   Aircraft Air-Conditioning Schematic**

increases pack cooling capacity by depressing the ram air heat sink temperature.

The **high-pressure water separator** condenses and removes moisture at high pressure upstream of the cooling turbine. A heat exchanger uses turbine discharge air to cool the high-pressure air sufficiently to condense most of the moisture present in the bleed air supply. The moisture is collected and sprayed into the ram airstream.

In the condensing cycle one turbine removes the high-pressure water and the second turbine does the final expansion to subfreezing temperature air that is to be mixed with filtered, recirculated cabin air. Separating these functions recovers the heat of condensation, which results in a higher cycle efficiency. It also eliminates condenser freezing problems because the condensing heat exchanger is operated above freezing conditions.

The air-conditioning packs are located in unpressurized areas of the aircraft to minimize structural requirements of the ram air circuit that provides the necessary heat sink for the air-conditioning cycle. This location also provides protection against cabin depressurization in the event of a bleed or ram air duct rupture. The most common areas for the air-conditioning packs are the underwing/wheel
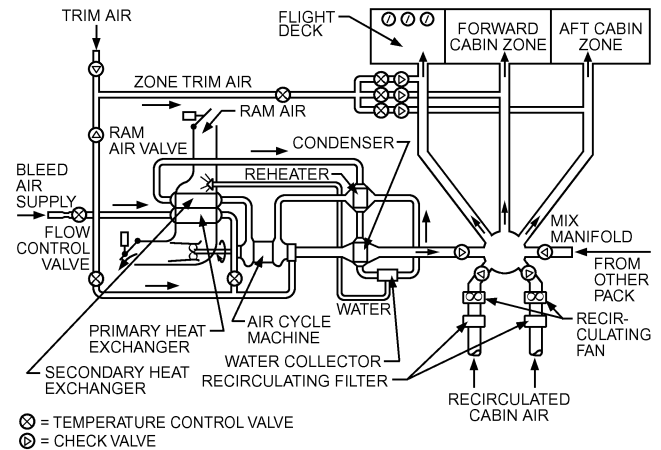
well area and the tail cone area aft of the rear pressure bulkhead. Other areas include the areas adjacent to the nose wheel and over-wing fairing. The temperature control components and recirculating fans are located throughout the distribution system in the pressurized compartments. The electronic pack and zone temperature controllers are located in the electrical/electronic (E/E) bay. The air-conditioning control panel is located in the flight deck. A schematic of a typical air-conditioning system is shown in Figure 12.

## Cabin Pressure Control

Cabin pressure is controlled by modulating airflow discharged from the pressurized cabin through one or more cabin outflow valves. The cabin pressure control includes the outflow valves, controller, selector panel, and redundant positive-pressure relief valves. Provisions for negative-pressure relief are incorporated in the relief valves and/or included in the aircraft structure (door). The system controls the cabin ascent and descent rates to acceptable comfort levels, and maintains cabin pressure altitude in accordance with cabin-to-ambient differential pressure schedules. Modern controls usually set landing field altitude, if not available from the flight management system (FMS), and monitor aircraft flight through the FMS and the air data computer (ADC) to minimize cabin pressure altitude and rate of change.

The cabin-pressure-modulating and safety valves (positive-pressure relief valves) are located either on the aircraft skin, in the case of large commercial aircraft, or on the fuselage pressure bulkhead, in the case of commuter, business, and military aircraft. Locating outflow valves on the aircraft skin precludes handling of large airflows in the unpressurized tailcone or nose areas and provides some thrust recovery; however, these double-gate valves are more complex than the butterfly or poppet-type valves used for bulkhead installations. Safety valves are poppet-type valves for either installation. Most commercial aircraft have electronic controllers located in the E/E bay. The cabin pressure selector panel is located in the flight deck.

## 2.   TYPICAL FLIGHT

A typical flight scenario from London's Heathrow Airport to Los Angeles International Airport would be as follows:

While the aircraft is at the gate and the engines have not been started yet, the ECS can be powered by compressed air supplied by the auxiliary power unit (APU), or bleed air from a ground cart. The APU or ground-cart bleed air is ducted directly to the bleed air manifold upstream of the air-conditioning packs. Once started, the

engines become the compressed air source and the ground carts are disconnected.

Taxiing from the gate at Heathrow, the outside air temperature is 59°F with an atmospheric pressure of 14.7 psia. The aircraft engines are at low thrust, pushing the aircraft slowly along the taxiway.

