Related Commercial Resources

CHAPTER 4. TALL BUILDINGS

TALL buildings have existed for more than 100 years and have been built in cities worldwide. Great heights only became possible after the invention of the elevator safety braking system in 1853; subsequent population and economic growth in cities made these taller buildings very popular. This chapter focuses on the specific HVAC system requirements unique to tall buildings.

ASHRAE Technical Committee (TC) 9.12, Tall Buildings, defines a tall building as one whose height is greater than 91 m. The Council on Tall Buildings and Urban Habitat (CTBUH 2014) defines a tall building as one in which the height strongly influences planning, design, or use; they classify recently constructed tall buildings as **supertall** (buildings taller than 300 m) and **megatall** (buildings taller than 600 m).

Traditionally, model codes in the United States were adopted on a regional basis, but recently the three leading code associations united to form the International Code Council (ICC 2018), which publishes the unified *International Building Code*® (IBC). Another important national code, developed by the National Fire Protection Association (NFPA), is NFPA *Standard* 5000®. These codes address the requirements of tall buildings to some extent, but many local or international locations may have their own modifications or alternatives to these model codes.

The overall cost of a tall building is affected by the floor-to-floor height. A small difference in this height, when multiplied by the number of floors and the area of the perimeter length of the building, results in an increase in the area that must be added to the exterior skin of the building. The final floor-to-floor height of the office occupancy floors of any building is jointly determined by the owner, architect, and structural, HVAC, and electrical engineers.

There are increasing numbers of tall buildings in the world (either planned or built) that will have a much greater height than 91 m. There is also a trend that many new tall buildings today are of the mixed-use type: for example, many will have a combination of commercial offices, hotel, apartments, observation deck, club floor, etc., stacked on top of each other. Tall buildings with these heights and mixed uses will significantly affect HVAC system design. For further information, see Ross (2004).

1. STACK EFFECT

Stack effect occurs in tall buildings when the outdoor temperature differs from that of the vertical hoistways (e.g., stairwells, chases, risers, elevator shafts) indoors. The temperature of the occupied zone is not directly relevant; it is the temperature in the vertical shafts that drives stack effect. The temperature difference leads to an indoor/outdoor density difference, which then leads to a different static pressure change as a function of height inside and outside the building. This pressure difference pushes air into the building at the bottom and pulls it out at the top in winter, with the reverse happening in summer. Stack effect is sometimes mistakenly attributed to buoyancy, although buoyancy is in play within the building. The summer (cooling mode) stack effect is sometimes called **reverse stack effect**, although in some climates this is the dominant form of stack effect.

The pressure differential created by stack effect is linearly proportional to the height of the building as well as to the density difference between the indoor and outdoor temperatures. The stack effect driving force (e.g., the total pressure difference created by stack effect) can approach 1 kPa for a megatall building in a cold climate.

When the temperature outside the building is warmer than the temperature inside the building, the stack effect phenomenon is reversed. This means that, in very warm climates, air enters the building at the upper floors, flows down through the building, and exits at the lower floors. The cause of **reverse stack effect** is the same in that it is caused by the differences in density between the air in the building and the air outside the building, but in this case the heavier, denser air is inside the building.

Reverse stack effect is not as significant a problem in tall buildings in warm climates because the difference in temperature between inside and outside the building is significantly less than the temperatures difference in very cold climates. Accordingly, this section focuses on the problems caused by stack effect in cold climates. Note that these measures can be very different than those in hot and humid climates.

Theory

For a theoretical discussion of stack effect, see Chapter 16 in the 2021 *ASHRAE Handbook—Fundamentals*. That chapter describes calculation of the theoretical total stack effect for temperature differences between the inside and outside of the building. It also points out that every building has a **neutral pressure level (NPL)**: the point at which interior and exterior pressures are equal at a given temperature differential. The location of the NPL is governed by the building itself through features such as the permeability of its exterior wall, internal partitions, and the construction and permeability of stairs and shafts, including elevator shafts and shafts for ducts and pipes.

Another factor that influences the location of the NPL is the operation of air-conditioning systems. For example, makeup air systems that positively pressurize buildings will lower the NPL. Exhaust systems that extract air throughout the entire height of the building tend to raise the NPL. Under winter conditions, the negative pressurization of the building that draws the NPL upward will increase the total pressure differential experienced at the base of the building. This also increases infiltration of outdoor air into the lower levels.Positively pressurizing a building in winter will push the NPL downward, thereby reducing the pressure difference at the bottom of the building and therefore the infiltration driving force. Positively pressurizing a building during summer will drive the NPL upward.

A third factor that can affect the NPL is the location of large openings. Open doors, windows, and operable walls can create large openings in the facade, which changes how the building resists the stack-effect-driven pressure difference. An opening at the bottom of a building will pull the NPL downward, and one at the top will pull the NPL upward.

Finally, wind pressure, which typically increases with elevations and is stronger at the upper floors of a building, also can shift the neutral plane, and can be considered as an additional pressure to stack effect when locating the neutral plane.

Figure 1 depicts airflow into and out of a building when the outdoor temperature is cold (left; stack effect) and hot (right; reverse stack effect). The different arrow lengths indicate different pressure forces acting on the building envelope: the summer pressures are as strong as the winter ones. Not shown is the movement of air up or down in the building caused by infiltration and exfiltration of air at different levels of the building. The NPL is the point in the building elevation where pressure difference is zero: if there are openings, then air neither enters nor leaves the building. Vertical movement of air in the building occurs at the paths of least resistance, including but not limited to shafts and stairs in the building as well as any other openings at the slab edge or in vertical piping sleeves that are less than totally sealed. Figure 1 also indicates that air movement into and out of the building increases as the distance from the NPL increases. Elevator shafts, especially ones that connect the top and bottom of a tall building (e.g., a fire lift), are typically paths of least resistance for airflow. The total theoretical pressure differential can be calculated for a building of a given height and at various differences in temperature between indoor and outdoor air.

The theoretical stack effect pressure gradient for alternative external temperature is shown in Figure 2. The diagram shows the potential maximum differentials that can occur (which are significant even for relatively small temperature differences) between the exterior and the interior vertical shaft running top to bottom in the building. The elements that take up this pressure on each level include the exterior facade, internal partitions, and doors, as well as doors to the shaft itself. As noted previously, the wind effect and operation of the building air-handling systems and fans also affect this theoretical curve. Thus, the diagram should be considered an illustration of the possible magnitude of stack effect, not as an actual set of values for any building.

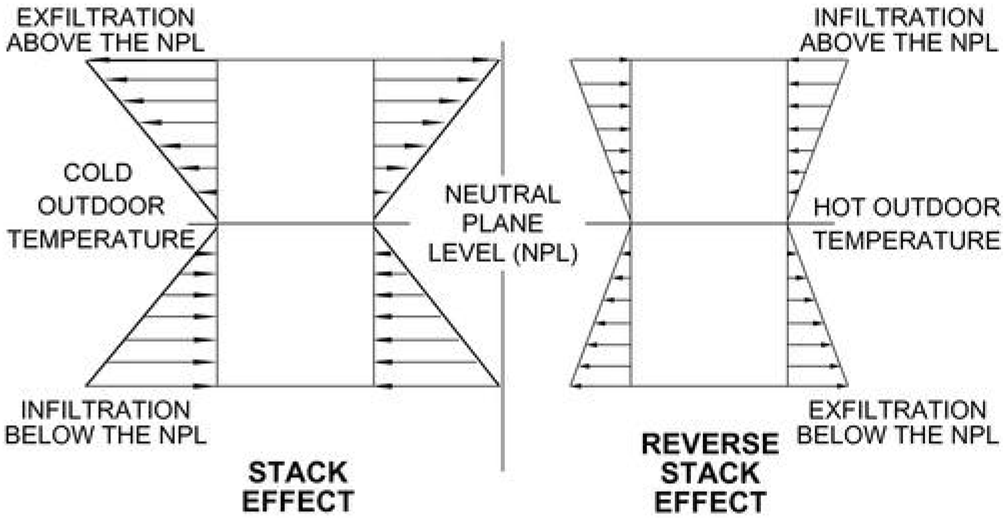

Figure 1. Airflow Driven by Winter and Summer Stack Effect and Reverse Stack Effect (Adapted from Ross 2004, in Simmonds and Phillips 2022)

The actual location of the NPL in any building is difficult to determine exactly. Often it is cited as being at the mid-height of a building, but this is a simplification: larger openings at the base of buildings can lower the NPL. Simmonds and Phillips (2022) discuss how the NPL for a static building (e.g., no HVAC pressurization) can be estimated by assessing the ability of the building to allow airflow to travel from the exterior into the shafts at the core. Assuming a building with a facade and core that contains one elevator and one stair shaft, then flow areas allowing air into the stair shaft are in parallel with those of the elevator. These two flow areas are in series with those at the perimeter/facade. At the facade, the flow areas can include leakage through doors and operable windows as well as through the leakage in the facade itself. Hence, calculating the NPL requires estimating all of the flow (infiltration) areas and results in an expression for **equivalent crack area (ECA)** at any one level being

(1)

$$\text{ECA} = \frac{1}{\frac{1}{\Sigma A_F + A_D + A_W} + \frac{1}{\Sigma(A_S + A_E)}}$$

where A represents the crack areas of the facade, doors, windows, stair shaft (walls and doors), and elevator shaft (walls and doors) on any one particular floor. The NPL is then the height-weighted average of these equivalent crack areas:

$$\text{NPL} = \frac{\Sigma_{I=1}^{n} \text{ECA}_i h_i}{\Sigma_{I=1}^{n} \text{ECA}_i} \quad (2)$$

where h is the height of the floor i being summed. The equation can be extended for additional components in the flow path on the floor if desired. Two key assumptions though are that (1) the elevator and stairwell run the same height in the building and are not broken, and (2) there is no pressure adjustment from wind or the mechanical system.

A real building, especially a tall building, may have multiple neutral planes because of the effects of elevator and stair transfers. Each shaft section (e.g., low-rise elevator shaft) imparts its own stack effect and can create variations in the building pressure profile at the top and bottom of the shaft. Further, if the elevators or stair shafts are at different temperatures, then they will have a stack effect relationship with respect to the outdoors, as well as with each other. Clearly, stack effect can be troublesome, and its possible effects must be recognized in the design documentation for a project.

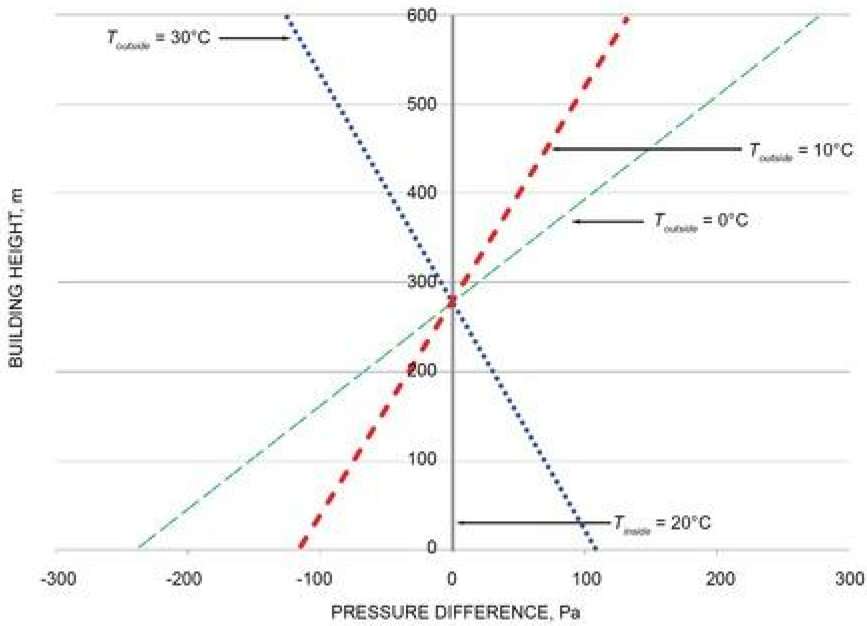

Figure 2. Theoretical Stack Effect Pressure Gradient for Various External Temperatures

Practical Considerations

Stack effect in tall buildings often presents major problems:

- **Elevator doors** may fail to close properly because of the pressure differential across the doors, which causes the door to bind in its guideway enough that the closing mechanism does not generate sufficient force to overcome it.
- **Elevator piston effect** may be exacerbated by stack effect because it can be additive to the stack effect pressures, particularly in tall buildings with high-speed elevators and minimal shaft clearances around elevator cabs due to building core space restrictions.
- **Manual doors** may be difficult to open and close because of strong pressure created by stack effect.
- **Odor and other contaminants** can enter the building driven by stack effect. This is a concern in loading bays in winter, because they are typically open and often lead directly to the service elevator. Idling engine exhaust can enter the building easily.
- **Smoke and odor propagation** can occur within buildings and be transported through the air path of stack effect. This can be particularly acute in residential buildings, with smoking and cooking odors transported through various shafts and between units on floors.

- **Noise** from excessive airflow through shafts and doors may exist as whistling and whooshing.
- **Heating issues** can occur in lower areas of the building in winter that may be difficult to heat because of a substantial influx of cold air through entrances and across the building's outer wall (caused by higher-than-anticipated wall permeability). Heating problems can be so severe as to freeze water in sprinkler system piping, cooling coils, and other water systems on lower floors. The National Association of Architectural Metal Manufacturers (NAAMM) specifies a maximum leakage per unit of exterior wall area of 0.00003 cm^3/m^2 at a pressure difference of 75 Pa exclusive of leakage through operable windows. In reality, tall buildings in cold climates can exceed this pressure difference through a combination of stack, wind, and HVAC system pressure. Even when leakage similar to the NAAMM criterion is included in project specification, it is not always met in actual construction, thereby causing potential operational problems.
- **Cooling issues** may occur in summer (reverse stack effect conditions), and it may be difficult to keep upper levels of a building adequately cool due to excessive infiltration of hot, and potentially humid, air. Hotels in hot climates with amenity decks at the top of buildings can suffer from this issue.
- **Fan operational issues** may occur if systems fans are not designed and controlled to overcome the static pressure developed by stack effect.

Calculation

Uncontrolled infiltration and ventilation is caused by climate, wind pressure, and stack effect; environmental factors associated with stack effect include wind pressure, stack pressure difference, airflow rate, outdoor and indoor temperature, building height, and building construction.

