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managing the ins and outs of…
Commercial Building Pressurization

from the editor…
Providing energy-efficient thermal comfort without *adversely affecting indoor air quality or violating codes poses a considerable design challenge. Yet something as subtle as air movement through the building envelope can determine whether an otherwise well-designed HVAC system performs effectively.*

This EN reviews the importance of controlling building pressure. It identifies the effects of indoor–outdoor air pressures on building performance, and then evaluates two common methods for directly controlling pressure in commercial buildings.

Why Pressure Matters in Commercial Buildings

Untreated outdoor air leaks into—**infiltrates**—the building when indoor pressure is less than the pressure outside. Control strategies typically strive to limit or eliminate infiltration as a means of minimizing HVAC loads and related operating costs. Infiltration isn't always bad, however. During the heating season, for example, a small amount of dry outdoor air leaking into the building envelope discourages moisture from condensing there.

But *excessively negative* pressure causes problems. Uncomfortable drafts and stratification interfere with temperature control and may encourage odor migration. Outward-swinging doors become difficult to open, and inward-swinging doors fail to reclose, compromising security.

Any amount of infiltration during the cooling season can raise the dew point within the building envelope, which increases the likelihood of microbial growth and structural deterioration. Infiltration of warm, moist air also affects occupied spaces by increasing latent loads.

Conditioned indoor air leaks out of—**exfiltrates** from—the building when the pressure inside is greater than the pressure outside.

During the summer, exfiltration of cool, dehumidified indoor air benefits the building by keeping the envelope dry. But *excessively positive* pressure makes opening and closing doors difficult and creates noisy high-velocity airflow around doors and windows. It can also wreak havoc with temperature control by impeding supply airflow into occupied spaces.

During the winter, even slightly positive pressure forces moist indoor air into the building envelope. Moisture may

Ducted or Plenum Return?

Ducting return air from a building's occupied spaces back to the air handler increases the initial cost of the system, so why do it? Is it to meet local codes? Sometimes. Is it to facilitate return-path cleaning? Maybe. Is it to avoid moisture problems in the ceiling plenum? Probably not. To understand why, consider the following example…

Suppose that the pressure in the return air plenum must be approximately 0.03 in. wg less than the pressure in the occupied space to overcome the return-grille pressure drop. If building pressure is controlled to 0.05 in. wg, then the plenum pressure will be +0.02 in. wg with respect to outdoors. This slight difference between the indoor and outdoor pressures will induce very little infiltration. ■

condense on cold surfaces inside walls, hastening structural deterioration.

Ideally, the net pressure inside the building relative to outside should range from slightly negative or neutral during cold weather (minimizing exfiltration) to slightly positive during warm weather (minimizing infiltration). Excessive building pressure, whether negative or positive, should be avoided.

Semantics of Building Pressure Control

True or False: "Relief" and "exhaust" are interchangeable descriptors for air removed from a building.

Although it's true that both relief air and exhaust air leave the building, their purposes (and definitions) differ.

Exhaust airflow—which may be central or local, constant or variable—carries contaminants from the building. Local codes or industry standards define how much exhaust air must be removed from specific types of spaces (rest rooms, for example), regardless of pressure-related concerns or operating mode.

Relief airflow removes air from the building (again, either centrally or locally) to balance intake airflow and maintain proper building pressure.

Intake airflow describes the rate at which the air handler brings air into the building. Local codes or industry standards require a minimum amount of intake airflow for proper ventilation and to dilute and remove general contaminants. Additional outdoor air is brought into the building during economizer operation to provide "free" cooling.

In the absence of infiltration and exfiltration, negative building pressure results when exhaust-plus-relief airflow exceeds intake airflow. Conversely, positive building pressure results when exhaust-plus-relief airflow is less than intake airflow. ■

Forces that Affect Pressure

Preventing extreme building pressures is much easier said than done. In most structures, the indoor–outdoor pressure difference results directly from the combined effect of weather, wind, and operation of the mechanical ventilation system.