### Engine Bleed Air Control

As air from outside enters the compressor stages of the engine, it is compressed to 32 psig and a temperature of 330°F. Some of this air is then extracted from the engine core through one of two openings (bleed ports) in the side of the engine. Which bleed port extracts the air depends on the positioning of valves that control the ports. One bleed port is at a higher engine compressor stage (e.g., fifteenth stage), commonly called high stage. The second is at a lower compressor stage (e.g., eighth stage), commonly called low stage or intermediate stage. The exact stage varies depending on engine type. At low engine power, the high stage is the only source of air at sufficient pressure to meet the needs of the bleed system. Bleed stage selection is totally automatic, except for a shutoff selection available to the pilots on the overhead panel in the flight deck.

As the aircraft turns onto the runway, the pilots advance the engine thrust to takeoff power. The engine's high stage compresses the air to 1200°F and 430 psia. This energy level exceeds the requirements for the air-conditioning packs and other pneumatic services; approximately 50% of the total energy available at the high-stage port cannot be used, so the bleed system automatically switches to the low-stage port to conserve energy.

Because the engine must cope with widely varying conditions from ground level to flight at an altitude of up to 43,100 ft, during all seasons and throughout the world, air at the high or low stage of the engine compressor seldom exactly matches the pneumatic systems' needs. Excess energy must be discarded as waste heat. The bleed system constantly monitors engine conditions and selects the least wasteful port. Even so, bleed port temperatures often exceed fuel auto-ignition temperatures. The precooler automatically discharges excess energy to the atmosphere to ensure that the temperature of the pneumatic manifold is well below that which could ignite fuel in the event of a fuel leak.

The aircraft climbs to a cruise altitude of 39,000 ft, where the outside air temperature is –70°F at an atmospheric pressure of 2.9 psia, and the partial pressure of oxygen is 0.6 psi. Until the start of descent to Los Angeles, the low-stage compressor is able to compress the low-pressure cold outdoor air to more than 30 psia and above 400°F. This conditioning of the air is all accomplished through the heat of compression: fuel is added only after the air has passed through the compressor stages of the engine core.

Figure 13 shows the temperature of the air leaving the bleed system (labeled "to airplane" in Figure 10) from the time of departure to the time of arrival at Los Angeles.

The air then passes through an ozone converter on its way to the air-conditioning packs located under the wing at the center of the aircraft.

### Ozone Protection

While flying at 39,000 ft, several ozone plumes are encountered. Some have ozone concentrations as high as 0.8 ppm, or 0.62 ppm sea-level equivalent (SLE). This assumes a worst-case flight during the month of April, when ozone concentrations are highest. If this concentration of ozone were introduced into the cabin, passengers and crew could experience chest pain, coughing, shortness of breath, fatigue, headache, nasal congestion, and eye irritation.

Atmospheric ozone dissociation occurs when ozone goes through the compressor stages of the engine, the ozone catalytic converter (which is on aircraft with a route structure that can encounter high ozone concentrations), and the air-conditioning packs. The ozone further dissociates when contacting ducts, interior surfaces, and the
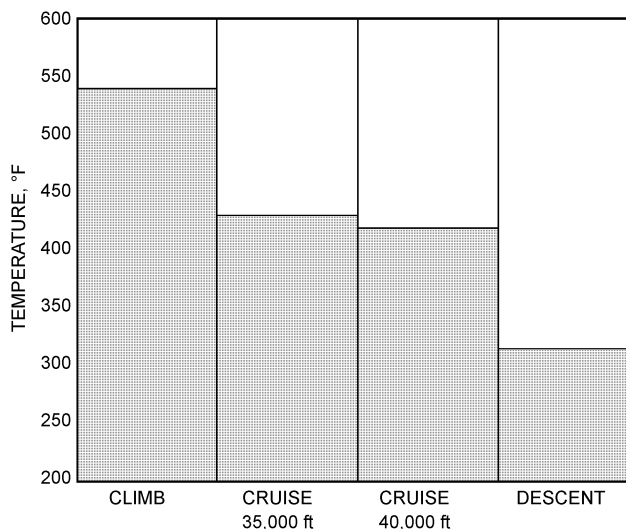


**Fig. 13 Bleed Air Temperatures**

recirculation system. The ozone converter dissociates ozone to oxygen molecules by using a noble catalyst such as palladium. A new converter dissociates approximately 95% of the ozone entering the converter to oxygen. It has a useful life of about 12,000 flight hours.