Wind creates a distribution of static pressure on the building envelope that depends on wind direction and velocity against the building envelope. The basic formula to determine this pressure can be expressed as

$$\Delta P_W = C_p \rho V_w^2/2 \qquad \textbf{(3)}$$

where

ΔP_W	=	wind pressure above outdoor air (OA) pressure, Pa
C_p	=	surface (location on building envelope) pressure coefficient, dimensionless
ρ	=	air density, kg/m^3 (about 1.2)
V_w	=	wind speed, m/s
o	=	outdoor

Table 1 Parameters for New York Example Building

	Summer	Winter
Outdoor temperature, °C	32.2	4–10.0
Indoor temperature, °C	24	20
Relative humidity, %	54	15
Height above sea level, m	0	0
Wind speed, km/h	18.0	18.0
Air pressure, Pa	101 419	101 419

When using this equation, wind pressure is 25 Pa at 6.7 m/s on the windward side when C_p is equal to 1.0. See Chapter 24 of the 2021 *ASHRAE Handbook—Fundamentals* for details about wind pressures on buildings.

Air density varies with temperature. In cold weather, low-density air infiltrates the lower levels of a high-rise building and rises in the building's vertical shafts as it warms, creating stack effect pressure. The basic stack effect theory is expressed as

$$\Delta P_s = C_2 \rho_i g (h - h_{neutral})(T_i - T_o)/T_o \qquad \textbf{(4)}$$

where

ΔP_s	=	stack pressure difference (indoor – outdoor), Pa
$C_2 \rho_i g$	=	air density and gravity constant, 1.0 × 1.2 kg/m^3 × 9.81 = 11.77 $kg/(m^2 \cdot s^2)$ m/s^2
h	=	building height, m
$h_{neutral}$	=	height of neutral pressure level, m
i	=	indoor
o	=	outdoor
T	=	temperature, K

When using Equation (2), the stack pressure from the neutral plane at the half height of the building to the top of the building is 218 Pa for a total 60-story building (e.g, 210 m with 30 stories above the neutral plane) and for temperature conditions at T_o = –23°C and T_i = 21°C. Notice that, for a building under winter conditions, above the neutral plane, the pressure is positive and outward, below the neutral plane for that building, the pressure is negative and inward.

Once the wind pressure ΔP_W and stack pressure difference ΔP_s are calculated, and taking into account building pressurization, total pressure ΔP_{total} at any level can be found, based on the indoor and outdoor pressure difference, and ultimately used to calculate the airflow rate:

$$\Delta P_{total} = (P_o - P_i) + \Delta P_W + \Delta P_s \quad (5)$$

Calculation Example. For the calculation examples, New York was selected because it has many tall buildings and a significant range between warm summer and cold winter temperatures (stack effect influences buildings differently at different temperatures). The following example investigates performance in both summer and winter conditions.

ASHRAE climate data were used (see Chapter 14 of the 2021 *ASHRAE Handbook—Fundamentals*). The data provided include winter and summer design temperatures and humidity levels, which can be used to calculate stack effect.

Table 1 gives the example parameters, and Figures 3 to 6 show various conditions. The pressure differences were calculated using a variable atmospheric pressure and temperature (see Chapter 1 of the 2021 *ASHRAE Handbook—Fundamentals*). As shown in Figure 4, the biggest difference between internal and external pressure occurs in winter. In addition, when the building gets taller, its NPL on the windward side rises: the extreme is for a building height of 500 m, for which the NPL on the windward side is almost on the top of the building.

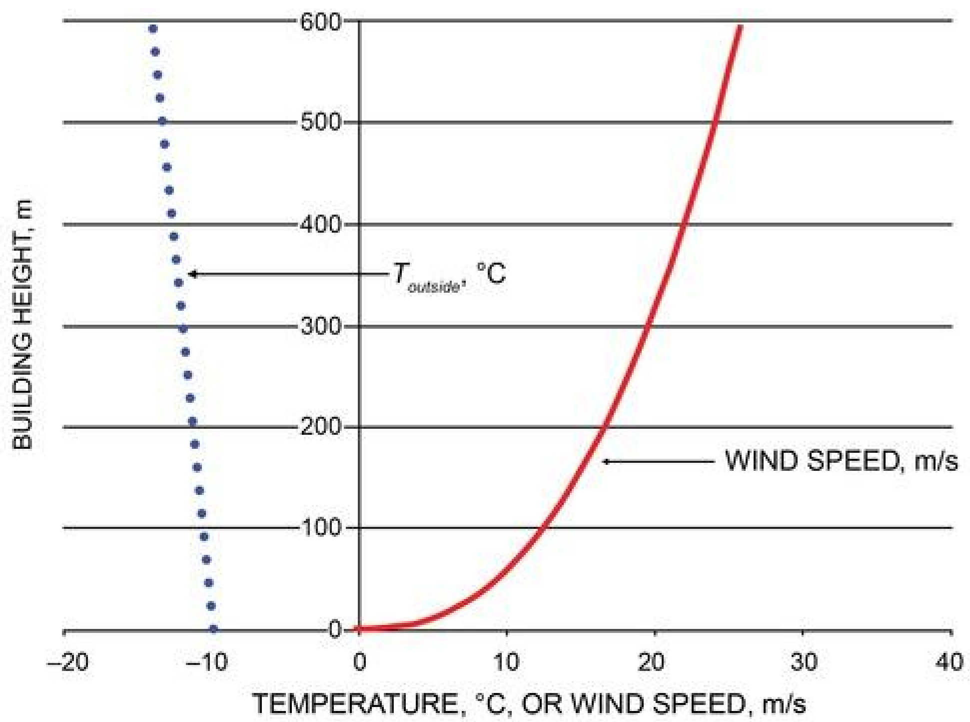

Figure 3. Temperature and Wind Speed as Function of Height in Building: Winter Conditions

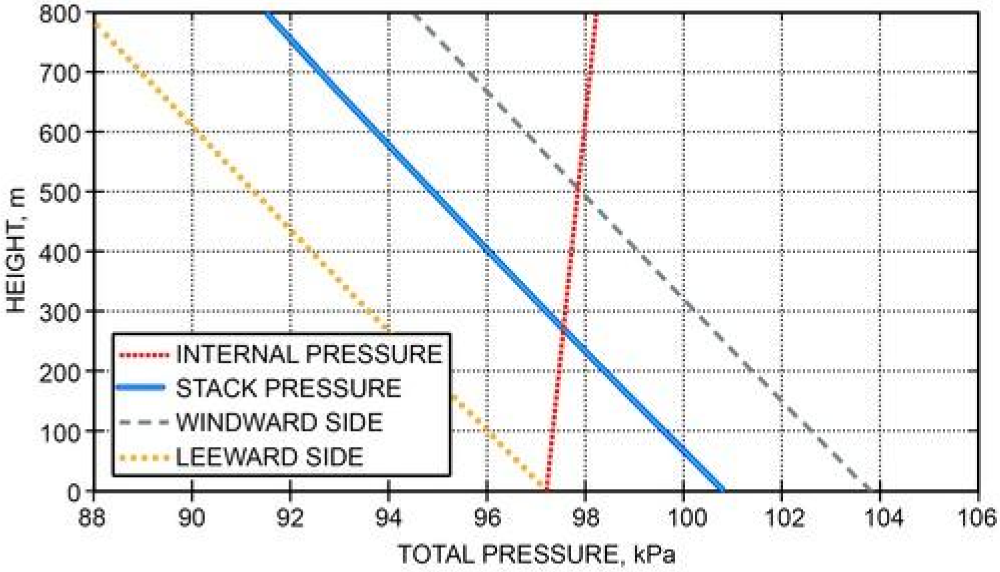

Figure 4. Windward, Leeward, and Stack Pressures in Winter Conditions

For a climate similar to New York's, which is cold and dry in winter and warm and humid in summer, **stack effect** is much more intense in the winter than it is in the summer. Stack effect during cold outdoor conditions may cause problems (e.g., elevator doors not closing properly because the pressure differential across the doors results in the doors sticking in their guideways if the closing mechanism cannot overcome this friction.

Another difference for New York compared with other cities occurs in the wintertime, when **NPL** is slightly lower, or below the middle of the building as a result of building pressurization, the base of the building being leakier, or a combination of both.

Minimizing Stack Effect

During design, the architect and HVAC design engineer should take steps to minimize air leakage into or out of (and vertically within) the building. Although it is not possible to completely seal any building, this approach can help mitigate potential problems that could be caused by stack effect.

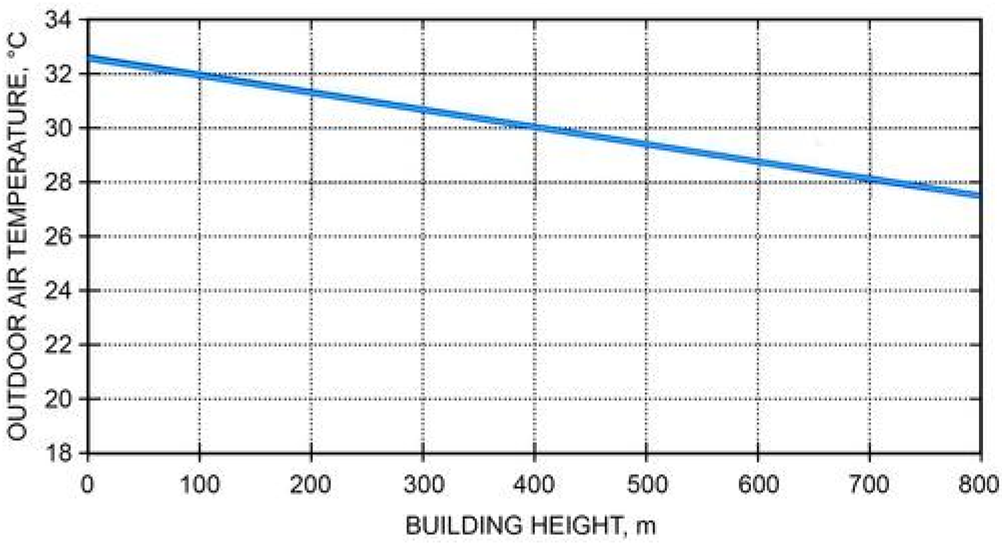

Figure 5. Temperature and Wind Speed as Function of Height in Building: Summer Conditions

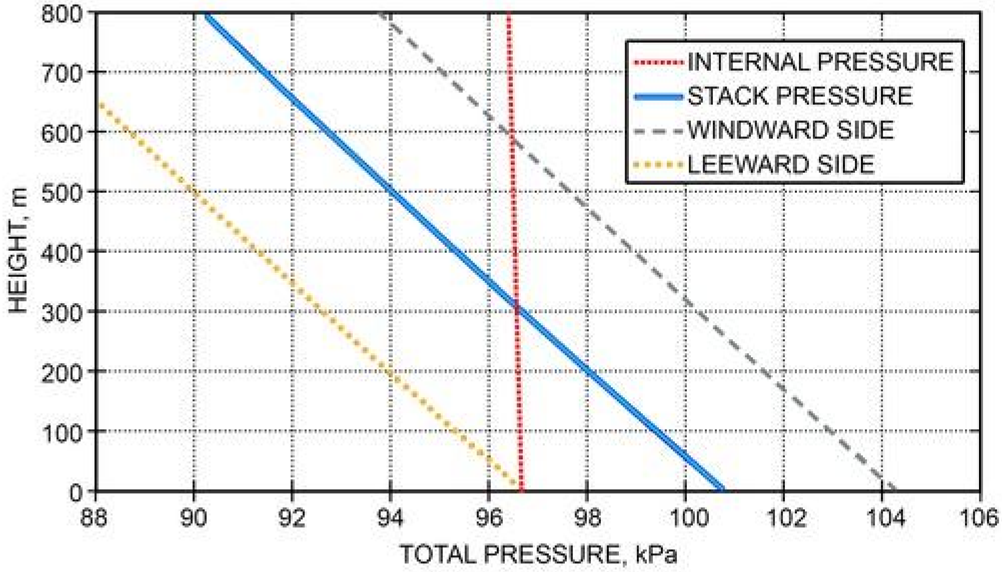

Figure 6. Windward, Leeward, and Stack Pressures: Summer Conditions

A tight building envelope and continuous curtainwall system, as well as isolation of vertical shafts from exterior environment through a minimum of two air barriers, are fundamental to protecting a building against uncontrolled air movement into and out of the building. A tight specification, testing, and careful monitoring during construction are required. Although most curtain walls are traditionally tested in the factory, increasingly more field tests (either spot tests or whole-building pressure tests) are specified in some buildings. A whole-building pressure test is difficult in tall buildings, and currently there is a limit on how many floors can be pressurized. Sectionalizing a tall building can be used to perform a localized test.

Outdoor air infiltration points include building entry doors, doors that open to loading docks, outdoor air intake or exhaust louvers, construction overhangs with light fixtures, or other recessed items, located immediately above the ground level that are not properly sealed against leakage or provided with heat, and any small fissures in the exterior wall itself. Internally, the building allows air passage through fire stairs, elevator shafts, mechanical shafts for ducts and piping, and any other vertical penetrations for piping or conduit or at the edge of the floor slab at the exterior wall. All these are candidates for careful review to ensure, as much as possible, that the exterior wall is tight, all shafts are closed, and all penetrations sealed. Vestibules or airlocks can be provided for loading docks, with good door seals on the doors to and from the loading dock. Doors added for stack effect mitigation can be left open during months with lower stack effect driving forces, but they are necessary to control stack effect on the worst days.

Entrances for tall buildings in cold and hot climates should use revolving doors. Doors of this type are balanced, with equal pressure in opposite directions on the panels on either side of the central pivot, making operation relatively simple and requiring no special effort to turn. A good-quality revolving door will have solid gaskets that always provide closure. Some revolving doors leak, and care needs to be taken when selecting and installing a revolving door. Give special consideration to hotel entries where people carry large luggage through: larger revolving doors are required to avoid people bypassing the revolving doors altogether. For locations where swing doors are required and there is a risk of a large pressure difference across it, balanced doors can be used; their pivot point is somewhere near the width of the door rather than it being hinged at the edge. Alternatively, a vestibule should be considered.

Design and layout of sky lobbies in super- and megatall buildings should be carefully considered to isolate building elevator shafts and exit stairs from the exterior environment. A vestibule may be added at the elevators to provide a second air barrier in addition to the building envelope.

Two-door vestibules are acceptable for the loading dock, assuming the doors are properly spaced to allow them to be operated independently and with one door to the vestibule always closed, and sufficient heat is provided in the space between the doors. If properly spaced, simultaneous opening of both doors on either side of the vestibule can be controlled. However, two-door vestibules in cold climates are inadequate for personnel entry because, with large numbers of people entering the building at various times, both doors will be open simultaneously. This results in a breach in the facade, and the pressure managed by the facade moves to interior doors and most often the elevator doors, which are unable to manage the pressures involved. Having both doors of an entrance vestibule open simultaneously during very hot or very cold conditions usually results in significant quantities of unconditioned outdoor or cooled air, respectively, passing through the door. In cold climates, revolving doors are strongly recommended at all points of personnel entry. Self-centering revolving doors are preferred to create a tighter seal when the door is not in use.