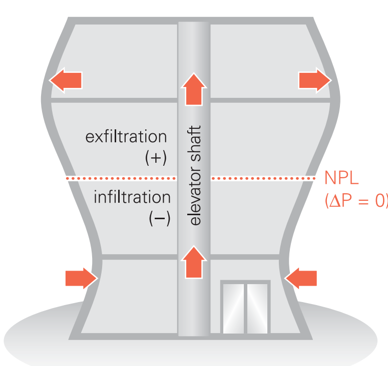
Weather. Like a column of water in a pipe, the weight of a column of air results in a "head" pressure that increases from the top of the column to the bottom. Described as hydrostatic pressure, but more commonly known as "stack pressure," the weight of the air column is affected by local barometric pressure, temperature, and humidity ratio.

Temperature-related differences in indoor and outdoor air density create differences in pressure that can affect infiltration, exfiltration, and the direction of air movement within shafts and stairwells (Figure 1).

When indoor air is warmer than outdoor air, the less dense column of air inside the building results in a net negative pressure below the **neutral pressure level (NPL)** and a corresponding net positive pressure above it. Because all building envelopes contain unavoidable cracks and openings, this pressure difference induces outdoor air to enter the lower floors and indoor air to leave the upper floors. These leakage characteristics also encourage upward airflow—normal stack effect—within shafts and stairwells.

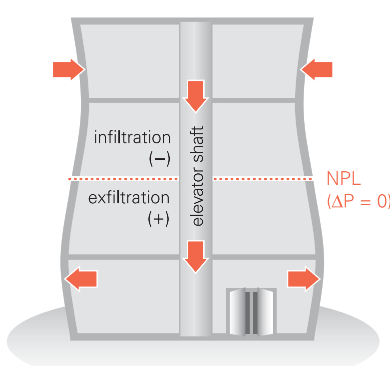
When indoor air is cooler than outdoor air, the column of air inside the building is more dense. The result is a net negative pressure at the top of the building and a corresponding net positive pressure at the bottom. Unless building pressure is controlled, outdoor air will infiltrate the upper floors while indoor air exfiltrates from the lower levels. The pressure difference also induces downward airflow in stairwells and shafts—reverse stack effect.

Figure 1. Stack effect and building pressure



Winter (normal) stack effect

- Inward-swinging doors may not latch
- Exfiltrating indoor air drives moisture into building envelope



Summer (reverse) stack effect

- Outward-swinging doors may stand open
- Infiltrating outdoor air drives moisture into building envelope

The *2001 ASHRAE Handbook–Fundamentals* provides an equation to quantify the stack-effect pressure difference:[1]

$$\Delta p_s = C_1 \cdot \rho_o \cdot \left(\frac{T_o - T_i}{T_i}\right) \cdot g \cdot (H_{NPL} - H)$$

where,

Δp_s = difference between indoor and outdoor stack pressures, in. wg

C_1 = conversion factor, 0.00598 in. wg · ft · sec²/lb$_m$

ρ_o = outdoor air density at outdoor air temperature, lb$_m$/ft³

g = gravitational constant, 32.2 ft/sec²

H = height above reference plane, ft

H_{NPL} = height of neutral-pressure plane above reference plane, ft

T_i = indoor air temperature, °R

T_o = outdoor air temperature, °R

The following example illustrates the magnitude of stack effect in a four-story, air-conditioned building (H = 50 ft, T_i = 75°F = 535°R). Assuming that cracks and openings are evenly distributed throughout the building envelope, the neutral pressure level exists at mid-height (H_{NPL} = 25 ft).

On a hot day (T_o = 95°F = 555°R, ρ_o = 0.0715 lb$_m$/ft³), the difference in indoor–outdoor air densities produces a +0.013 in. wg pressure difference at the ground floor. Without building pressure control, conditioned indoor air exfiltrates from the lower floors (H = 0 ft), keeping that part of the envelope dry. A less desirable condition exists at the top floor (H = 50 ft), however, where the –0.013 in. wg pressure difference encourages entry of hot (possibly humid) outdoor air.