As the air leaves the ozone converter, it is still at 400°F and a pressure of 30 psia. Assuming a worst case when the converter is approaching the end of its useful life, with an ozone conversion efficiency of 60%, the ozone concentration leaving the converter is about 0.25 ppm SLE. This air goes through the air-conditioning packs and enters the cabin. The ozone concentration in the cabin is about 0.09 ppm. As mentioned in the section on Regulations, the FAA sets a 3 h time-weighted average ozone concentration limit in the cabin of 0.1 ppm and a peak ozone concentration limit of 0.25 ppm.

### Air Conditioning and Temperature Control

Air next enters the air-conditioning packs, which provide essentially dry, sterile, and dust-free conditioned air to the airplane cabin at the proper temperature, flow rate, and pressure to satisfy pressurization and temperature control requirements. For most aircraft, this is approximately 5 cfm per passenger. To ensure redundancy, typically two (or more) air-conditioning packs provide a total of about 10 cfm of conditioned air per passenger. An equal quantity of filtered, recirculated air is mixed with air from the air-conditioning packs for a total of approximately 20 cfm per passenger. Automatic control for the air-conditioning packs constantly monitors airplane flight parameters, the flight crew's selection for temperature zones, cabin zone temperature, and mixed distribution air temperature. The control automatically adjusts the various valves for a comfortable environment under normal conditions. The pilot's controls are located on the overhead panel in the flight deck, along with the bleed system controls. Normally, pilots are required only to periodically monitor the compartment temperatures from the overhead panel. Temperatures can be adjusted based on flight attendant reports of passengers being too hot or too cold. Various selections are available to the pilots to accommodate abnormal operational situations.

### Air Recirculation

The air has now been cooled and leaves the air-conditioning packs. It leaves the packs at 60°F and 11.8 psi. The relative humidity is less than 1% and ozone concentration is less than 0.25 ppm. The

carbon dioxide concentration remains unchanged from that of the outside air at about 350 ppm. As this air enters a mixing chamber, it is combined with recirculated air.

The recirculated air is filtered before entering the mix manifold. Over 99.9% of the bacteria and viruses that reach the recirculation filters are removed from recirculated air by HEPA filters, which are used on most modern aircraft.

## Air Distribution

The filtered and bleed air mixture leaves the mixing chamber on its way through the air distribution system. At this time, its humidity has increased relative to bleed air by about 5 to 10% rh. The temperature of the mixture is determined by the cooling requirements of the dominant zone. Control for the remaining zones is achieved by adding hot air to the zone supply. The hot-air source is the same bleed supply as the packs, so very small amounts of air are required to adjust the temperature.

Carbon dioxide levels in the distribution system are about halfway between the levels in bleed air and in the cabin. At a 6000 ft cabin altitude, the level is about 1000 ppm in the distribution system.

The mixture leaves the air distribution system and enters the cabin through high-velocity diffusers. The diffusers run the length of the cabin. In order to minimize fore-to-aft flow and mixing between zones, flow is provided at a uniform amount per unit length of cabin. Even though the air change rates are high compared to buildings, they are low when looking at the plug flow velocity. If ventilation air were provided uniformly across the cabin, as in plug flow, the velocity would be less than 5 fpm. Momentum from the diffusers increases velocity up to comfortable levels of 15 to 65 fpm.

Once the air mixes with the air in the cabin, the humidity rises by another 5 to 10% rh to stabilize at 10 to 20% rh, and the carbon dioxide level rests at about 1700 ppm (at 6000 ft cabin altitude).

## Cabin Pressure Control

The cabin pressure control system continuously monitors ground and flight modes, altitude, climb, cruise or descent modes, and the airplane's holding patterns at various altitudes. It uses this information to position the cabin pressure outflow valve to maintain cabin pressure as close to sea level as practical, without exceeding a cabin-to-outside pressure differential of 8.60 psi. At a 39,000 ft cruise altitude, the cabin pressure is equivalent to 6900 ft or a pressure of 11.5 psia. In addition, the outflow valve repositions itself to allow more or less air to escape as the airplane changes altitude. The resulting cabin altitude is consistent with airplane altitude within the constraints of keeping pressure changes comfortable for passengers. The cabin pressure control system panel is located in the pilot's overhead panel near the other air-conditioning controls. Normally, the cabin pressure control system is totally automatic, requiring no attention from the pilots.