To control airflow into the elevator shaft, consider adding doors at the entry to the elevator banks. This creates an elevator vestibule on each floor that minimizes flow through open elevator doors. This is especially critical for freight elevators, which typically have a taller continuous shaft and openings at each floor. These doors can be left open during months with lower stack effect pressures.

As noted previously, very tall buildings will have multiple neutral planes because of elevator and stair transfers, with each shaft section imparting its own stack effect on the overall building pressure and airflow dynamic. As such, special attention should be paid to the floors at the bottom and top of each main shaft section, especially because these often coincide with a more direct connection to the outdoors such as mechanical floor louvers or a building observation deck.

Elevator shafts are also a problem because an air opening may be required at the top of the shaft. In many tall buildings, however, the elevator hoistways are not vented for smoke, using sprinkler heads instead. Alternatively, some jurisdictions accept the installation of a motorized damper on the hoistway vent; the damper is initiated by a smoke detector and opens immediately when smoke is sensed in the hoistway. These vents should be tightly sealed during normal operations. Poorly sealed vents at the top of elevator hoistways or stairwells can result in pressure and flow problems at the bottom of the building.

Elevator cars can act as pistons to increase the pressure in elevator hoistways ahead of the moving cab. Careful sequencing of elevator cabs, especially when multiple cabs are located in a single shaft, must be considered to provide proper relief and sequencing of door openings.

It can be helpful to interrupt stairs intermittently with well-sealed doors to minimize vertical airflow through buildings. This is particularly useful for fire stairs that extend through the entire height of the building. Entrances to fire stairs should be provided with good door and sill gaskets. (See the section on Door-Opening Forces under Pressurization System Design in Chapter 54 for guidance on ensuring doors in fire stairs can be opened during an emergency.)

Building air supply and pressurization systems should be configured in a maximum of 20- to 40-floor increments to facilitate effective building pressurization corresponding to building stack effect and wind pressure profiles.

The last key item is to ensure a tight exterior wall, which requires specification, proper testing, and hiring a qualified contractor to erect the wall.

The preceding precautions involve the architect and allied trades. The HVAC designer primarily must ensure that mechanical air-conditioning and ventilation systems supply more outdoor air than they exhaust, to pressurize the building above atmospheric pressure. This is true of all systems where a full air balance should be used for the entire building, with a minimum of 5% more outdoor air than the combination of spill and exhaust air provided at all operating conditions, to ensure positive pressurization. In addition, it is good design, and often required by code for smoke control, to have a separate system for the entrance lobby. Sometimes building engineers will use this system to operate in extreme winter outdoor air conditions with 100% outdoor air. This can have the effect of lowering the pressure across the exterior facade; however, it tends to increase pressure on the elevator doors. Depending on the type of elevator, this can result in the elevator door seizing. Thus, if considering providing overpressurization to lower areas (e.g., the entrance lobby), take care that this does not move the problem from the exterior facade to an interior element. Lastly, if two-door vestibules must be provided, consider pressurizing the vestibule with conditioned outdoor air.

Wind and Stack Effect Pressure Analysis

The world trend toward super- and megatall buildings suggests that both wind and stack effect will greatly affect designs of future tall building and HVAC systems. It is advisable to carry out both wind and stack effect analyses by computational fluid dynamic (CFD) or wind tunnel analysis during concept and schematic design phases of the project, such that advance precautionary measures could be implemented in the early design stage. Stack effect analysis can be conducted using a network flow model by including wind conditions imposed in the model.

Safety Factors

System designers typically apply safety factors at various points in the design process to avoid undersizing equipment. Judicious use of safety factors is good engineering practice. However, safety factors are too often misapplied as a substitute for engineering design, and this practice typically results in grossly oversized equipment. Therefore, care is necessary in applying safety factors.

2. SYSTEMS

Systems used in tall buildings have evolved to address owners' goals, occupants' needs, energy costs, and environmental concerns (including indoor air quality).

Chapter 37 discusses mechanical maintenance and life-cycle costing, which may be useful in the evaluation process with regard to alternative systems. Chapter 1 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment* provides guidelines for a quantitative evaluation of alternative systems that should be considered in the system selection process. Chapter 19 of the 2021 *ASHRAE Handbook—Fundamentals* provides means for estimating annual energy costs. Ross (2004) provides a more detailed discussion of systems to be considered.

With the increasing focus on carbon emissions, system design for tall buildings should include whole-life carbon studies.

3. SYSTEM SELECTION CONSIDERATIONS

In a fully developed building (including the core and shell as well as space developed for occupancy), the cost of mechanical and electrical trades (i.e., HVAC, electrical, plumbing, and fire protection) is typically 30 to 35%, and for a high-rise commercial building is usually over 25%, of the overall cost (exclusive of land). In addition, the mechanical and electrical equipment and associated shafts can consume 7 to 10% of the gross building area. The architectural design of the building's exterior and the building core is fundamentally affected by the system chosen. Consequently, HVAC system selection for any tall building should involve the entire building design team (i.e., owner, architect, engineers, and contractors), because the entire team is affected by this decision.

The points of concern and analysis methods do not differ in any way from the process that would be followed for a low-rise building. Possible alternative systems also are very similar, but the choices for high-rise buildings are typically more limited.

Air-Conditioning System Alternatives

Several alternative systems are used in tall buildings. Although the precise system configurations are subject to the experience and imagination of the design HVAC engineer, the most common ones are variations of generic all-air and air/water systems.

Unitary, refrigerant-based systems, such as through-the-wall units, are used in conjunction with all-air systems providing conditioned ventilation air from the interior zone, but this combined solution has been limited to retrofits of older buildings that were not previously air conditioned and smaller low-rise projects. They are seldom used in first-class tall commercial buildings.

Another option is panel-cooling-type systems, including chilled-ceiling and chilled-beam systems. Though not common in the United States, these systems are used in Europe as a retrofit alternative in existing buildings that were not previously air conditioned, because these systems can be installed with minimal effect on existing floor-to-ceiling dimension.

All-Air Variable-Air-Volume Systems. All-air variable-air-volume (VAV) systems in various configurations are one of the most common solutions in tall buildings. Conditioned air for VAV systems can be provided from a central fan room or from local floor-by-floor air conditioning units. These alternative means of delivering conditioned air are discussed in the section on Central Mechanical Equipment Room Versus Floor-by-Floor Fan Rooms. This section is primarily concerned with system functioning, configurations in use, and possible variations in system design.

VAV systems control space temperature by directly varying the quantity of cold supply air in response to the cooling load requirements. VAV terminals or boxes are available in many configurations; pressure-independent terminal units are recommended. Interior spaces that have a year-round cooling load regardless of outdoor air temperature can use any of the alternative types of VAV boxes:

- A **single-duct VAV terminal** reduces supply air volume directly with a reduction of the cooling load. This is a very common terminal in commercial projects, and has the smallest height of any terminal used in office buildings. Usually a stop is used to maintain minimum airflow, for proper ventilation.
- A **series-flow fan-powered VAV terminal** maintains constant airflow into a space by mixing the required amount of cold supply air with return air from the space. The VAV terminal contains a small fan to deliver constant airflow to the space. The fan operates any time the building is occupied. The primary advantage of the fan-powered box is that airflow in the space it supplies is constant at all conditions of load. This is of particular import if low-temperature air is used to reduce the distributed air quantity and the energy necessary to distribute the system air. In cold climates and when the perimeter serving terminal unit locations are at ideal distance from the perimeter wall, the series-flow fan-powered terminal continuously recovers internal heat to be used for partial heat of perimeter spaces.
- A **parallel-flow fan-powered VAV terminal** maintains variable airflow into a space and mixes the required amount of cold supply air at minimum flow requirements with return air from the space. The VAV terminal contains a small fan that starts only in heating mode to deliver mixed primary and return airflow to the space. The fan operates only when heating is required to deliver warm return air, mixed with cool primary air when the building is occupied. Unlike the series-flow box, this option delivers increased airflow to the space during heating but can also shut off primary air and operate only the fan to deliver return air during unoccupied periods. The central system fan must also operate at higher static pressure to accommodate the pressure loss through low-pressure ductwork, VAV terminals, and diffusers, in addition to all of the medium-pressure duct distribution. A box-mounted heating coil (hot-water or electric) supplements the heat provided by return air when heating requirements increase. The parallel approach does not ensure constant air volume to the space, as can be obtained with the series approach, but it does provide a minimum airflow at significantly lower operating cost. Parallel-flow fan-powered VAV terminals are seldom used in new construction design.
- An **induction box** reduces supply air volume and induces room air to mix with supply air, thus maintaining a constant supply airflow to the space. These units require higher inlet static pressure to achieve velocities necessary for induction, with a concomitant increase in supply fan energy requirements. Moreover, operational problems have been experienced, especially at reduced primary airflow quantities. Thus, these boxes are now seldom used in commercial projects.

The exterior zone can use any VAV box type, but in geographical locations requiring heat, the system must be designed with an auxiliary means of providing the necessary heating. This can be done by installing hot-water baseboard, controlled either directly by thermostat or by resetting the hot-water temperature inversely with the outdoor air temperature. Other alternatives are thermostatically controlled electric baseboard on the exterior wall, or either electric or hot-water heating coils in the perimeter VAV boxes.

Low-Temperature-Air VAV Systems. All of the preceding variations can be designed using conventional temperature differentials (9 to 11 K) between the supply air and room temperature. Buildings have been successfully designed, installed, and operated for decades with low-temperature supply air between 8.9 and 10°C. This increases the temperature supply differential to approximately 16 K, thus dramatically reducing primary air quantities and subsequently reducing air-handling system size and air duct distribution.

This lower-temperature air can be obtained by operating the refrigeration machines with chilled water leaving at 4.4°C or by using ice storage. If the chiller supplies 4.4°C chilled water, operating costs of the refrigeration plant increase and the chiller must operate for a longer time before an economizer cycle can occur. Moreover, use of absorption refrigeration machines may not be possible, because they usually cannot provide chilled water as cold as 4.4°C.

However, the reduced quantity of air distributed also reduces fan power, which more than offsets the additional energy used by the chiller. This lower-temperature air requires series-flow fan-powered VAV terminals or induction-type air supply terminals to mitigate draft and dumping concerns at the diffuser due to supplying low-temperature air directly to the space. The air delivery terminals mix room and cold supply air to deliver warmer air to the space to offset heat gain.

Using low-temperature supply air requires elimination of air leaks and proper installation of the correct thickness of duct insulation to prevent moisture condensation. Note that the decrease in supply duct size when using cold air can make lower floor-to-floor heights more practical.

Dedicated Outdoor Air Systems (DOAS). These systems deliver 100% outdoor air to occupied spaces for ventilation, pressurization, and makeup air to exhaust systems such as toilet or electrical transformer exhaust. Air is typically delivered at or near room neutral temperatures so that ventilation is divorced from space heating and cooling requirements. Space heating and cooling can be provided by hydronic systems (radiant floors or panels, fan coil units, baseboard, chilled beams, etc.) or by variable refrigerant flow (VRF) systems.

By separating ventilation from space heating and cooling, DOAS can dramatically reduce the fan energy required. Primary duct systems are also much smaller than comparable all-air systems because the primary system typically delivers minimum ventilation air only. DOAS does not provide full air-side economizer free cooling like an all-air system. However, when coupled with an efficient radiant heating and cooling system or a heat recovery VRF system, DOAS can often reduce total building energy use intensity in many climate zones and applications.

Underfloor Air Distribution (UFAD) Systems. In underfloor air distribution (UFAD) systems, the space beneath a raised floor is used as a distribution plenum. Most installations use manually adjustable supply diffusers or automatically controlled terminal units beneath the floor to control air delivered to the space above. (In contrast, for more traditional systems, terminal units are installed above the ceiling and supply air is delivered from above.) When properly designed, either underfloor or ceiling-mounted air distribution systems can meet occupants' comfort requirements. UFAD systems typically have a higher first cost because of the raised floor, but operating costs are usually lower because less fan power is required. However, if a raised floor is a design requirement for electrical distribution and information technology cabling, UFAD may offer savings in overall first and operating costs.

The UFAD system can use central fan rooms or floor-by-floor fan units. Conditioned air is typically provided at 16 to 18°C in the raised-floor plenum (between the structural slab and the raised floor), but in locations requiring dehumidification, the air must first be cooled to approximately 12.8°C to remove moisture and then blended with return air (often using a vertical air column unit or an underfloor-mounted series fan-powered box or similar arrangement) to achieve supply air temperatures of 16 to 18°C. The suspended ceiling acts as a return plenum but can be reduced in depth because of the absence of supply ductwork.

A major concern with UFAD in tall buildings is the perimeter zone, which has widely varying loads between summer and winter conditions, especially in buildings with large glass exterior elements. Thermostatically controlled fan-coils beneath the floor or finned-tube radiation along the perimeter walls can be cost-effective solutions. Additionally, extreme caution is needed in sealing all structural floor penetrations to prevent short-circuiting of supply air.

Underfloor air conditioning for a tall building must be selected early in the design process, because it affects architectural (e.g., floor-to-floor heights, exterior facade treatment, stairs, elevators), structural (e.g., depressed structural slabs), and electrical (e.g., plenum-rated cabling) design considerations. All design disciplines must be involved in this decision process.

The combination of system components and the resultant system configuration for a specific building are limited only by the designer's imagination. The chosen alternative is of interest and concern to the owner, architect, and other engineering consultants, and should be subjected to scrutiny and review by the entire design team before final selection is made.

Underfloor air-conditioning systems are a newer approach, where the space beneath the raised floor is used as a distribution plenum or where terminal units are installed beneath the raised floor (in contrast with more traditional systems, where the terminal units are installed above the ceiling). Either system, with ceiling-mounted terminals or one distributing air through the raised floor, when properly designed, will meet occupants' comfort requirements. The underfloor air-conditioning system typically has higher first cost than comparable overhead distribution systems because of the cost of the raised-floor system. The cost premium can vary as a function of design details for the project, and can be substantially offset if the owner decides to incorporate a raised floor for power wiring and information technology cable distribution. Without this fundamental decision, the increase in the cost of the floor itself and a possible increase in the floor-to-floor height, with the resultant premium that must be paid for the exterior wall and the extended internal shafts, piping, and stairs, may be too great to justify the inclusion of the underfloor distribution system. Figure 7 shows a typical underfloor conditioning/ventilation system.