On a cold day (T_o = 0°F = 460°R, ρ_o = 0.0863 lb$_m$/ft³), the density of the indoor air column produces net pressures of –0.058 in. wg at the ground floor and +0.058 in. wg at the top floor. This time, lack of building pressure control permits warm, moist indoor air to exfiltrate from the upper floors of the building, while cold air infiltrates the lower floors. The substantial pressure difference created by wintertime stack effect may make it difficult to open outward-swinging doors at building entrances.

Because it's impossible to control the weather, stack-effect pressure differences are best addressed using vertical **compartmentalization** to reduce the height of the indoor air column. (See "What's the *Right* Setpoint for Building Pressure?," p. 6.) Vestibule-type entries and revolving doors (which can accommodate a high pressure difference without compromising door operation) will minimize stack-induced air currents at entrances, elevators, and stairwells. To reduce air currents at the building envelope, use a well-designed, well-constructed air barrier.

Note: A building actually consists of many interconnected "containers" with differing pressures. Unless strict contaminant control is necessary (hospitals, clean rooms), however, most building-pressure control schemes treat the building as one "equi-pressure container" to regulate envelope airflow and permit proper door operation.

Wind. Wind pressure "pushes" outdoor air into the windward side of the building and "pulls" indoor air from the leeward side (Figure 2). The differential pressure exerted on building

[1] American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., 2001, *ASHRAE Handbook: Fundamentals* (Atlanta, GA: ASHRAE), 26.5–Equation 17.

Siting Pressure Sensors

Regardless of whether the relief system uses a return fan or a relief fan, direct control of building pressure requires a differential pressure sensor to monitor the indoor–outdoor pressure difference.

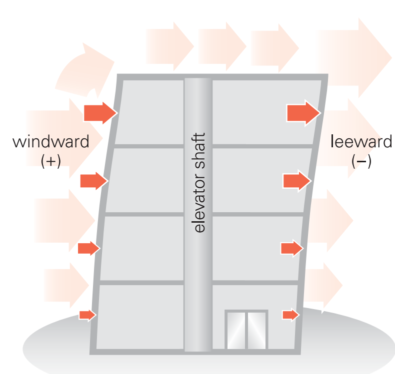
Indoor sensor. Two schools of thought exist regarding placement of the indoor sensor. Some designers place it near the door, where over-/under-pressurization effects are most noticeable; others isolate the indoor sensor from the door to dampen the effect of rapid pressure changes caused by door operation.

In either location, the indoor pressure sensor should include sufficient signal filtering to minimize the effects of high-speed pressure changes. It is also important to avoid perimeter locations that can be influenced by wind-induced pressure fluctuations.

Outdoor sensor. Again, placement of outdoor sensors typically follows one of two common practices. Many designers place the outdoor pressure sensor on the roof-mounted air handler. Others use multiple sensors (one at each corner of the building, at least 15 ft above the roof) and average their signals to cancel the effect of wind pressure. In any case, select sensors that will minimize wind effect.

For applications in which the building is tall and compartmentalized for pressure, position an outdoor pressure sensor at the elevation of each compartment. ■

Figure 2. Wind and building pressure



Seasonal effects of wind

- Summer: Wind drives moisture-laden outdoor air into windward envelope
- Winter: Exfiltrating indoor air carries moisture into leeward envelope

surfaces as a result of wind velocity is calculated as:[2]

$$\Delta p_w = C_2 \cdot s^2 \cdot C_p \cdot \rho_o \cdot \frac{(U_H)^2}{2}$$

where,

Δp_w = wind surface pressure relative to outdoor static pressure in undisturbed flow, in. wg

C_p = wind-surface-pressure coefficient, dimensionless (0.5 to 0.8 for this example)

C_2 = conversion factor, 0.0129 in. wg · ft³/lb$_m$ · mph²

ρ_o = outdoor air density at outdoor air temperature, lb$_m$/ft³

s = shelter factor (0.40 for this example)

U_H = effective wind speed, mph

Like stack effect, wind pressure varies with outdoor air density and building height; wind pressure also varies with the shelter provided by the immediate landscape, including nearby trees and buildings. To illustrate the magnitude of wind-effect pressure, let's revisit our example building at the hot and cold weather conditions described previously. If we assume that the effective wind speed (U_H) is 25 mph and that the wind-surface-pressure coefficient (C_p) is 0.50 at the ground floor (0 ft), then the windward pressure difference will be 0.023 in. wg on a hot day and 0.028 in. wg on a cold day.