Finally, as descent to LAX begins, the cabin pressure controller follows a prescribed schedule for repressurization. The cabin altitude eventually reaches sea level, the doors can then be opened at the gate, and passengers depart.

## 3. AIR QUALITY

### Factors Affecting Perceived Air Quality

Several factors can influence comfort and *perceived* cabin air quality. These cabin environmental parameters, in combination with maintenance-, operations-, individual-, and job-related factors, collectively influence the cabin crew and passenger perceptions of the cabin environment. **Cabin environmental quality (CEQ)** must be differentiated from **cabin air quality (CAQ)**, because many symptoms, such as eye irritation, for example, may be caused by humidity (CEQ) as well as contaminants (CAQ).
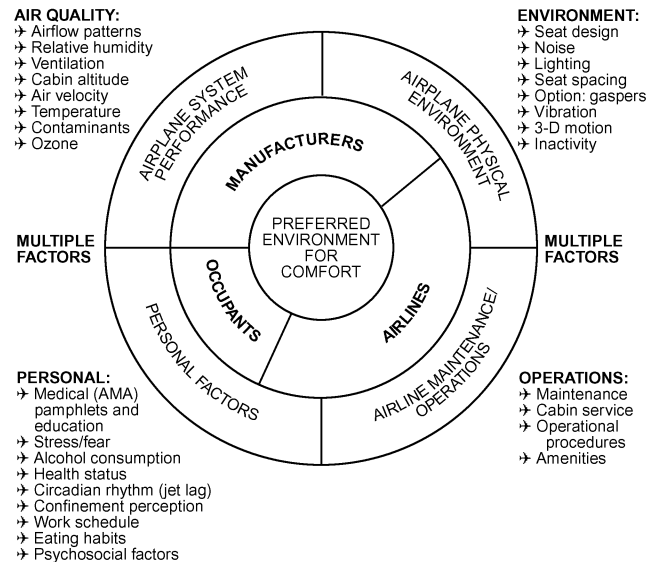


**Fig. 14   Multiple Comfort Factors**
(Adapted, with permission, from STP 1393—Air Quality and Comfort in Airliner Cabins, copyright ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19428)

Strictly, air quality is a measure of pollutant levels. Aircraft cabin air quality is function of many variables including: the quantity of ventilation flow, ambient air quality, the design of the cabin volume, the design of the ventilation and pressurization systems, the way the systems are operated and maintained, the presence of sources of contaminants, and the strength of such sources.

Figure 14 depicts the three groups that can influence cabin environmental quality: manufacturers, airlines, and the occupants themselves. Airplane manufacturers influence the physical environment by the design of the environmental control system integrated with the rest of the systems on the airplane. Airlines affect the environmental conditions in the cabin by seating configuration, amenities offered, and procedures for maintaining and operating the aircraft. Finally, cabin environmental comfort is influenced by the individual and job-related activities of the cabin crew and passengers.

Factors that can individually or collectively affect aircraft cabin air quality are discussed in the following sections.

### Airflow

The airflow per unit length of the airplane is typically the same for all sections. However, economy class has a lower airflow per passenger because of its greater seating density compared to first class and business class.

The flight deck is provided with a higher airflow per person than the cabin in order to (1) maintain a positive pressure in the cockpit to prevent smoke ingress from adjacent areas (abnormal condition), (2) provide cooling for electrical equipment, and (3) account for increased solar loads and night heat loss through the airplane skin and windows.

The bleed or outdoor air quantity supplied on some aircraft models can be reduced by shutting off one air-conditioning pack. The flight crew has control of these packs to provide flexibility in case of a system failure or for special use of the aircraft. However, packs should be in full operation whenever passengers are on board.

### Air Changes

Confusion abounds over the use of air exchange rate (also called "air change rate") when making comparisons between dissimilar systems. Further, there is no air quality equivalence in the compar-

ison of systems unless the occupied volumes are equal. This is because high air exchange rates can be achieved in two ways. As airflow increases, the air change rate increases; however, as volume decreases, the air change rate also increases but without a proportionate increase in air quality. Air exchange rate is the ratio of ventilation flow to volume:

$$ACR = \frac{Q}{V}$$

*where*

    $ACR$ = air change rate, h$^{-1}$
      $Q$ = flow, ft$^3$/h
      $V$ = volume, ft$^3$

A close inspection of the definition reveals the subtle relationship between air quality $c = q/Q$ (steady state) and air exchange rate:

$$c = \text{Air quality} = q/(ACR)V$$

*where*

      $c$ = contaminant levels
      $q$ = contaminant generation rate

It is incorrect to assume that a smaller, single-aisle aircraft has better air quality than a larger, double-aisle aircraft simply because the air exchange rate is higher. Similarly, comparisons of buildings are in error. Remember, air quality is related to flow, which is the product of air change and volume.