Multiple variations of underfloor air-conditioning system design are possible. Underfloor air distribution systems use the principle of displacement ventilation. Designs typically are implemented with all-air systems in which air is distributed beneath the floor, with the void between the slab and the raised floor serving as a supply air plenum. The conditioned air is provided at relatively elevated temperatures of approximately 16 to 18°C by blending cold, dehumidified supply air with warm return air. This air then passes at low velocities from the air-conditioned floor through floor outlets and rises vertically to the ceiling through its own buoyancy, removing heat from occupants, office equipment, and lighting as it rises. The ceiling and the space above it function as a return air plenum where distributed air is collected and returns to the air-conditioning supply system, which can be either a central or floor-by-floor system. Because supply ductwork is not needed, the plenum above the ceiling can be reduced in depth compared to that required for an overhead distribution system.

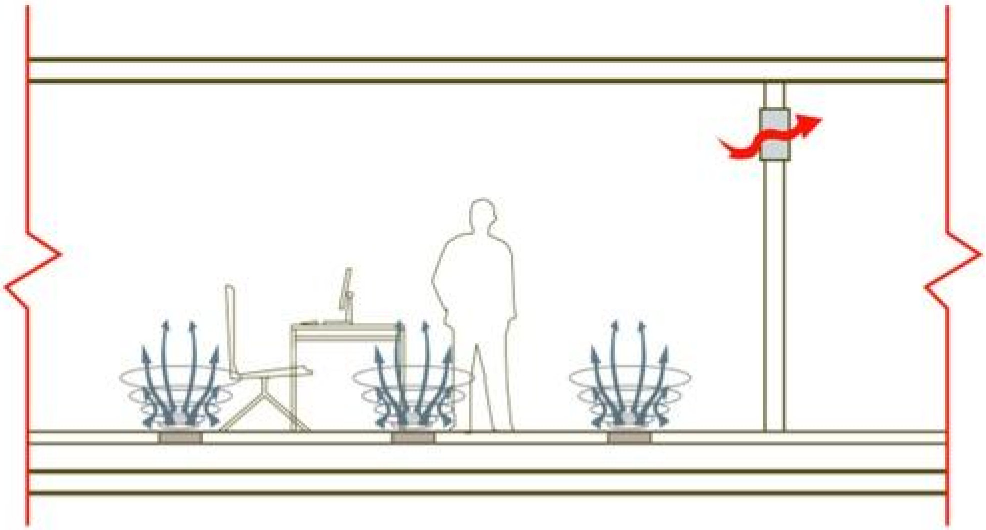

Figure 7. Typical UFAD System

A variation of the underfloor air-conditioning system is using all-air terminals or fan-coil units beneath the floor in the exterior zone. A thermostatically controlled terminal can be advantageous in altering unit capacity in the exterior zone with its widely varying loads. In addition, using a fan-coil unit, which can modify its capacity output as the load varies and has an inherently greater capacity on a percent basis than an all-air terminal, may provide a more cost-effective solution for tall commercial buildings, particularly those with larger glass elements in the exterior wall. The design using fan-coil units is the same as with all-air terminal designs: air is distributed through floor grilles, with the ceiling acting as a return air plenum.

Many commercial and office projects in Europe include a raised floor for power wiring and information technology cabling, so underfloor distribution systems have been widely accepted throughout the continent. These systems have found more limited application in the United States, probably because raised floors are used infrequently and the *National Electric Code®* (NFPA *Standard* 70) requires that all cabling in an air plenum must be installed in conduit or carry a plenum rating if the raised floor is used for free discharge of supply air. (Where a raised floor is used for cable distribution only, conduit or plenum-rated cabling is not required.) This can increase the cost of cabling significantly and can therefore be a significant consideration in the decision process.

Underfloor distribution systems using variable-air-volume or fan-coil terminals are applied more widely. These systems have a lower space reconfiguration cost as occupancy changes, because all that is required is relocation of a floor diffuser to meet the altered space needs (akin to relocation of an electrical outlet to serve a new occupant layout). This lower cost of interior modifications should be fully considered by the owner and the design team.

Floor supply systems that mix with the total air mass in the occupied zone are not displacement systems. Displacement systems result in temperature gradients in the occupied space, whereas fully mixed systems minimize room temperature gradients.

The displacement system effectively delivers supply air to those parts of the space where heat gain occurs and not the whole occupied volume, so less supply air should be needed.

Fully mixed floor supply systems can handle spaces with high heat gains (>100 W/m^2), and have considerably greater capacity than displacement systems alone (~40 W/m^2). The floor supply system creates zones of discomfort near the outlet, between 1 and 1.5 m radius, where sedentary occupants should not be located. There is a relatively low air volume per outlet compared with high-level diffuser systems, which require the use of more supply outlets.

Because the air supply stream is delivered directly into the occupied zone, supply velocity and temperature are restricted, limiting maximum sensible cooling load to 40 W/m^2 for a 3 m high floor to ceiling height; higher loads can be handled where the floor-to-ceiling height is greater.

Use great caution with floor-to-ceiling heights less than 3 m, because the higher temperatures developed at the ceiling may cause uncomfortable radiant effects. System performance improves with ceiling height.

Consider using exhaust air heat recovery. Recirculation of room air should be minimized, because this air will be hot and vitiated, generally with a higher specific enthalpy than outdoor air.

If air patterns in the space are subject to considerable disruption (e.g., by occupant movement or high infiltration rates), system effectiveness will be reduced.

A displacement ventilation system should not be used for heating because the low-velocity heated air makes effective air distribution very difficult. A separate perimeter heating system should be provided.

Selection of supply outlets should be based on minimizing the zone of discomfort around the supply outlet; this entails using more small outlets rather than fewer large ones. The geometry of the supply outlet is not as critical as that for diffusers and registers used in conventional mixing systems.

Match the supply volume flow to the volume flow rate of the plumes set up by internal heat sources at the given boundary height.

The height of the boundary plane depends on supply air volume: it will be higher if excessive air is delivered, and lower if supply air is insufficient.

Displacement Ventilation

Displacement ventilation effectiveness is improved compared to conventional mixed systems, which depend on dilution to reduce contaminants. However, system success relies on reasonable ceiling heights and maintaining relatively fragile air movement patterns.

The system works better with a high temperature difference between supply and exhaust air, and is not suitable for applications that require tight temperature and humidity control. In this respect, displacement ventilation functions better where a large floor-to-ceiling height exists and therefore favors applications such as industrial spaces or large auditoriums, atriums, concourses, and some office spaces, where higher ceiling heights mean higher extract temperatures can be tolerated.

Figure 8 shows the principle of a typical displacement ventilation system.

Displacement ventilation has the potential for improving energy efficiency and indoor air quality control for the following reasons:

- There is little mixing between contaminants and bulk air, thereby improving air quality.
- Ventilation is more effective, so fan energy requirements are lower.
- Higher supply temperature means greater use can be made of free cooling of outdoor air. There are, however, some potential pitfalls that may reduce the benefits, such as heating performance; disruption of air patterns in the space by infiltration, occupancy traffic, or other cooling sources (e.g., chilled beams); and dehumidification control.

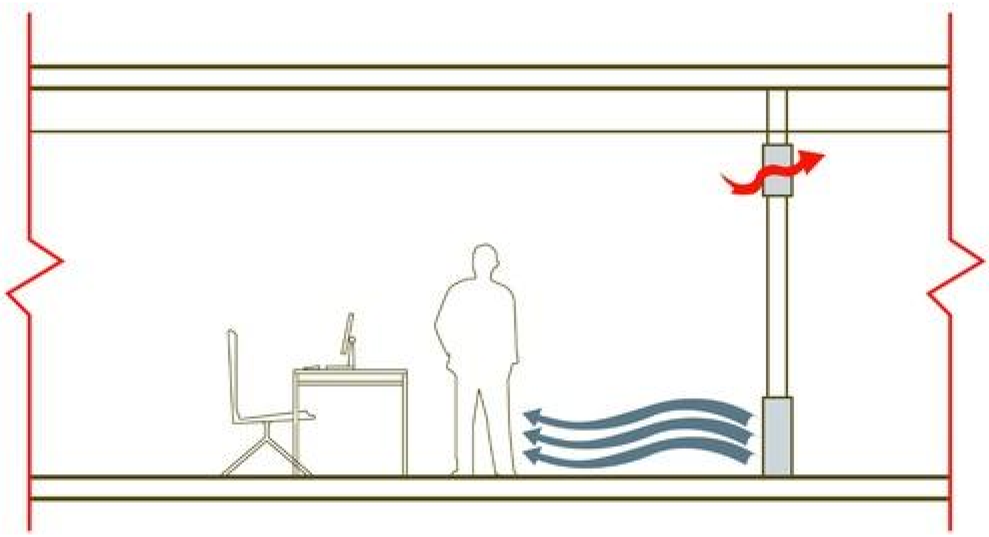

Figure 8. Displacement Ventilation System Diagram

Displacement ventilation is based on the concept of an ideal airflow pattern. Instead of total mixing achieved by other air distribution systems, the flow is unidirectional, with the minimum spreading of contaminants as possible. This ideal airflow pattern can be achieved by supplying air to the room at low level at a temperature slightly lower than that of the occupied zone, with the removal of hot, vitiated air at high level.

Supply air enters the occupied space at a low velocity and a relatively high temperature compared with conventional systems. This creates a pool of fresh air, which is distributed evenly across the floor. At local heat sources (e.g., occupants, machinery), the air temperature is raised. The natural buoyancy of the heated air gives rise to air currents.

Cool, clean air rises in the plume created by the heat source and replaces the warmed/contaminated air. The air plume generated from the heat source carries with it odors and gaseous and particulate contaminants emitted in the occupied space. These warm contaminated plumes spread out below the ceiling, and an upper contaminated layer is formed. The art of designing a displacement ventilation system is to ensure this hot contaminated region is outside the occupied zone. The supply and exhaust are balanced to produce a boundary layer above which the air is contaminated, and below which is clean, conditioned air in the occupied zone.

Air/Water Systems. Air/water systems historically included induction systems, but modern systems quite often use fan-coil units outside the building, with interior spaces typically supplied by an all-air variable-air-volume (VAV) system. Exterior zones are typically provided with a constant volume of air from either (1) the interior VAV system in sufficient quantities to meet requirements of ASHRAE *Standard* 62.1's multiple-spaces equation, or (2) a separate dedicated outdoor air system providing exterior-zone outdoor air ventilation. Fan-coil units in a tall building that requires winter heat are usually designed with a four-pipe secondary water system to provide coincidental building heating and cooling to different zones.

An advantage of the air/water system is that it reduces the required capacity of the central supply and return air systems and the size of distribution air ducts, compared to those needed with an all-air system (including low-temperature all-air). At the same time, it reduces the air-conditioning supply system's mechanical equipment room space needs. However, air/water systems require space for heat exchangers and pumps to obtain the hot and cold secondary water needed by the fan-coil unit system.

Chilled Beams

Chilled beams are a type of air/water system that have had increasing success in tall buildings. These units are available in both passive and active types, with active units offering higher capacity. Passive chilled-beam units rely on a combination of radiant and convective heat transfer to provide space conditioning from heated or chilled water delivered to the unit. With active units, primary supply air delivered to the unit causes induced room air to circulate through a hot- or chilled-water coil to provide additional conditioning capacity.

Chilled beams allow an overall reduction in the ductwork required to condition the space, because water has a greater heat-carrying capacity than air. Consequently, sheet metal costs and potentially space requirements for supply and return air ductwork can also be reduced. Use caution, however, because chilled-beam units have no condensate drain and should be designed without latent cooling capacity, so the primary supply air must be conditioned to deliver air at a low enough dew point to provide the required dehumidification of the space served.

Radiant Ceilings

Radiant cooling follows the same principles as radiant heating: heat transfer occurs between the space and the panels through a temperature differential. However, unlike in radiant heating, the colder ceiling absorbs thermal energy radiating from people and their surroundings. The major difference between cooled ceilings and air cooling is the heat transport mechanism. Air cooling uses convection only, whereas cooled ceilings use a combination of radiation and convection. The amount of radiative heat transfer can be as high as 55%; convection accounts for the remainder. With cold ceilings, the radiative heat transfer occurs through a net emission of electromagnetic waves from the warm occupants and their surroundings to the cool ceiling. On the other hand, convection first cools the room air because of contact with the cold ceiling, creating convection currents in the space, which transfers the heat from its source to the ceiling, where it is absorbed.

Because air quality must be maintained and radiant panels remove only sensible heat from the space, radiant cooling panels are used in conjunction with a small ventilation system. The panels provide most of the sensible cooling, and the air system provides ventilation and air moisture (latent load) control. To prevent high humidity levels in a room, the supply air must be drier than that of the supplied space, especially when there are additional moisture sources in the room. Consequently, outdoor air must be dehumidified, which is usually done by cooling to a dew point of approximately 15°C. If the environment is dry, the ventilation system is used to humidify the air. Because the ventilation system is used only to maintain the air quality and to regulate the latent load, the airflow required is small relative to conventional cooling systems. Best results are usually attained with a straight displacement ventilation system with no air recirculation. This system typically supplies air through outlets near or at the floor, at temperatures below that of the room air; this approach provides a uniform layer of fresh air at floor level. In turn, people and other heat sources create a passive convective flow of fresh air to the ceilings, where it can be exhausted. This reduced airflow and radiant panels' relatively high surface operating temperature (mean temperature of 16°C) make radiant cooling a more comfortable way of cooling a space than conventional systems.

A cooled ceiling operates in direct proportion to the heat load in the room. Typically, a person sitting at a desk emits 130 W of energy, whereas a computer emits 90 to 530 W to its surroundings. The radiant panel capacity should be determined by the operation conditions (water temperature and flow) and the space temperature. The greater the number of people and/or appliances and exposure to sunlight, the greater the space heat load (and therefore greater increased capacity of the cool ceiling). Generally, cool ceilings can handle between 100 and 225 W/m^2 with up to 50% of the ceiling space used for cooling.

Condensation Control

Condensation on the surface of the panels is not a problem with radiant cooling as long as the supply water temperature is properly controlled. Because condensation of water occurs when the panel temperature reaches the space dew-point temperature, proper water temperature control helps avoid condensation. The space dew-point temperature should be monitored by a sensor linked to a controller, which modulates the inlet water temperature accordingly. Therefore, if there is risk of condensation, the water temperature is raised or water flow is shut off. However, the lower the panel's inlet temperature is, the more work the panels do; the inlet temperature should be at least 1 K above the room's dew-point temperature. Consequently, the cooling capacity of a radiant cooling system is generally limited by the minimum allowable temperature of the inlet water relative to the dew-point temperature of the room air.

Electronically Commutated Motor (ECM) Fan-Coils

Fan-coil units, either vertical stacked or horizontal, are often used in tall hospitality or residential buildings. Fan-coil units with ECM provide an energy advantage to the overall building energy consumption, as well as improving temperature control in spaces conditioned by these units. For details, see the section on Fan-Coil Unit Systems in Chapter 20 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment*.