At the top floor (50 ft), where the wind-surface-pressure coefficient may reach 0.80, the windward pressure difference rises to 0.037 in. wg on a hot day and 0.044 in. wg on a cold day.

Arguably, the best way for designers to mitigate the effect of wind is by maintaining a very negative building pressure during the winter (deterring leeward exfiltration) and a very positive building pressure during the summer (deterring windward infiltration). However, *successful* implementation also requires the use of a vestibule to prevent interference with door operation, *and* an effective air barrier in the building envelope to prevent large indoor–outdoor pressure differences from creating undesirable airflows.

Mechanical ventilation system. Some fans force air into the building; others force it out. The balance between **intake airflow** and **relief airflow** determines whether the net building pressure is positive or negative. (See "Semantics of Building Pressure Control," p. 2.) Excess intake airflow pressurizes the building by creating a net positive pressure (Figure 3); excess relief airflow depressurizes the building by creating a net negative pressure.

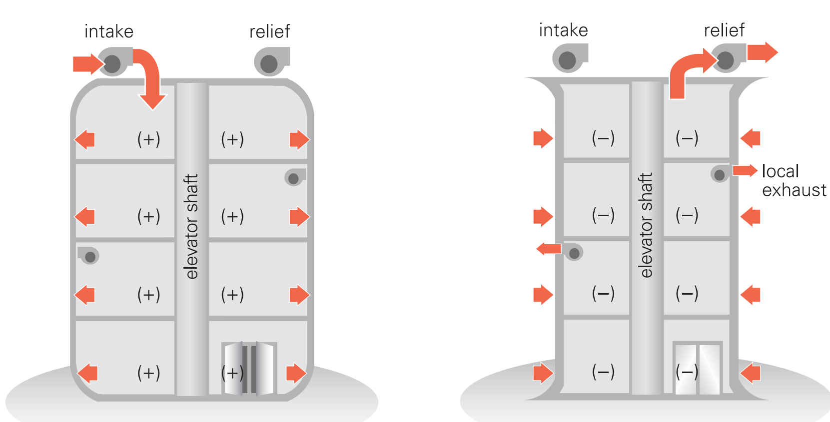
Depending on the system type, control strategy, and operating schedule, intake and relief airflows may vary during normal system operation. As examples, the relief fan may operate intermittently on demand, and intake (outdoor) airflow will modulate with airside economizer operation.

Controlling Building Pressure

Depending on the season and the height of the structure, the *preferred* building pressure may be positive or negative. Meanwhile, the *actual* building pressure can be positive or negative due to the combined forces of wind, weather, and operation of the mechanical ventilation system. (See "What's the *Right* Setpoint for Building Pressure?," p. 6.)

Establishing the preferred building pressure in the face of continuously changing conditions usually requires an automated control scheme. For VAV applications with airside economizers, designers typically modulate relief airflow to directly or indirectly maintain building pressure within an acceptable range.[3]

Figure 3. Effect of fan operation on building pressure



Intake airflow only
- Outward-swinging doors may stand open
- During winter, exfiltrating indoor air drives moisture into building envelope

Relief and local exhaust airflows only
- Inward-swinging doors may not latch
- During summer, infiltrating outdoor air drives moisture into building envelope

[2] Ibid., 26.5–6.

[3] Noteworthy articles include "Comparing Economizer Relief Systems" by Steven Taylor, PE, (2000) *ASHRAE Journal* 42 no. 9: 33–42; and "The Impact of Airtightness on System Design" by Wagdy A.Y. Anis, AIA (2001) *ASHRAE Journal* 43 no. 12: 31–35.