The air exchange rate (bleed air to volume ratio) for an airplane cabin is typically between 11 and 15 ach [air changes per hour (ACH)]. Dilution rates for these air changes are between 25 and 18 min for replacement of 99% of the air. The particulate equivalent of an air exchange rate (total ventilation to volume ratio, where total ventilation = bleed + HEPA filtered recirculation) is between 20 and 30 equivalent air changes per hour.

## Ozone

Ozone is present in the atmosphere as a consequence of the photochemical conversion of oxygen by solar ultraviolet radiation. Ozone levels vary with season, altitude, latitude, and weather systems. A marked and progressive increase in ozone concentration occurs in the flight altitude of commercial aircraft. The mean ambient ozone concentration increases with increasing latitude, is maximal during the spring (fall season for southern latitudes), and often varies when weather causes high ozone plumes to descend.

Residual cabin ozone concentration is a function of the ambient concentration; design, operation, and maintenance of the air distribution system; and whether catalytic ozone converters are installed.

Cabin ozone limits are set by FAR *Standards* 121.578 and 25.832. Catalytic ozone converters are generally required on airplanes flying mission profiles where the cabin ozone levels are predicted to exceed these limits (refer to the FAA Code of Federal Regulations for other compliance methods).

## Microbial Aerosols

Biologically derived particles that become airborne include viruses, bacteria, actinomycetes, fungal spores and hyphae, arthropod fragments and droppings, and animal and human dander. One study has documented the occurrence of an outbreak of infectious disease related to airplane use. In 1977, because of an engine malfunction, an airliner with 54 persons onboard was delayed on the ground for 3 h, during which the airplane ventilation system was reportedly turned off. Within 3 days of the incident, 72% of the passengers became ill with influenza. One passenger (the index case) was ill while the airplane was delayed. With the ventilation system shut off, no bleed air was introduced into the cabin to dilute microbial aerosols and $CO_2$ or to control cabin temperatures.

The airplane ventilation system should never be shut off when passengers are on board, although the air packs (but not recirculation fans) may be shut off for a short time during takeoff only.

To remove particulates and biological particles from the recirculated air, use filter assemblies that contain a HEPA filter with a minimum efficiency of 99.97% on a dioctyl phthalate (DOP) test, as measured by MIL-STD-282. A HEPA filter is rated using 0.3 μm size particles. A filter's efficiency increases over time as particulates become trapped by the filter. However, system performance degrades because of increased pressure drop. Overlapping capture mechanisms in a filter also increase efficiency for particles smaller and larger than the most penetrating particle size (MPPS). For an airplane filter, the MPPS is about 0.1 to 0.2 μm.

Viruses typically range from about 0.01 to 0.2 μm, and are effectively removed by the air filtration mechanism of diffusional interception. Bacteria are typically about 0.5 to 1.5 μm, and are effectively removed by inertial impaction.

## Activity Levels

Respiratory rates (also called minute ventilation) and, hence, air contaminant doses vary with activity level. Elevated activity levels increase respiration rate, and thereby may increase the dose of some airborne contaminants. Breathing rates range from approximately 0.3 cfm for a seated passenger to 0.6 cfm for a working flight attendant.

## Volatile Organic Compounds

Volatile organic compounds (VOCs) can be emitted by material used in furnishings, pesticides, disinfectants, cleaning fluids, and food and beverages.

## Carbon Dioxide

Carbon dioxide is the product of normal human metabolism, which is $CO_2$'s predominant source in aircraft cabins. Concentration in the cabin varies with bleed-air flow rate, number of people present, and their individual rates of $CO_2$ production, which vary with activity and, to a smaller degree, with diet and health. $CO_2$ has been widely used as an indicator of indoor air quality, typically serving the function of a surrogate. According to the DOT (1989), measured cabin $CO_2$ values of 92 randomly selected smoking and nonsmoking flights averaged 1500 ppm.