These units can be either complete with cabinets (which can be exposed in the space) or built into the general construction (less obtrusive to building aesthetics). Vertical units are even available with vertical pipe risers factory installed, reducing field-installed piping and overall construction costs. Although these internal components are generally designed and tested for elevated pressure capabilities, the actual pressure on these components for a particular building height should be investigated.

Variable-Refrigerant-Flow (VRF) Systems

VRF systems for heating and cooling are becoming more prevalent for reducing energy consumption in space conditioning. Heat recovery VRF systems transfer heat from one to another and efficiently provide simultaneous heating and cooling to perimeter and interior zones; they are appropriate for most climate zones and applications. This system option is viable for use in a tall building, particularly water-cooled condensing unit systems. Air-cooled conditioning may also be viable, but requires significant amounts of space outside the building, and tall buildings typically have small roof areas and limited space on the ground. In addition, the refrigerant lift available from these units is limited, which typically makes air-cooled options less desirable. For details, see Chapter 18 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment*.

4. CENTRAL MECHANICAL EQUIPMENT ROOM VERSUS FLOOR-BY-FLOOR FAN ROOMS

Project needs for conditioned air can be met by one or more central mechanical equipment room(s) serving multiple floors, or by systems installed in separate, local fan rooms on each floor, supplying air only to the floor on which the system is installed. Either chilled-water cooling or self-contained air-conditioning units in the floor-by-floor scheme can be used. The choice of any of the three alternative schemes is one of the most fundamental decisions made during the conceptual design phase. This issue concerns the owner, each member of the design team, and the constructing contractors, because it affects space requirements, space distribution, standard versus custom HVAC equipment, and piping and electrical distribution costs.

Central Fan Room (Alternative 1)

In central fan rooms, the supply of conditioned air for each office floor originates from multiple air-handling systems located in one or more central fan room(s), which are frequently identified as central mechanical equipment rooms (MERs). Each air-handling system can be provided with an outdoor air economizer through minimum and variable outdoor air dampers, as dictated by the annual ambient temperature and humidity conditions and building code requirements. Multiple systems in a fan room can be interconnected by delivering supply air into a common discharge plenum from all supply systems on that floor.

Air from the central fan room(s) is distributed to each floor by means of vertical duct risers in fire-rated shafts (typically 2 h rated) within the core of the building. At each floor, horizontal duct taps are made into each riser. This horizontal duct tap contains a fire damper or a fire/smoke damper, as required by the local building code, that must be installed where the supply air duct exits the rated shaft enclosure. In many situations, an automatic, remotely controlled two-position damper, which can be rated as a smoke damper, provides individual-floor overtime operation and smoke control. The position (open or closed) is typically controlled by the building management system either on an occupancy schedule or by occupancy sensor or manual reset switch.

Return air from each floor's ceiling plenum also enters the vertical shaft though a return air fire damper at each floor.

Return air is often not ducted within the shaft, so the air is carried back to the central fan room in the 2 h rated drywall shaft. In each central fan room, multiple return air fans draw return air from the return air shafts and deliver it to a headered return air duct system in the central room and then to each air-handling unit.

With an outdoor air economizer, return air is either returned to the supply air system or exhausted to atmosphere, as determined by the relative dry-bulb temperature (or enthalpy) of the return air and the outdoor air being provided to the building. Quantities of outdoor and return air depend on the season and the resultant outdoor temperature and humidity. In warmer climates where the systems operate on minimum outdoor air at all times, return air is always returned to the supply air system except during morning start-up or where the fans are operating in smoke-control mode.

A typical central fan room and supply and return air shaft arrangements are shown in Figure 9.

Floor-by-Floor Fan Rooms with Chilled-Water Units (Alternative 2)

The air supply for each office floor under this alternative originates from a local floor fan room, typically located in the building core. This room contains a chilled-water air-handling unit with a cooling coil, filters, and fan(s). Morning heating at start-up in cold climates can be provided by a heating coil in the air-handling unit, a unit heater installed in the local fan room, or heating coils in the VAV or fan-powered VAV (FPVAV) boxes. The unit on a given floor usually only supplies the floor on which the unit is installed. Typically, one unit is installed on each floor, but multiple units may be used with interconnected air systems on large floors. Chilled water for the cooling coil is provided by a central chilled-water plant in the building, sized to meet the combined capacity requirements of all of the cooling and heating needs. The supply air fan in the air-conditioning system both supplies air and returns it from the zone served. Return air is typically directed to the fan room through the ceiling plenum, but may be either ducted or unducted in the fan room. In most cases, however, the fan room acts as a return air plenum.

This system typically operates on minimum outdoor air during all periods of occupancy. Outdoor air for the system is provided by an air-handling unit serving as a dedicated outdoor air system (DOAS), located on the roof or in a central mechanical equipment room. This unit provides conditioned outdoor air to the unit on each floor by a vertical air riser routed to each air-handling unit. The outdoor air unit may include preheat and cooling coils to treat incoming outdoor air, and should contain filtration to clean this air. This unit can contain heat recovery to precondition the outdoor air by recovering heat or cool from exhaust air, which may be required by the applicable energy code.

Although chilled water is typically provided by a central refrigeration plant, economizer requirements can be provided by cooling the chilled water in mild weather by condenser water from the cooling tower. During periods of low wet-bulb temperature, the condenser water cools the chilled water through a heat exchanger in the central chilled-water plant or by refrigerant migration through the refrigeration unit.

A typical local fan room supply, return, and outdoor air arrangement is shown in Figure 10. The unit heater shown provides morning heat. It can use electric energy or hot water as its heat source.

As shown in Figure 10, the walls around the local floor fan room are not fire rated because the duct penetration serves only this floor. The vertical shaft that contains the outdoor air duct from the central fan room, and perhaps the smoke exhaust ducts, constitute a fire-rated shaft. Accordingly, fire dampers are only provided at the point where ducts penetrate the shaft wall, not as they leave or enter the local floor fan room itself. Although fire dampers are shown in the smoke exhaust ducts, many codes prohibit their use in an engineered smoke control system to avoid the possibility of having a closed damper when smoke removal is required.

Floor-by-Floor Fan Rooms with Direct-Expansion Units (Alternative 3)

A variation of the floor-by-floor alternative consists of a floor-by-floor air-conditioning supply system that is virtually identical to that in the chilled-water alternative. In this alternative, a packaged, self-contained, water-cooled direct-expansion (DX) unit, complete with one or more refrigeration compressors and water-cooled condensers, is used to produce the cooling. The heat of rejection from the compressor is handled by a circulating condenser water system and cooling tower. If geographic location dictates an economizer, this need can be met by a free-cooling coil installed in the packaged unit that will only operate when condenser water delivered to the unit is cold enough to provide effective cooling. The only central cooling equipment is a cooling tower, condenser water pumps, and the central outdoor air supply unit. If an open tower system is used, consider providing a way to remove particulates from the circulating condenser water. Depending on the size of anticipated particles, typical options include sand filtration, media filtration, and centrifugal separators. For an open system, condensers should be cleanable. Bear in mind that significant water will end up on the floor during condenser cleaning, so it is important to ensure that the room has a recessed floor drain and that the floor is moisture sealed.

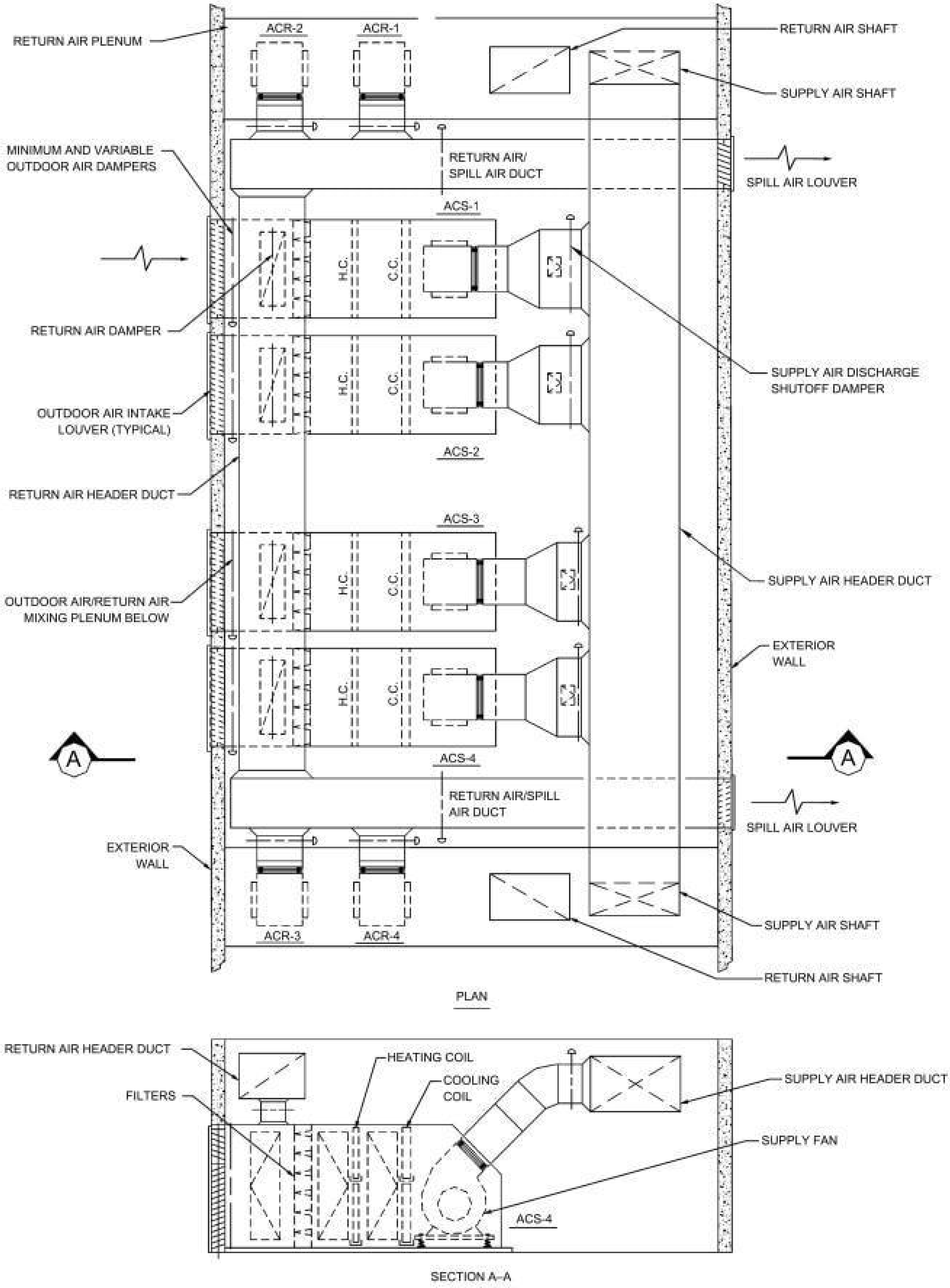

Figure 9. Central Fan Room Arrangement

The physical arrangement of the supply air unit does not differ from that shown in Figure 10, except that the chilled-water risers are replaced by condenser water piping.

Floor-by-Floor Units Located on Outer Wall (Alternative 4)

A popular variant location for a packaged floor-by-floor unit is on an outer wall. This location obviates the need for a separate outdoor air unit in a central fan room. Outdoor air can be directly introduced to the floor-by-floor unit through a louver and automatic louver damper for each unit. Moreover, this arrangement may allow using an air-cooled condenser to handle heat of rejection. If the location requires an economizer, include a minimum and variable air damper behind the outdoor air louver.

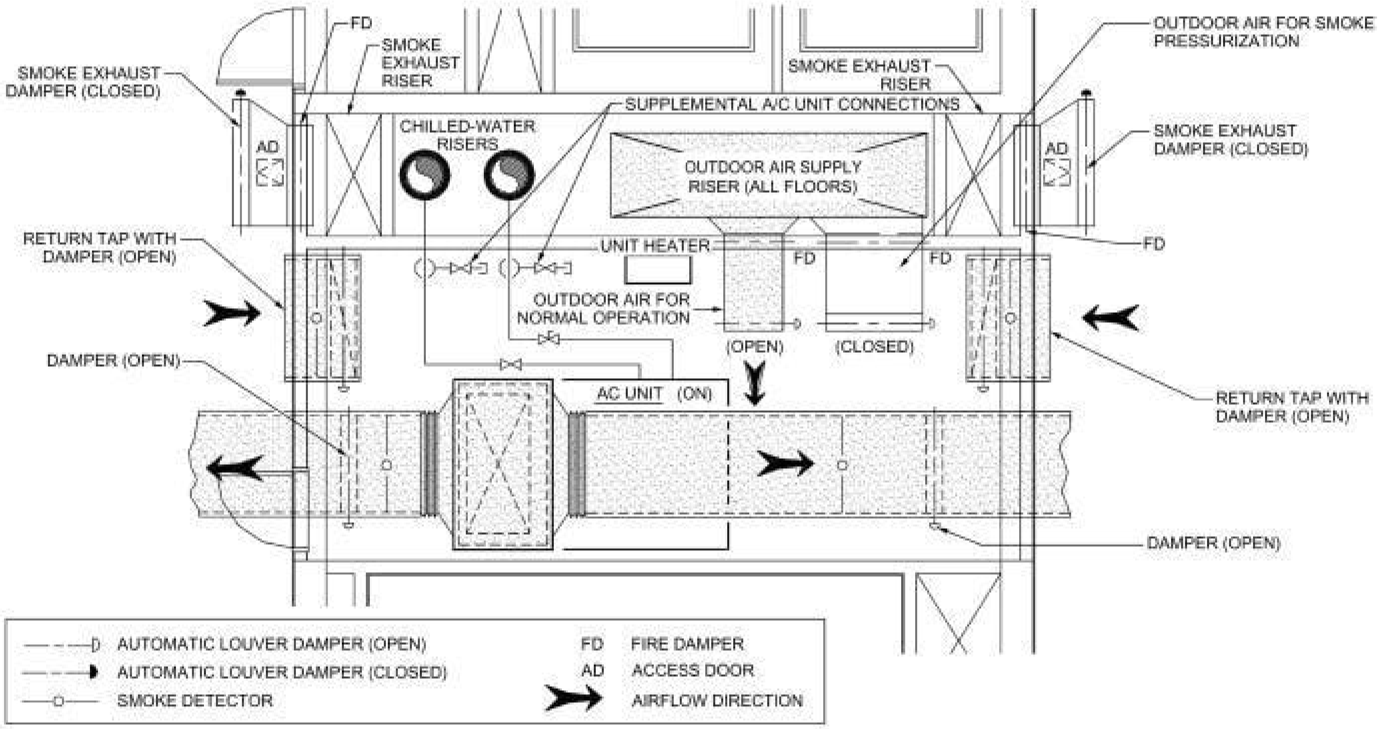

Figure 10. Floor-By-Floor Air-Conditioning Unit Layout (Normal Operation)

Several precautions are necessary. If an outdoor air economizer is used, the return air spill damper must be located carefully to ensure that outdoor air and spill air do not mix. Similar care must be taken to avoid air-cooled condenser intake air mixing with air previously spilled to atmosphere. There must be no possibility of mixing heated discharge air with either the condenser intake air or the outdoor ventilation air for the supply air-conditioning unit. This can become a complicated arrangement, which may necessitate locating the air-cooled condenser remote from the local fan room.