Alternatives for Return-Fan Control

ASHRAE Guideline 16P recommends using the pressure in the return air plenum as the basis for controlling a return-fan relief system. (See “Return fan with direct control,” pp. 5–6.) This simple, direct approach is inexpensive to implement; it’s also more reliable than the following commonly used control schemes: signal tracking and flow tracking.

Signal tracking monitors supply-duct pressure to regulate the speeds of the supply *and* return fans. Building pressure is controlled indirectly (and ineffectively) because of the disparity between the fan curves.

Flow tracking indirectly controls building pressure by monitoring both supply and return airflows. The capacity of the return fan “tracks” supply airflow to maintain a fixed differential between the two.

Flow tracking works best in applications with constant local exhaust. Successful implementation also requires expensive, well-calibrated flow sensors because the difference between supply and return airflows can be a very small fraction of the sensed airflow. ■

Note: Intake airflow is usually modulated to control ventilation and economizer cooling.

For controls to maintain either positive or negative building pressure by modulating relief air, the *minimum intake airflow must exceed maximum exhaust airflow;* relief airflow can then be used to “trim” the difference between airflow into and out of the building.

Minimum relief airflow yields positive building pressure, while maximum relief airflow yields negative building pressure. For systems with airside-economizer operation, minimum relief airflow may be zero, while maximum relief airflow may approach maximum intake airflow.

Building pressure can be regulated passively or actively. **Passive building pressure control** most commonly consists of a gravity-operated damper in the occupied space. When the economizer operates, the positive pressure that develops inside the space pushes air out of the damper and prevents overpressurization.

Relief dampers are often inexpensive to install; however, susceptibility to wind and stack effect often limits their use to small HVAC systems and single-story buildings.

Depending on the configuration of the air distribution system, schemes for **active building pressure control** involve either a return fan or a relief fan. Table 1 (p. 8) compares the pros and cons of these two approaches.

Return fan with direct control.

Figure 4 illustrates a typical VAV system with a return fan and direct control of building pressure:

1 A flow sensor (in this case, a flow-measuring damper) monitors intake airflow to maintain the proper volume of outdoor air for ventilation.

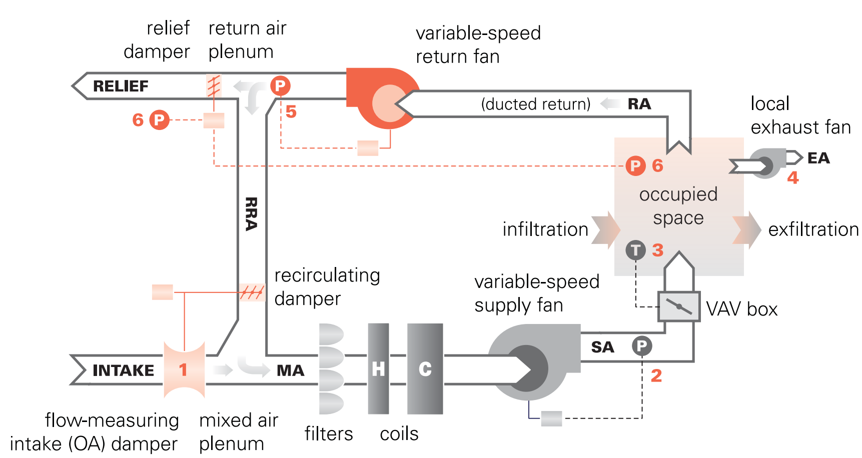
The pressure in the mixed-air plenum changes as the actuator modulates the linked intake and recirculating dampers.

Note: An intake airflow sensor controls ventilation more accurately than supply/return airflow tracking. Monitoring intake airflow also costs less and is usually more reliable than using an injection fan, pressure sensor, and variable frequency drive.

2 A pressure sensor monitors supply-duct static pressure and adjusts supply-fan capacity accordingly.

Note: For DDC/VAV systems, ASHRAE Standard 90.1 requires duct-static-pressure reset based on VAV-box position to minimize supply-duct static pressure and, therefore, supply-fan horsepower.