The environmental exposure limit adopted by the Association of German Engineers (VDI 2004) and the American Conference of Governmental Industrial Hygienists (ACGIH) is 5000 ppm as the time-weighted average (TWA) limit for $CO_2$; this value corresponds to a bleed air ventilation rate of about 2.3 cfm per person at sea level, if the only source of $CO_2$ is the occupants at rest. Other sources of $CO_2$ within the cabin or cargo (e.g., dry ice) would of course require more ventilation. 14CFR/CS/JAR 25.831 also limits $CO_2$ to 5000 ppm (0.5%).

## 4. REGULATIONS

The Federal Aviation Administration (FAA) regulates the design of transport category aircraft for operation in the United States under section 14 of the Code of Federal Regulation (CFR) Part 25 (commonly referred to as the Federal Aviation Regulations [FARs]). ECS equipment and systems must meet these requirements, which are primarily related to safety of the occupants. Certification and operation of these aircraft in the United States is regulated by the FAA in FAR Part 121. Similar regulations are applied to European nations by the European Aviation Safety Agency (EASA), which represents the combined requirements of the airworthiness authorities of the participating nations; the current equivalent design regulation is Certification Specification (CS) 25, although many airplanes were designed and certified to the former Joint Aviation Regulations (JARs) Part 25. Operating rules based on FAA or EASA regulations are applied in-

dividually by the nation of registry. Regulatory agencies may impose special conditions on the design, and compliance is mandatory.

Several 14 CFR and CS/JAR Part 25 paragraphs apply directly to transport category aircraft ECS. Those most germane to the ECS design requirements of this chapter are as follows:

- 14CFR/CS/JAR 25.831    Ventilation
- 14CFR/CS 25.832    Cabin ozone concentration
- 14CFR/CS/JAR 25.841    Pressurized cabins
- 14CFR/CS/JAR 25.1301    Function and installation
- 14CFR/CS/JAR 25.1309    Equipment, systems, and installations
- 14CFR/CS/JAR 25.1438    Pressurization and pneumatic systems
- 14CFR/CS/JAR 25.1461    Equipment containing high energy rotors

These regulatory requirements are summarized in the following sections; however, the applicable FAR, CS and JAR paragraphs, amendments and advisory material should be consulted for the latest revisions and full extent of the rules.

### 14 CFR/CS/JAR Paragraph 25.831: Ventilation

- Each passenger and crew compartment must be ventilated.
- Each crew member must have enough bleed air to perform their duties without undue fatigue or discomfort (minimum of 10 cfm).
- Crew and passenger compartment air must be free from hazardous concentration of gases and vapors:
  - CO limit is 1 part in 20,000 parts of air
  - $CO_2$ limit is 0.5% by volume, sea level equivalent. Many airplanes were designed/certified to a carbon dioxide limit of 3% by volume (the former requirement)
  - CO and $CO_2$ limits must be met after reasonably probable failures
- Smoke evacuation from the cockpit must be readily accomplished without depressurization.
- Occupants of the flight deck, crew rest area, and other isolated areas must be able to control the temperature and quantity of ventilating air to their compartments independently.

### 14 CFR 25.831, Amendment 25-87 (specifies new requirements)

- Under normal operating conditions, the ventilation system must be designed to provide each occupant with airflow containing at least 0.55 lb of bleed air per minute (or about 10 cfm at 8000 ft).
- The maximum exposure at any given temperature is specified as a function of the temperature exposure.

### FAA Advisory Circular (AC) 25-20/ Acceptable Means of Compliance/Advisory Circular-Joint 25.831

- The ventilation system should be designed to provide enough fresh air to prevent accumulation of odors and pollutants such as carbon dioxide.
- In the event of loss of one source or probable failure conditions, the supply of bleed air should not be less than 0.4 lb/min per person for any period exceeding 5 min. This is derived from the ventilation rate procedure of ASHRAE *Standard* 62-1981. However, temporary reductions below this flow rate may be accepted if the compartment environment can be maintained at a level that is not hazardous to the occupant.

### 14 CFR/CS 25.832: Cabin Ozone Concentration

Specifies the cabin ozone concentration during flight must be shown not to exceed the following:

- 0.25 ppm by volume, sea level equivalent, at any time above flight level 320 (32,000 ft)

- 0.10 ppm by volume, sea level equivalent, time-weighted average during any 3 h interval above flight level 270 (27,000 ft)

At present, JAR 25 has no requirement for cabin ozone concentration.