Comparison of Alternative Schemes

An accurate comparison of alternative schemes can only be made with a developed set of schematic plans in sufficient detail to allow a cost estimate to be completed by the contracting team or a professional estimating service. For an example, see Table 2.

Acoustics

Acoustical criteria should be established for the various types of occupancy that are expected in the building. For example, open-plan office space can be designed to meet a noise criteria level of NC-40, whereas private and executive offices or conference rooms should be no higher than NC-35, and may be required to be even lower. The acoustical engineer on a project sets these levels, and it is the responsibility of the HVAC designer to work with the acoustician to see that the criteria established are achieved in the final installation. (For details on sound levels, see Chapter 49 in this volume and Chapter 8 in the 2021 *ASHRAE Handbook—Fundamentals*).

Table 2 Comparison of Construction Alternatives

Alternative 1	Alternative 2	Alternative 3
Central Fan Systems	Floor-by-Floor Fan Systems	Floor-by-Floor DX Systems
Central Chilled Water	Central Chilled Water	Central Cooling Tower
First-Cost Considerations		
HVAC		
Fewer units, field erected.	More units, factory-fabricated and assembled.	More units, factory-fabricated and assembled.
More complex and expensive duct systems.	Simpler ductwork.	Simpler ductwork.
More complex field-installed controls.	Field-installed control system.	Factory-installed control system.
Central chilled-water plant.	Central chilled-water plant.	No central chilled-water plant; cooling tower only.

Building Management System		
Complex controls and interface with building management system (BMS) and smoke control system.	Controls are relatively simple but field installed. Interface with BMS and smoke control system less complex.	Unit controls provided by manufacturer. Interface with BMS and smoke control system simple.
Electrical		
Electrical loads concentrated in central location. Probably lowest electrical cost.	Minor cost premium for distributed fan motors. Probably higher electrical cost than alternative 1.	Additional cost for electrical distribution to local DX units. Highest electrical cost.
General Construction		
Additional gross floor space needed. No separate outdoor air or smoke exhaust shaft.	Additional cost of sound treatment of local floor-by-floor fan room. Need separate outdoor air and smoke exhaust shaft.	Additional cost of sound treatment of local floor-by-floor fan room. Need separate outdoor air and smoke exhaust shaft.
Construction Schedule		
General Complexity of Installation		
Central mechanical equipment room space and complex construction technology for both chiller plant and fan systems locations. Requires piping of a major chiller plant. Chiller plant location critical to construction schedule. Heavier slab construction at central mechanical equipment room. Extensive complex ductwork in central mechanical equipment room.	Chiller plant space is required, with need for more complex construction technology. Requires piping a major chiller plant. Chiller plant location critical to construction schedule. Heavier slab construction for chiller plant only. Limited ductwork, repetitive fan room arrangement on each floor.	Areas that contain complex construction technology are limited. No major chiller plant. Cooling tower only. Chiller plant is not required. Very limited special slab construction. Limited ductwork, repetitive fan room arrangement on each floor.
Owner Issues		
Marketing/Electric Metering		
Tenant lights and small power can be metered directly. Fan energy and chiller plant energy, as well as heating energy, operating costs are allocated unless heating is by electric resistance heat. Other common building operating costs are allocated.	Tenant lights, small power, and fan energy can be metered directly for any floor with a single tenant. Multitenanted floors require allocation of fan energy only. Chiller plant energy, as well as heating energy, operating costs are allocated unless heating is by electric resistance heat. Other common building operating costs are allocated.	Tenant lights, small power, fan, and cooling energy can all be metered for any floor with a single tenant. Multitenanted floors require allocation of fan energy and cooling energy only. Heating energy operating cost must be allocated unless heating is by electric resistance heat. Other common building operating costs are allocated.
Operating Costs		
For normal operating day, operating costs for all floors occupied are lower than alternative 3. Approximately equal to alternative 2. Overtime operation requires the chiller plant to operate in the summer. With variable-speed fan control and headered supply and return fans, energy costs equal to alternative 2. Operation more cumbersome. Fan and chiller plant costs must be allocated. Larger central fan system has limited turndown capability. Overtime operation of a single floor is more difficult to accommodate.	For summer operating day, operating costs for all floors occupied are lower because of lower energy consumption than alternative 3. Approximately equal to alternative 1. Overtime operation requires chiller plant to operate in summer but otherwise is simple. Chiller plant cost must be allocated.	For the summer operating day, operating costs for all floors occupied are higher because of higher energy consumption than alternatives 1 or 2 because of less efficient DX compressors. Overtime operation simplest but probably higher in cost than alternatives 1 or 2. Single-floor tenant cost for cooling tower only must be allocated.
Equipment Issues		
Equipment Maintenance		
All equipment is installed in central mechanical equipment room with centralized maintenance.	Requires more maintenance than alternative 1 but less than alternative 3, because of larger number of units with filters, motors, fan drives, bearings, etc.	Requires more maintenance than alternatives 1 or 2 because of larger number of units with filters, motors, fan drives, bearings, etc., plus compressor equipment on each floor.

	Chiller is in central mechanical equipment room, allowing centralized maintenance.	
Equipment Redundancy and Flexibility		
Can operate in reduced mode in case of limited failure because of headered fan arrangement. Can handle changing cooling loads and/or uneven cooling loads on a floor-by-floor basis within limits. Larger central fan system may only be able to turn down to supply air to minimum of two to three floors.	If unit fails, floor is without air conditioning. Cannot handle changing cooling loads or uneven cooling loads on a floor-to-floor basis without building in additional system capacity at design.	If unit fails, floor is without air conditioning. Cannot handle changing cooling loads or uneven cooling loads on a floor-to-floor basis without building in additional system capacity at design.
Equipment Life Expectancy		
Life expectancy of equipment is in excess of 25 years.	Life expectancy of equipment is in excess of 25 years.	Compressor life expectancy is probably approximately 10 years. Remainder of installation life expectancy is in excess of 25 years.
Architectural Issues		
Building Massing		
Central fan rooms usually require two-story MER.	Local fan room fits within floor-to-floor height of the office floor.	Local fan room fits within floor-to-floor height of the office floor.
Chiller plant room usually requires two-story MER.	Chiller plant room usually requires two-story MER.	No central chiller plant room required.
Usable Area		
Takes the least area per office floor.	Takes a greater area per floor.	Takes a greater area per floor.
Maximum usable area per office floor.	Less usable area per office floor than alternative 1.	Less usable area per office floor than alternative 1.
Gross Area		
Takes more gross building area than alternatives 2 or 3.	Takes more gross building area than alternative 3 but less than alternative 1.	Takes less gross building area than alternatives 1 or 2.

Equipment and system selection affects the required sound treatment and resultant noise levels in occupied areas. It is important that project acoustical standards and the final design are reviewed by the acoustical consultant to ensure that the desired noise levels can be achieved, particularly when floor-by-floor fan rooms are used.

5. CENTRAL HEATING AND COOLING PLANTS

Many, but not all, tall buildings require a central plant to provide chilled and hot water or steam to meet the cooling and heating needs of the building. If packaged direct-expansion equipment is used on a floor-by-floor basis, as discussed previously, then a chilled-water plant is not required. Similarly, in climates where heat is necessary in colder weather, if electric resistance heat (either along the base of the outer wall or in an overhead fan-powered air conditioning terminal supplying the periphery of a building) is used, then central hot-water or steam boilers are not required. In some locations, chilled water and/or steam or hot water are available from a central utility.

For most other installations, a central chilled-water plant with refrigeration machines and a central boiler plant are required. Factors that should be considered when deciding the type and location of the heating and cooling plant include the following:

- Weight, space requirements, and effect on structural system
- Effect on construction schedule
- Specific changes in mechanical equipment room detailing and slab construction
- Acoustical considerations
- Ease and cost of operation and maintenance
- Available energy sources
- Annual operating costs and possibly life-cycle costs of each alternative

Calculation of owning and operating costs is discussed in Chapter 38. Alternative refrigeration technologies are detailed in Chapters 1 to 3 of the 2022 *ASHRAE Handbook—Refrigeration*, and boilers are covered in Chapter 32 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment*. Useful reference information is also contained in ASME (2013).

Plant Economic Considerations

Detailed analysis is needed to determine the cooling method that should be installed in a project. The choices are usually limited to either centrifugal refrigeration or absorption chilled-water machines, although recent developments have made screw chillers more relevant for use in tall buildings. Centrifugal machines can be electric drive or steam drive; screw machines are available only with electric motor drives, and both are almost always water-cooled. Absorption machines can be single or double effect, but the latter require high-pressure steam to achieve their lower energy costs. High-pressure steam is rare in today's commercial projects unless the steam is available from a central utility.

Air-cooled refrigeration machines have been installed in tall buildings, but infrequently: commercially available sizes of air-cooled refrigeration equipment are limited, and space requirements are comparatively excessive. The largest air-cooled refrigeration machine that currently can be purchased at this time is approximately 2020 kW. Tall buildings, by nature, are typically large, and the number of air-cooled refrigeration machines and relatively large equipment space that would be required usually make air cooling not viable. In addition, air-cooled equipment's operating costs may be higher because of higher condensing temperatures developed by the refrigeration equipment caused by outdoor dry-bulb temperatures that are higher than the coincident wet-bulb temperature. Water-cooled equipment's refrigerant condensing temperature, on the other hand, is driven by the lower outdoor air wet-bulb temperature. This operating cost difference exists even though there is no cooling tower fan or condenser water pump.

Air-cooled equipment may, however, find application in tall buildings where water for cooling tower makeup either is not available or is prohibitively expensive.

For tall buildings that do not use electric resistance heat, the fuel-fired heating plant includes boilers fired by oil or gas, by both fuels (with oil as a standby fuel), or by electricity. These boilers provide hydronic heat and low-pressure steam for distribution to spaces in the building, or act as supplements to heat pumps or heat recovery systems. Choosing the correct solution for a building is subject to an economic analysis that considers space requirements, first cost, and operating expense.

Central Plant Location

Further complicating the energy transfer source decision is the location of the equipment within the building. This affects structural costs, architectural design, construction time, and availability of cooling or heating relative to the initial occupancy schedule. A below-grade location could potentially provide early heating availability, but also could complicate the design process and result in higher overall project costs. Locating cooling and heating plants on floors above grade, up to and including space immediately below the roof, is common and may be desirable for simplicity of construction and ease of providing the necessary ventilation air and other services to the equipment. Moreover, the two types of plants need not be installed at the same level in the building, because there is usually no direct interconnection of the two plants.

Virtually any location in a tall building can be used for the heating and cooling equipment. When choosing the location, consider the following:

- If a boiler is installed above grade, fuel (i.e., oil, gas, electricity) must be brought to the boiler and a flue and combustion air, in the case of a fuel-fired boiler, must be taken from the boiler to atmosphere.
- Boiler plant location should be determined by analysis following previously outlined parameters.
- Regardless of where it is installed, the design must include appropriate acoustical design considerations and vibration isolation.

Considerations for the refrigeration plant location are more complex. Not only must electricity, gas, oil, or steam be brought to the machine to operate the equipment, but chilled and condenser water also must be pumped from the refrigeration plant to the air-conditioning supply equipment. In addition, the cooling tower and the working pressure of the refrigeration machines, piping, fittings, and valves must be reviewed based on the static height of liquid above this equipment, as discussed in Ross (2004) and Chapter 40 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment*.

Because of the world trend of increasing building height and because tall buildings tend to be mixed use, split chiller and boiler plants are becoming more common: part of the heating and cooling production plant is located at the top part of the building, and part at the basement. The reason for this split is to limit pressure on both halves of the plant distribution systems.

In addition, installing a cogeneration or trigeneration plant in tall buildings to meet green and sustainability initiatives is becoming popular. These facilities use engine- or turbine-driven generators to deliver electricity to the building and generate either chilled water through absorption chilling and/or heating water.

Acoustical Considerations of Central Plant Locations

Acoustics and vibration also are key considerations during architectural, structural, and mechanical design. The HVAC designer and project acoustician should place mechanical equipment to achieve the desired acoustical levels in spaces above, below, or adjacent to the central plant. Achieving the proper solution involves understanding the characteristics of sound generated by the equipment and the various paths (e.g., through floors, ceilings, walls, building structure) for transmission of that noise and vibration to occupied areas of the building.

Regardless of the type of equipment being installed on a project, it is prudent to specify a maximum permissible sound level for equipment. Sound and vibration generation, transmission, and correction are discussed in Chapter 49 in this volume and in Chapter 8 of the 2021 *ASHRAE Handbook—Fundamentals*.

Effect of Central Plant Location on Construction Schedule

The locations of the boiler and chiller plant also affect the construction schedule. This concern is especially critical for the refrigeration plant, which is a complex installation that involves a significant amount of labor because of the need to complete the chilled-water, condenser water, and possible steam piping as well as provide for the electrical capacity requirements of the machines. The heaviest piping and most difficult installation process for piping in the building occur at the refrigeration plant. As a result, if the refrigeration plant is on the uppermost level of the building, installation of the machines and their associated piping can delay the overall schedule. Accordingly, if the refrigeration equipment cannot be installed in the below-grade level because that space has other priorities (e.g., parking, storage), the refrigeration plant may be best located above the lobby level and below the uppermost levels of the building.

6. WATER DISTRIBUTION SYSTEMS

Water distribution systems for a tall building require special consideration, primarily because the building height creates high static pressure on the piping system. This pressure can affect the design of the piping systems, including domestic water and sprinkler piping systems. This section, however, addresses chilled-, hot-, and condenser water systems.

The chilled- and hot-water systems are always closed systems (i.e., pumped fluid is not exposed to the atmosphere), whereas the condenser water system is usually open. Closed systems contain an expansion tank, which can be either open or closed to accept water expansion and makeup for contraction. An open expansion tank is located at the highest point of the piping system and is open to atmosphere; the exposed surface area of the water in the open tank is insignificant and the system is still considered closed.

In an open system, the pumped fluid is exposed to atmospheric pressure at one or more points in the piping system. In a zoned system, each separate closed system should have an expansion tank system. The condenser water piping distribution system is typically considered open because the water is exposed to atmosphere by the clean break in the piping at the open cooling tower.