Figure 4. Typical VAV system with central return fan



3 The thermostat in each occupied space detects the dry-bulb temperature and appropriately modulates the supply airflow.

4 Local exhaust fans (in rest rooms, for example) remove some of the air from the occupied spaces.

The remaining air either exfiltrates, if the spaces are pressurized; or, it returns to the air handler, accompanied by "infiltrated" air, via a return duct or ceiling plenum.

5 A pressure sensor in the return air plenum adjusts the capacity of the return fan. (See "Alternatives for Return-Fan Control," p. 5.)

The return fan, which operates whenever the supply fan does, pulls return air from the occupied space and pressurizes the return air plenum at the air handler. Air from this plenum either passes through the recirculating damper into the mixed air plenum or exits the building through the relief damper.

An energy-efficient enhancement to return-air-plenum control, **optimized damper control**, keeps one damper nearly wide open to ease the burden on the return fan. This strategy modulates the plenum-pressure setpoint, and therefore return-fan speed, based on the positions of the relief *and* recirculating dampers.

6 A differential pressure sensor monitors the indoor–outdoor pressure difference. Its signal modulates the position of the relief damper, directly controlling building pressure.

The outdoor intake and recirculating dampers can share the same actuator. However, the relief damper must be controlled separately to accommodate varying building-pressure setpoints.

What's the *Right* Setpoint for Building Pressure?

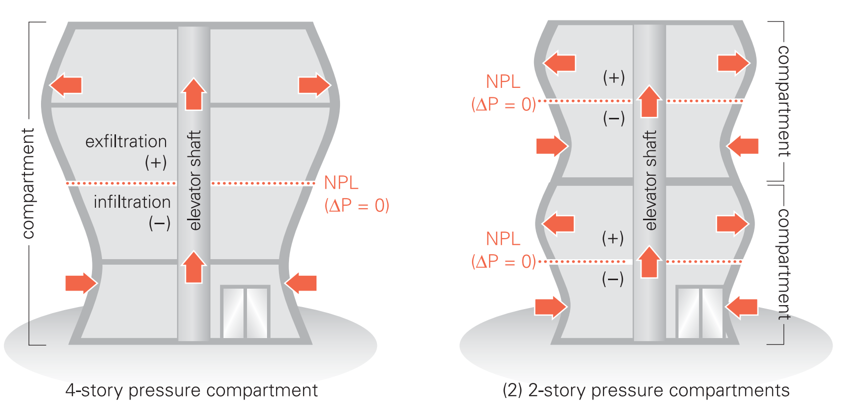
The answer depends on a number of factors: Where is the sensor? What is the building's geographic location? Is it sheltered? What's the climate like?

Conventional practice is to situate the indoor pressure sensor on the ground floor. A control scheme is then devised to maintain a slightly positive building pressure (0.00 in. wg to +0.05 in. wg or more) during summer operation. In hot humid climates, a setpoint greater than +0.10 in. wg may be appropriate, especially for tall buildings and multistory pressure compartments. The objective is to minimize or eliminate infiltration at the top floor by pressurizing the building as much as possible without interfering with proper door operation.

A similar tactic is employed for winter operation to discourage exfiltration of moist indoor air near the top of the building envelope. But this time, the target pressure is neutral or slightly negative (0.00 in. wg to –0.02 in. wg or less). In cold climates, where winter stack effect exerts considerable force, further depressurization is often necessary… perhaps –0.10 in. wg on a windy day for a building of only four stories. To cope with winter stack effect, tall buildings typically include vestibules with revolving doors. This arrangement effectively separates the indoor air column from outdoor air, enabling proper door operation despite the large indoor–outdoor pressure difference.

"Compartmentalizing" tall buildings—that is, vertically dividing the building into separate air distribution systems—can help minimize the effect of stack pressure differences by reducing the height of the indoor air column. (Elevators usually require a separate vertical compartment.)