### 14 CFR/CS/JAR 25.841: Pressurized Cabins

- Maximum cabin pressure altitude is limited to 8000 ft at the maximum aircraft operating altitude under normal operating conditions.
- For operation above 25,000 ft, a cabin pressure altitude of not more than 15,000 ft must be maintained in the event of any reasonably probable failure or malfunction in the pressurization system.
- The makeup of the cabin pressure control components, instruments, and warning indication is specified to ensure the necessary redundancy and flight crew information.

### 14 CFR Amendment 25-87

This revision imposes additional rules for high-altitude operation.

### 14 CFR/CS/JAR 25.1301: Function and Installation

Each item of installed equipment must be of a kind and design appropriate to its intended function, be properly labeled, be installed according to limitations specified for that equipment, and function properly.

### 14 CFR/CS/JAR 25.1309: Equipment, Systems, and Installations

- Systems and associated components must be designed such that any failure that would prevent continued safe flight and landing is extremely improbable, and any other failure that reduces the ability of the aircraft or crew to cope with adverse operating conditions is improbable.
- Warning information must be provided to alert the crew to unsafe system operating conditions so they can take corrective action.
- Analysis in compliance with these requirements must consider possible failure modes, probability of multiple failures, undetected failures, current operating condition, crew warning, and fault detection.

FAR *Advisory Circular* AC 25.1309-1A, CS AMJ 25.1309, and JAR ACJs 1 to 25.1309 define the required failure probabilities for the various failure classifications: probable, improbable, and extremely improbable for the FAR requirements; and frequent, reasonably probable, remote, and extremely remote for the CS/JAR requirements.

### 14 CFR/CS 25.1438: Pressurization and Pneumatic Systems

This standard specifies the proof and burst pressure factors for pressurization and pneumatic systems as follows:

- Pressurization system elements
  - Proof pressure: 1.5 times max normal pressure
  - Burst pressure: 2.0 times maximum normal pressure
- Pneumatic system elements
  - Proof pressure: 1.5 times maximum normal pressure
  - Burst pressure: 3.0 times maximum normal pressure

CS/JAR 25.1438 and AMJ/ACJ 25.1438 specify the proof and burst pressure factors for pressurization and pneumatic systems as follows:

- Proof pressure
  - 1.5 times worst normal operation
  - 1.33 times worst reasonable probable failure
  - 1.0 times worst remote failure

- Burst pressure
  - 3.0 times worst normal operation
  - 2.66 times worst reasonably probable failure
  - 2.0 times worst remote failure
  - 1.0 times worst extremely remote failure

### 14 CFR/CS/JAR 25.1461: Equipment Containing High-Energy Rotors

Equipment must comply with at least one of the following three requirements:

- High-energy rotors contained in equipment must be able to withstand damage caused by malfunctions, vibration, and abnormal temperatures.
  - Auxiliary rotor cases must be able to contain damage caused by high-energy rotor blades.
  - Equipment control devices must reasonably ensure that operating limitations affecting the integrity of high-energy rotors will not be exceeded in service.
- Testing must show that equipment containing high-energy rotors can contain any failure that occurs at the highest speed attainable with normal speed control devices inoperative.
- Equipment containing high-energy rotors must be located where rotor failure will neither endanger the occupants nor adversely affect continued safe flight.

### Categories and Definitions

Commercial users categorize their ECS equipment in accordance with the Air Transport Association of America (ATAA) *Specification* 100. The following ATAA chapters define ECS functions and components:

- **Chapter 21**, Air Conditioning, discusses heating, cooling, moisture/contaminant control, temperature control, distribution, and cabin pressure control. Common system names are the air-conditioning system (ACS) and the cabin pressure control system (CPCS).
- **Chapter 30**, Ice and Rain Protection, covers airfoil ice protection; engine cowl ice protection; and windshield ice, frost, or rain protection.
- **Chapter 35**, Oxygen, includes components that store, regulate, and deliver oxygen to the passengers and crew.
- **Chapter 36**, Pneumatic, covers ducts and components that deliver compressed (bleed) air from a power source (main engine or auxiliary power unit) to connecting points for the using systems (which are detailed in Chapters 21, 30, and 80). The pneumatic system is also commonly called the engine bleed air system (EBAS).

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