As stated in Chapter 13 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment*, "one major difference in hydraulics between open and closed systems is that some hydraulic characteristics of open systems cannot occur in closed systems. For example, in contrast to the hydraulics of an open system, in a closed system (1) flow cannot be motivated by static pressure differences, (2) pumps do not provide static lift, and (3) the entire piping system is always filled with water." The design of an open system must consider the static head (height difference between the cooling tower discharge to the point at which the condenser water enters the tower) and net positive suction head (NPSH) in pump selection. For details, see Chapter 44 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment*.

If an evaporative cooler or dry cooler (commonly called an industrial fluid cooler) were used for the condenser water rather than a cooling tower, the piping system would be closed rather than open. Using evaporative or dry coolers for an entire large commercial office building is extremely rare. However, they are used in portions of tall buildings to handle the heat of rejection from supplemental cooling systems that may be required for spaces or equipment that require additional cooling capacity.

Hydrostatic Considerations

A major consideration in piping system design for a tall building is the hydrostatic pressure created by the height of the building. This hydrostatic pressure affects not only the piping and its associated valves and fittings, but also equipment in the building; in the chilled-water system, this includes refrigeration machines, boilers, casings for water pumps, cooling and heating coils in air-conditioning systems, heat exchangers, and any fan-coil units at the exterior wall of the building that use this water for heating or cooling. A similar list of devices beyond piping, valves, and fittings can be developed for other pumped systems such as the condenser water or any hot-water system.

Dynamic pressures created by the pumps also must be added to the static pressure to determine the working pressure on any element at any point in the piping system. This dynamic pressure is the total of the following elements:

- Friction loss through piping, valves, and fittings
- Residual pressure required at the most remote (or critical) piece of heat transfer equipment for its proper operation (includes pressure loss through the equipment's control valve as well as drop through the equipment itself)

- Any excess pressure caused by pumps operating at reduced flow close to their shutoff pressure (*Note*: if a valve in the system should be closed or a control valve fails closed, a constant-speed pump could ride its curve and go to full shutoff head).

The working pressure of the piping and connected equipment at various elevations in the building must be known. This is found by adding the hydrostatic pressure at the specific location to the dynamic pressure that can be developed by the pumps at that location. The dynamic pressure at any point should include the pump pressure at or close to pump shutoff at full speed, even if variable-speed pumps are used, because it is possible for the pumps to operate at this shutoff point in the event of a VFD failure. This working pressure on piping and equipment invariably lessens as the static pressure at a specific location is reduced.

The trend of ever-greater height makes piping system hydrostatic pressure zoning design very important for both technical and economical reasons. Check the pressure rating of all major air-conditioning equipment to confirm whether the required pressure-rated equipment is economically available in the market.

Effect of Refrigeration Machine Location

The level on which the refrigeration machines and the supporting chilled- and condenser water pumps are located in a building can affect the cost of refrigeration equipment, the pumps, the piping, and the fittings and valves associated with the piping. There is economic impact because of the working pressure to which the equipment, piping, fittings and valves will be subjected by the height of the system above.

Using the following information, calculate the effect of alternative chiller locations in a tall building: at basement level, a midlevel mechanical equipment room, and a mechanical equipment room on the roof. There would be an open expansion tank at the top of the building (the highest point in the system) in all three alternatives. If a closed expansion tank is used, the maximum pressure must be established and considered in the determination of the system's working pressure.

Example 1. For 2000 kPa fittings, work backwards to calculate the static building height that will not exceed 2000 kPa when the pumps are not operating. . If the pump circulating this water has a shutoff head of 31 m (299 kPa), system components downstream of the pump will experience a pressure equal to the height of water above it plus those 31 m of dynamic head. Hydrostatic pressure in a liquid can determined using the following equation:

$$P = \rho g h \tag{6}$$

where

P = pressure in fluid, Pa

ρ = density of liquid = 1000 kg/m^3

g = acceleration of gravity = 9.81 m/s^2

h = height of fluid column at which pressure is measured, m

$$P = (1000\ \text{kg/m}^3)(9.81\ \text{m/s}^2)(200\ \text{m}) = 1962\ \text{kPa}$$

It is therefore recommended to have a pressure break every 169 m in a supertall and megatall building. Fittings with pressure higher than 2000 kPa can also be used, but at a substantial increase in cost. Also, note that piping, valves, and fittings that are rated for 2000 kPa can withstand higher pressures (e.g., a 2000 kPa valve can withstand 3900 kPa at 315°C), but other system components may not be able to withstand that higher pressure.**}**

Alternative refrigeration plant locations (at midlevel and top of the building) must also be calculated. For a 70-story, 274 m building, working pressure would be 1345 kPa at the midlevel location, and 0 kPa at the top of the building. Add to those pressures a pump shutoff head (assumed to be 31 m (296 kPa), and the pressures at these levels will be 1640, 2985, and 296 kPa, respectively.

The standard working pressure for coolers and condensers on large refrigeration machines from all of the major manufacturers in the United States is 1000 kPa. These machines can be manufactured for any working pressure above 1000 kPa for additional cost. The incremental increase in the cost of a given vessel becomes larger with each unit of increase in the working pressure. Accordingly, it is necessary for the HVAC design engineer to accurately determine and separately specify the working pressure on both the cooler and the condenser of the refrigeration machines.

Working pressure on the refrigeration machine can be reduced by locating the chilled-water pump on the discharge side rather than the inlet side of the machine. If this is done, the residual pump pressure on the refrigeration machine water boxes is reduced to the hydrostatic pressure from the height of liquid above the chiller. This can reduce the cost of the refrigeration machines but does not alter the pressure on the pump casing and flanges, which must still be the sum of the static and dynamic pressures.

Chilled-Water Pressure Reduction

Pressure on (and cost of) refrigeration equipment can be reduced by locating it above the basement; this, however, will not alter the maximum pressure experienced by the pipe, fittings, and valves at any location that is used. It is possible, however, to reduce the chilled-water working pressure on both the machines and piping by using plate-and-frame heat exchangers, which segregate groups of floors into separate static pressure zones.

In the 610 m tall example building with the refrigeration machine in the basement, it is possible to break the chilled-water system into three separate zones (Figure 11). With a 2069 kPa pressure limit, each of these three zones will max out at or slightly above 2069 kPa if the 138 kPa pressure drop indicated is the sum of equipment and friction loss. The pump shutoff head should also, however, be checked to verify that at this point the 2069 kPa pressure limitation is not significantly exceeded.

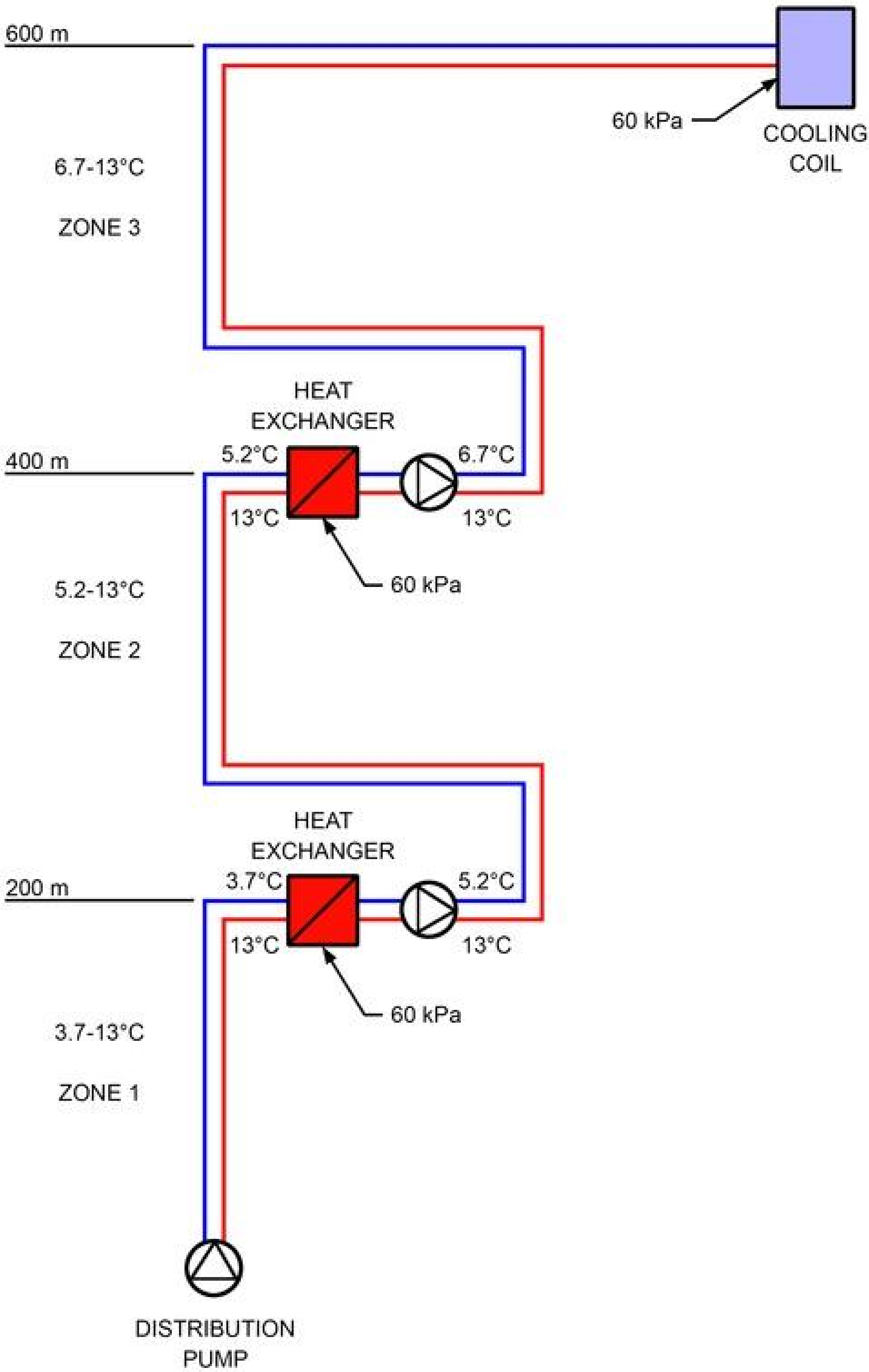

Figure 11. Typical Chilled-Water Distribution System for Supertall or Megatall Building

Each zone has static pressure of one-third of the total building height, or 200 m. All of the pumps are located on the discharge side of the refrigeration machines or the secondary zone heat exchangers. The result is that the maximum head of each zone is 2069 kPa, which is well above the threshold standard design pressure of 1000 kPa, or the point at which an increased pressure rating for the chiller and other heat transfer equipment must be considered. To limit equipment and system pressures in this example to 1000 kPa, doubling the number of zones would be required, the cost of which would likely be significantly higher than the cost of increased pressure rating of the chiller and other system equipment.

Finally, with the additional zones and the resultant chilled-water temperature increase, there is a requisite increase in the volume of water flowing through the systems on the upper floors. Accordingly, although there are benefits in the reduction in pressure, there are partially offsetting considerations that must be analyzed to determine the overall cost effectiveness of using flat-plate heat exchangers to reduce the operating pressure on the equipment, pipe, valves, and fittings at a given level. The costs associated with a single zone must be compared to any cost increases associated with the increased temperatures and temperature differentials at the upper zones.

Use of flat-plate heat exchangers and their location in a chilled-water piping system is subject to an economic analysis by the design HVAC engineer to determine the first cost of alternative arrangements as well as the operating cost differentials, if any, for any scheme considered.

Using a flat-plate heat exchanger to reduce working pressure on the condenser, although feasible, is not often considered, because the condenser water piping is usually in a single shaft with minimal (if any) offsets and a resultant small number of fittings. Valves are also only installed at the machines and are few. This limited number of fittings and valves may not be sufficient to offset the cost of the flat-plate heat exchanger and its valving as well as the added pump on the secondary side of the heat exchanger. Beyond that, there is an increase in the temperature of the condenser water, which increases the cost of operating the refrigeration machines.

Piping, Valves, and Fittings

The working pressure on the piping, valves, and fittings at various levels in a building must be determined so that proper piping material can be specified. In the United States, with steel pipe, Schedule 40 pipe is the standard wall thickness for pipes up to 250 mm diameter. For pipes 300 mm and larger, the pipe standard that is used has a wall thickness of 9.5 mm. Either of these standards would accommodate the working pressures experienced in any expected pipe diameter in any tall building. The allowable pressures for various pipe diameters can be found in ASME *Standard* A17.1 and the *Boiler and Pressure Vessel Code* (ASME 2021) and in the publications of various pipe manufacturers. The valves used should be reviewed in the valve manufacturers' literature to ensure their ability to meet the project's pressure requirements.

For steam condensate piping or for condenser water piping, where corrosion is a possible concern, pipe with a heavier wall thickness should be considered, although not because of the working pressure on either system.

Piping materials other than steel are often used. For pipe sizes below about 80 mm, in the cases of runouts or in open condenser water piping where corrosion is a concern, copper is the usual choice. Copper pipe is rare, but copper tubing is common. The limiting factor in the use of copper tubing is usually at the joints, where the ability to handle higher working pressure is restricted.

Piping Design Considerations

Other factors to consider include

- Expansion and contraction in the piping and the associated static and dynamic loads, because they are reflected in the structural steel framing system of the building
- Access to expansion joints and the anchors and guides for the piping, which should be inspected periodically after the building is constructed and placed in operation
- Firestopping between the pipe and the sleeve located at all penetrations of rated slabs, walls, and partitions
- Seismic restraints (if required) on the piping systems and pumps

In addition to expansion and contraction of the piping caused by changes in the ambient or fluid temperature, frame shortening can be a problem in concrete buildings. Concrete shrinks as it cures: over time, this shortening can be in the range of 3 mm per floor. Although this movement is relatively small, it amounts to about 225 mm for a 70-story building. This condition requires that pipes above, below, and between anchor points be flexible enough to allow for pipe movement with respect to the structure shortening. To properly design for this condition, the HVAC designer should obtain from the structural engineer the exact amount of movement that the piping system can be expected to experience.

Economics of Temperature Differentials

In the past, many refrigeration machines in the United States have used a 5.6 or 6.7 K temperature differential between entering and leaving water in the chiller and a 5.6 K differential or 0.054 mL/J of capacity for the condenser. These guidelines are appropriate for small buildings, because they have little effect on project cost, but may be less ideal for large buildings, particularly tall buildings. In projects of this type, the capital costs of piping, valves, and fittings can be substantially reduced, with a possible penalty in refrigeration machine operating cost, by using larger temperature differentials with lower water flow and a consequent reduction in piping diameter. Lower water flow also translates to lower pumping energy, which could offset additional refrigeration machine operating cost.