Compartmentalization and winter stack effect



Without compartmentalization, minimizing air leakage through the entire building envelope due to stack effect would require a very positive setpoint during the summer and a very negative setpoint during the winter.

Ultimately, the extent to which a building can be pressurized depends on its construction (whether it is "tight," "leaky," or something in-between) and its operation. A well-sealed building must include controls to avoid developing excessive pressure, while even marginal pressurization may be unachievable in a "leaky" building. ■

Relief fan with direct control. Figure 5 illustrates another typical VAV system, but in this case, a relief fan directly controls building pressure:

1 The flow sensor (a flow-measuring damper, as in the previous example) monitors intake airflow to maintain proper ventilation.

2 Supply-fan capacity is based on the signal of a pressure sensor that monitors supply-duct pressure.

3 Airflow from each VAV box is modulated based on the dry-bulb temperature detected by the thermostat in each occupied space.

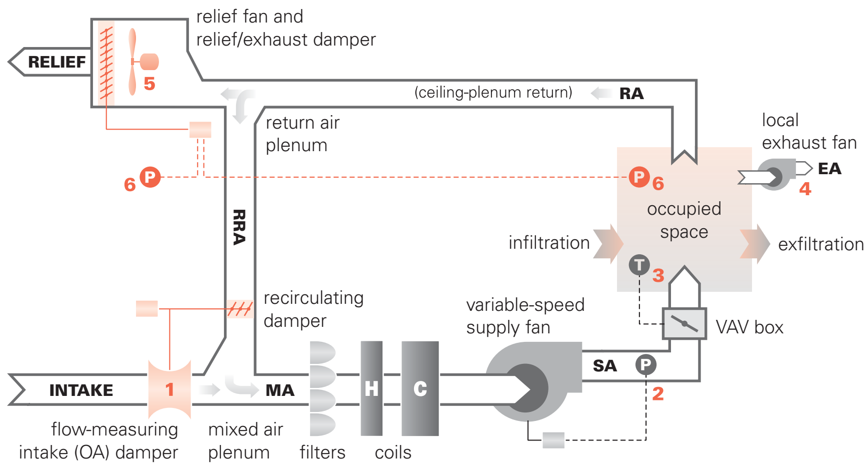
4 Local exhaust fans and exfiltration remove a percentage of air from occupied spaces; the rest (including "infiltrated" air) returns to the air handler, usually by way of a ceiling-plenum return.

5 The relief fan only operates when necessary to relieve excess building pressure. With minimum intake airflow, relief airflow is seldom necessary during mechanical cooling and heating operation. Note, too, that without a return fan it is unnecessary to monitor and control the static pressure in the return air plenum.

Although the relief fan (when running) relieves the burden on the supply fan, the latter still must be sized to handle the pressure drop of the entire system at design airflow. For this reason, the relief-fan configuration is typically applied in ceiling-plenum-return systems.

6 As in the return-fan example, a differential pressure sensor monitors and directly controls building pressure by adjusting the relief fan's capacity.

Figure 5. Typical VAV system with central relief fan



Capacity control can be accomplished by "riding the fan curve" as the relief damper modulates or by equipping the relief fan with speed control.

Air from the return air plenum either passes into the mixed air plenum through the recirculating damper, or exits the building through the relief damper.

Why pick one relief method versus another? Choosing a relief system based on the unique requirements of each application lets you optimize the costs of installing and operating it.

Generally, the relief-fan configuration works best in VAV systems designed with a ceiling-plenum return. Relief fans effectively control building pressure; they are also easier to control, less expensive to install, and less costly to operate than return-fan configurations.

When a ducted return is necessary (see "Ducted or Plenum Return?" p. 1), be sure to evaluate both relief- and return-fan configurations: If the supply fan can handle the pressure drop from the air-handler's discharge opening to its return opening, then the relief-fan configuration is preferred. Use a return fan if the ducted return adds more pressure drop than a reasonably sized supply fan can handle.

Closing Thoughts

Building pressure control is important for two reasons:

- It is fundamental to attaining the design targets for infiltration and exfiltration.
- It enables proper door operation by preventing excessively positive or negative pressure.

Both factors affect the performance and longevity of the building and its systems. Direct control of building pressure, whether with a return fan or a relief fan, best manages the combined effects of weather, wind, and mechanical ventilation.

Return fan control works. Although it requires at least one additional pressure sensor (which can be difficult to situate) and continuous operation of the return fan, it also permits a smaller supply fan. Use this type of relief if the air distribution system includes return ducts.

Relief fan control works, too. And it's often less costly to install and operate than a central return fan. The fan horsepower necessary to overcome the pressure drops of the relief damper and return path is about the same as for return-fan relief. But unlike the return fan, the relief fan only operates when needed (usually during the economizer mode).

Use relief fan control when the supply fan can overcome the combined pressure drop of the supply and return paths—usually in systems with ceiling plenum return or with very short return ducts—or when the system can benefit from locating the relief fan remotely from the air handler. ■

By Dennis Stanke, applications engineer, and Brenda Bradley, information designer, Trane.

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Table 1. Pros and cons of return fan vs. relief fan in VAV systems

Return fan	Relief fan
Advantages	*Advantages*
■ **Lower differential pressure across the supply fan** if the pressure drop of the return air path is greater than the pressure drop of the outdoor air path.	■ **Lower operating cost.** Typically, the relief fan can remain off during "non-economizer" hours and operate at low airflow during many "economizer" hours. Also, the recirculating damper can be sized for a lower pressure drop.
■ **Potentially lower initial cost for systems with ducted returns.** Less supply fan pressure can mean lower fan horsepower and/or a smaller fan and smaller variable-speed drive.	■ **Greater layout flexibility.** The relief fan can be positioned anywhere in the return path (lower initial cost) because the supply fan draws the return path negative (relative to the occupied spaces) during modulated economizer operation. A ground-floor air handler with top-floor relief can take advantage of winter stack effect to lower operating cost.
	■ **Simpler control scheme.** One less sensor and one less actuator simplifies installation and balancing. Applications with a low return-path pressure drop can accommodate lower-cost fans as well as fewer (less costly) controls.
Disadvantages	*Disadvantages*
■ **Higher operating costs**, especially in climates with extended hours of economizer cooling (The return fan must run whenever the supply fan operates.)	■ **Negative building pressure at low loads.** This condition can occur when a variable-speed drive controls relief-fan capacity, the supply airflow rate is low, *and* required relief airflow is less than the minimum airflow at lowest fan speed. (Using a constant-speed relief fan with a modulated relief damper avoids this disadvantage.)
■ **More complex (expensive) fan-speed control.** Return-air-plenum pressure control requires an additional pressure sensor and modulating device (either a damper actuator or variable-speed drive).	■ **Greater likelihood of outdoor air leakage at the relief damper.** The return air plenum operates at negative pressure whenever the relief fan is off. (Using low-leak relief dampers can minimize air leakage from outdoors.)
■ **Difficult to situate the return-air-plenum pressure sensor** (in systems with return-air-plenum pressure control) because the return air plenum is usually small and turbulent.	■ **Higher differential pressure across the supply fan** than in return-fan systems. When the relief fan is off, the supply fan must overcome the pressure drops of the return path as well as the supply path. (For this reason, relief fans may or may not be appropriate for systems with ducted returns.)
■ **Requires more fan horsepower at part load.** Return-air-plenum pressure must always be positive enough to establish relief airflow; the recirculating damper must therefore drop significant pressure between the negative mixed air plenum and positive return air plenum. (Optimized damper control can reduce part-load fan horsepower.)	
■ **Limited layout flexibility.** The return fan must be situated between the air handler and the closest leg of the return path (usually near the air handler) because it must draw the entire return path negative relative to the occupied spaces. It must also discharge into the return air plenum during modulated economizer operation.	

Trane believes the facts and suggestions presented here to be accurate. However, final design and application decisions are your responsibility. Trane disclaims any responsibility for actions taken on the material presented.

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