For a large project with a total cooling capacity requirement of 14 000 kW and chilled-water flow at a 5.6 K temperature differential, 600 L/s is circulated through 500 mm piping at approximately 3.0 m/s. If an 8.9 K temperature differential is used, total flow from the refrigeration plant is 380 L/s and the piping is 400 mm. Cost savings on the piping using the greater temperature differential would be significant. The flow reduction in this example contributes to a nearly 35% pumping energy reduction. Also, although the kilowatts per unit of cooling under both conditions should be studied, with the same discharge temperature, the operating energy consumption is likely unchanged or possibly lowered.

For the 14 000 kW refrigeration plant with a 5.6 K differential, the condenser water flow is 760 L/s and 600 mm piping is required. If this temperature differential were increased to 8.3 K, condenser water would be reduced to 500 L/s, and the piping to 500 mm. Again, this change results in a significant first-cost savings as well as pumping energy savings, depending on the distance between the refrigeration machines and the cooling towers.

Energy consumption for the refrigeration machines might marginally increase, because the condensing temperature of the refrigerant and the resultant energy usage is largely (but not solely) a function of the leaving condenser water temperature. Increases in chiller energy consumption are typically offset by reduced pumping energy. ASHRAE *Standard* 90.1 recognizes this energy savings and includes a prescriptive requirement for minimum 8.3 K **temperature differential across cooling coils**. Furthermore, large chiller plants designed to maximize chilled- and condenser-water temperature differentials (lower flow and smaller piping) can offer substantial savings in piping system installation cost.

To design chilled-water systems with a wider temperature differential, it is often advantageous to generate low-temperature chilled water between 2.2 and 4.4°C if using an all-air system. Low-temperature chilled-water facilitates low-temperature air systems, which can provide the equivalent cooling capacity with a reduced air volume. For example, a 236,000 L/s central fan system would be reduced to 175,000 L/s by using 8.9°C primary air distribution in lieu of traditional 12.8°C primary air. This reduction can provide substantial savings for installation cost, fan room space requirement, duct riser shaft space requirement, and fan energy.

7. VERTICAL TRANSPORTATION

The HVAC designer's main involvement with elevators in a tall building is to provide cooling in the elevator machine room to ensure reliable operation. Many codes now require that this machine room be conditioned by a separate HVAC system that is independent of other building systems. This section addresses the possible code requirement of elevator shaft and machine room ventilation to atmosphere.

Elevator Machine Room Cooling

The elevator machine room's cooling loads consist not only of the electric motor that drives the hoisting mechanism but also of extensive heat-generating electronic elevator controls. The electronic components that are part of the system require that the elevator machine room be maintained at a temperature between 27 and 16°C. This can be accomplished by means of a packaged DX condenser water-cooled unit in the elevator machine room; however, because of possible significant operational availability restrictions on the use of water in the machine room, the HVAC designer should review this alternative with the building developer and possibly code officials. Using a packaged DX condenser water unit may be necessary for a low- or mid-rise elevator bank with its machine room in the middle of the building, without easy access to outdoor air unless the remainder of the floor is used as a mechanical equipment room. At the top of the building, the cooling equipment can be air cooled.

The ultimate size of DX units is determined by information provided by the elevator manufacturer. The elevator consultant can provide the necessary general information to allow the design to proceed through bidding. The amount of cooling for this equipment can be significant: as much as 35 to 52 kW for a single elevator equipment room.

Elevator Hoistway and Machine Room Venting

All elevators installed in the United States must conform to ASME *Standard* A17.1, as modified by local authority and applicable building code. One requirement of many codes is to include a vent opening at the top of each elevator shaft that is 3.5% of the plan area of the hoistway or 0.27 m^2 per elevator, whichever is greater. The purpose of this requirement is to allow venting of smoke during a building fire. To accomplish this, a duct must be provided from the vent to atmosphere. This is simple at the top of the building, but for low- and mid-rise elevators, where the elevator equipment room is not located in a mechanical room with perimeter access, extending the connecting duct to atmosphere may be difficult.

Under many codes, including the model *International Building Code®* (IBC [ICC 2015]), for a building that is fully sprinklered, the need for the vent and its extension to atmosphere may be waived for passenger elevators, except for buildings where there is overnight sleeping (e.g., hotels, residences). The vent is typically still required for a dedicated service elevator car.

In addition, under the IBC, the vent may be closed under normal building operating conditions by including an automatic damper in the atmospheric vent or, under some code jurisdictions, by installing a piece of glass that will break in a fire. This damper must open on detection of smoke by any of the elevator lobby smoke detectors. Dampers have a distinct advantage in that they are manually and remotely resettable.

Where elevator speeds are greater than 7 m/s, vents at the bottom of the shafts may be required by code to allow rapid escape of air when the high-speed car is descending.

Elevator Shaft Pressurization

In super- and megatall buildings, express (or shuttle) elevators are provided to quickly carry occupants to upper-level occupancies, typically in hotels or residential uses. These elevators are commonly used as evacuation elevators in emergency situations. To maintain the safety of these elevators for this use, the elevator shaft(s) should be pressurized to keep the shaft and cars free of smoke. Refer to the section on Smoke Management for more details.

Air-Conditioning Equipment Delivery by Freight Elevators

If part of the chilled-water or boiler plant is located in the top zone of the supertall buildings, the freight elevator should have sufficient capacity and cab size to deliver and transfer all major equipment from the ground level to the area where the upper plant is located, to aid in maintenance of the equipment located there.

8. LIFE SAFETY IN TALL BUILDINGS

Life safety challenges for tall buildings are similar to those of shorter high-rise buildings. It is impractical to rely on stairs as the means of egress to grade. Elevators should play a major role in safe evacuation of occupants and response of emergency forces. Areas or floors of refuge are needed to provide staging points for occupants evacuating and emergency forces responding. Codes have developed means to confront this challenge. The following provides a brief review of those life safety measures.

Codes and Standards

In the United States, the *International Building Code®* (IBC) is the predominant building code; in Canada, it is the *National Building Code of Canada* (NRC 2010). The National Fire Protection Association's (NFPA) *Standard* 5000 generally incorporates NFPA *Standard* 101. These codes do not define a "tall building," but have additional requirements for a high-rise building greater than or equal to 128 m in height.

Components of Life Safety Systems for Tall Buildings

Tall buildings share many of the code requirements of other high-rise buildings. The IBC (ICC 2018) defines a high-rise building as "a building with an occupied floor located more than 22 860 mm above the lowest level of fire department vehicle access." Additional requirements are imposed for buildings 36.6 and 128 m above grade. No specific definition of "tall building" is contained in the codes.

Key fire safety provisions for tall buildings should include the following:

- Smoke detection for elevator lobbies, elevator machine rooms, and HVAC systems
- Complete automatic sprinkler protection
- Fire standpipe system
- Smoke management system for enclosed exits, stairs, elevators, and areas or floors of refuge
- Emergency power for life safety systems
- Fire department or first-responder elevator
- Redundant exit stair or elevator emergency evacuation provisions
- Area or floor of refuge
- Fire command center

Detection

Automatic smoke detection should be provided in elevator lobbies, elevator machine rooms, mechanical and electrical equipment rooms, and any other spaces not provided with automatic sprinklers. The detection system should be connected to the automatic fire alarm system. Duct smoke detectors should be provided in the main return air and exhaust air plenum of each air-conditioning system with a capacity greater than 0.94 m^3/s. Duct smoke detectors are also needed at each connection to a vertical duct or riser serving two or more floors from a return air duct or plenum.

The smoke detection system should be designed in accordance with NFPA *Standard* 72.

Residential buildings should have smoke alarms in each room used for sleeping purposes and on the ceiling or wall outside of each separate sleeping area. The smoke alarms should be interconnected so that activation of any smoke alarm in the dwelling unit activates all of the smoke alarms in that unit. This does not require activating smoke alarms in other apartments in the building.

Automatic Sprinkler Protection

Complete automatic sprinkler protection should be provided in accordance with NFPA *Standard* 13.

Standpipe System

Standpipe systems should be provided in accordance with NFPA *Standard* 14.

Smoke Management

The essential features of smoke management design are described in Chapter 54. Additional information is contained in NFPA *Standard* 92A.

The IBC requires exit stairs to be smoke protected. One way to achieve this is with a smokeproof tower of pressurized stairs. To enhance egress for buildings 128 m high or more, the codes require either an additional exit stairway beyond those required by the typical exit calculations, or pressurization of the elevator shafts. To prevent smoke spread through the elevator without elevator shaft pressurization, elevator vestibules with a minimum 1 h fire resistance rating are required.

Codes also require an elevator for use by emergency responders, with access from a vestibule directly connected to an egress stair.

Elevators to be used for occupants in an emergency require special protection, including pressurized elevator shafts, an emergency voice/alarm communication system, elevator lobbies with direct access to a exit enclosure, and a means to protect the elevator from automatic sprinkler system water infiltrating the hoistway enclosure. Automatic sprinklers are prohibited from the elevator machine room, and shunt trips for elevators shutdown should not be provided.

Emergency Power

All life safety systems are required to have standby power designed and installed in accordance with NFPA *Standards* 110 and 111, as appropriate.

Fire Command Center

A fire command center is required in a protected location at or near grade to monitor all fire safety and emergency systems. It should also have controls for the smoke management system and emergency power system.

Pandemic Considerations in Tall Buildings

Airborne transmission of infectious respiratory diseases in indoor environments has drawn attention, particularly with the outbreak of severe acute respiratory syndrome (SARS) and COVID-19. This section gives some background information, but consult local, state, and federal health authorities for specific recommendations and requirements.

One concern is that there may be multiple transmission routes across households in high-rise residential buildings, from natural buoyancy-moved ventilation airflow from one flat to another through open windows, and combined HVAC or plumbing risers in all buildings. Gao et al. (2008) suggested natural ventilation airflow between flats of a high rise building through open windows is possible, also, multiple COVID-19 outbreaks were reported in different high-rise buildings: 110 cases and 1 death in Hamilton, Ontario; possible aerosol outbreaks in a Korean apartment building (Hwang et al. 2021); even possible fecal transmission through drain piping system in a 12-story building in Guangzhou, China. Consideration should be given to drain piping to ensure secure water trap, and potential backdraft or motorized dampers to isolate the space when the air system is not running. Other best practices include providing code-required outdoor air, MERV-13 filtration or higher for indoor air, and possibly installing ultraviolet (UV) light and portable air cleaners. See Chapter 62 for details on UV light applications.

9. RENEWABLE ENERGY CONSIDERATIONS

Tall buildings can generate renewable energy on site, either by exploiting their height (e.g., for solar and wind energy) or by using the ground to provide thermal energy or deep geothermal heat to generate power.

Solar energy often increases with elevations because atmospheric aerosols decrease with height. Solar renewable energy can be generated through photovoltaic (PV) or solar thermal. PV can generate electricity for on-site usage or export to the grid, and can provide savings in transmission loss and electricity costs, reduce pollution, and add to the architectural appeal of a building. However, PV also carries embodied carbon that can be significant and needs to be reviewed together with operational carbon. Hamot (2019) found that PV can be up to 23% of the new building embodied carbon in a net zero operational energy building.

In tall buildings, PV can be integrated into the facades of buildings, replacing traditional glass windows with completely transparent, semi-transparent thin-film, or crystalline solar panels. These surfaces have less access to direct sunlight compared to rooftop systems, but typically offer a larger available area; its configuration should be optimized to maximize output. New coating technologies allow transparent window with a coating to block off UV and infrared spectra to reduce air-conditioning loads and convert that energy to electricity.

Solar thermal devices use solar power to generate hot water and are typically more efficient than PV. Solar thermal devices can be unglazed, transpired, flat-plate, evacuated tube, or concentrating vacuum tubes, and in general, they are more difficult to integrate with vertical facades.

Wind turbines can be either vertical or horizontal axis and can take advantage of exponential increases in wind speed atop tall buildings. A wind turbine is essentially a very large, inverse fan: the wind produces electricity instead of electricity producing wind. Since power generation is to the cube of velocity, increases in wind velocities with height in tall buildings can be beneficial. The formula is

$$P = 0.5\rho A C p V^3 N_g N_b \quad \textbf{(7)}$$

where

P = power, W

ρ = air density, kg/m^3 (about 1.2)

A = rotor swept area, m

C_p = coefficient of performance

V = wind velocity, m/s

N_g = generator efficiency

N_b = gear box bearing efficiency

For horizontal axis wind turbines (HAWT), the plane of the rotor (i.e., the blades and the hub) turns so that the wind is perpendicular to it and can flow around the blades to make them rotate around the hub. HAWTS prefer to align with prevailing wind direction and are thus more difficult to integrate with tall buildings in an urban environment, where wind directions tend to be more turbulent.

Saeed (2017) studied three HAWT turbines, each rated at 225 kW, installed in the Bahrain World Trade Center. Table 3 shows operating results from 2008 to 2016, with annual averaged running-hour percentages of 7.5, 10.5, and 12.5% (from topmost fan to bottommost fan). The turbines were running in average below the rated capacities of 225 kW each.

Vertical axis wind turbines (VAWT) do not requires aligning with prevailing wind, so they are more convenient to install in an urban environment. Pearl River Tower installed 4 VAWT in the tower, the actual energy consumption of the building is at 58 kWh/M^2/year.

Geothermal energy can be used to heat or cool a building, and deep geothermal heat can generate electricity. Like low-rise buildings, Ground-source heat pumps can provide thermal energy for either tall or low-rise buildings. However, the limited footprints available in urban settings mean that closed-loop systems can only support a relatively small portion of a tall building. Open-loop systems can support a larger building, if the water body is large enough. For example, in New York, many projects are supported by open-loop heat pump systems.

In seismic areas, deep geothermal heat can generate electricity. Often, 150°C steam or pressurized hot water can be harvested at 1500 m depth or more to generate power. For example, Iceland's position over a rift in continental plates with a high concentration of volcanoes allows them to produce approximately 66% of their electricity geothermally (Orkustofnun 2022).

Table 3 Bahrain World Trade Center Turbine Production Data from 2008-2016

Turbine Location	Total Operating Time, h	Total Electricity Produced during Operation, kWh
Turbine no. 1 (lowest)	8735	352,054.50
No. 2 (middle)	7434	238,358.00
No. 3 (top)	5224	168,523.30
Total running hours	21393	—
Total KWh produced	—	758,935.80

Pertamina Tower in Indonesia was a proposed design to achieve net zero through geothermal electric power. It is a 99-story office headquarters, 530 m tall, for the Indonesian state-owned energy company. It went 2500 m deep to extract deep ground geothermal heat to generate the required electricity to achieve net zero on site (see Figure 12).

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