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Another HVAC Design Parameter to Consider

Stack Pressure-Created Airflows in Insulation Envelopes, Part 2: Passenger Aircraft

BY DOUGLAS S. WALKINSHAW, PH.D., P.ENG., FELLOW/LIFE MEMBER ASHRAE; RAYMOND H. HORSTMAN, P.E., FELLOW ASHRAE

Aircraft design codes do not address stack pressure-driven air circulation through insulation envelopes. While the moisture problems associated with these flows (condensation, microbial growth, corrosion, dead weight) are well known, the effect on ventilation flow due to them is not. The authors' measurements and calculations indicate that if 25% or more of the cabin conditioned air travels through the insulation envelope (the space between the cabin liner—the cabin walls and ceiling—and the aircraft skin), up to 11.6% of the cabin conditioned air (half of which is filtered, recirculated air and the other half engine bleed air) effectively bypasses the occupants.

This paper provides the science behind these stack pressure effects, reviews the limitations of current measures and details a set of proposed measures that, if taken together, will offset these stack pressures and eliminate all their negative consequences.

This article addresses a specific aspect of the design of passenger aircraft. It proposes small additions/changes within the interior wall lining and fuselage, which would reduce condensation, yet provide benefits for the interior aircraft air for some cabin designs.

This is the second of a two-part series of papers on the subject of insulated envelope stack pressures. Part 1,[1] which was in the April issue of *ASHRAE Journal*, addressed buildings.

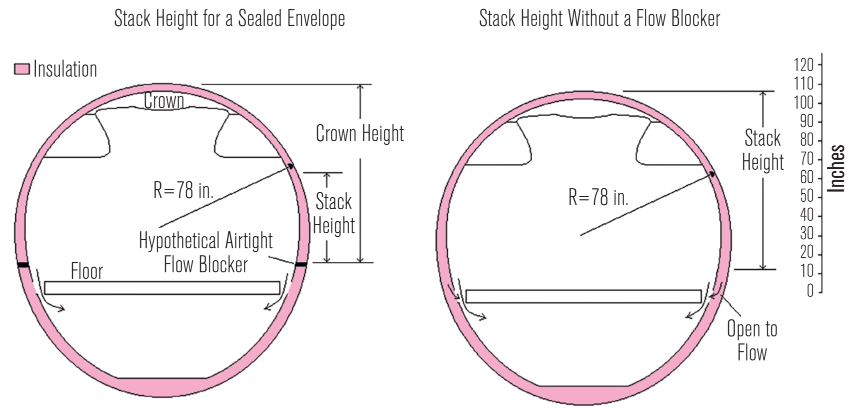
When water condenses on the airplane structure in flight, it freezes and remains there until the airplane is in an environment warm enough to melt the ice and allow the water to flow with gravity. Water can also condense on the cold structure in humid environments for some period after the plane lands. The water can

Douglas S. Walkinshaw, Ph.D., P.Eng., is president, Indoor Air Technologies, Inc., VEFT Aerospace Inc., and ECHO Air Inc, Canada and USA. Raymond H. Horstman, P.E., is an Indoor Air Technologies affiliate.

accumulate in puddles, then overflow as the airplane changes attitude during climb, for example.

Occupants are the source of water vapor and most contaminants in flight. The same air that brings water vapor into the insulation envelope also brings cabin air contaminants with it. If the air is drawn from cleaner areas of the cabin, some outdoor (fresh) air is lost. If the air comes from more humid (and more contaminated) areas of the cabin, the cabin air quality improves, but the condensation rate increases.

FIGURE 1 Stack height with and without flow blockers with flow through floor.



There have been a few approaches and proposals to prevent dripping, such as how insulation is arranged, or ways to prevent or reduce the condensation itself, all with limited success.[2] Very little, if any, attention has been given to the effect of envelope flow on cabin air quality. These will be discussed after an introduction to stack pressure.

Stack Pressure

Stack or buoyancy pressure differentials across perimeter insulated envelopes are created by temperature differences between indoors and outdoors. These pressure differentials increase with increased temperature differential. Some airplane designs use flow blockers (fire stops) to reduce envelope flow. Even with an airtight flow blocker in the envelope, the stack effect will draw air through cracks in the upper sections of the cabin liner wall and ceiling and expel air through cracks in the lower sections of the cabin liner. The stack pressure itself is then roughly half that of an envelope without the flow blocker (*Figure 1*).

Stack pressures are predicted by[3,4]

$$\Delta P = (\rho_2 - \rho_1) \times g \times h \qquad (1)$$

Substituting

$$\rho = P/RT \qquad (2)$$

Gives

$$\Delta P = P_1 (1/T_1 - 1/T_2) \times g \times h/R \qquad (3)$$

where

ρ_1 = air density in the living space (slug/ft^3; one slug is 32.1740 lb)

ρ_2 = air density behind the insulation (slug/ft^3; one slug is 32.1740 lb)

h = height above the neutral plane (ft)

P_1 = cabin air pressure (lb/ft^2) (psia × 144)

T_1 = temperature in room (°R) (°F + 459.67)

T_2 = temperature behind the insulation (°R) (°F + 459.67)

R = individual gas constant for dry air = 1,716 ft^2/(s^2·°R)

g = acceleration due to gravity (32.2 ft/s^2)

ΔP = stack pressure (lb/ft^2) or customarily in units of Pa (47.88 Pa/lb·ft^2)

The stack pressure at the crown (the top of the cabin structure) of the aircraft wall when sealed at the cabin floor will draw conditioned cabin air behind the insulation between mid-height and the crown and expel it between mid-height and the cabin floor. If the cabin air temperature is assumed to be 72°F (22°C) at a pressure of 11.02 psia (75.98 kPa), the stack pressures can be calculated to determine the effect of the flow blocker.

Using *Equation 3*, the stack pressure at the crown of the cabin with an airtight flow blocker near the floor (*Figure 2a*) and without a flow blocker (*Figure 2b*) are given for a range of crown heights and temperatures behind the insulation.

Airflows Behind the Insulation

The airflow rate through the insulation envelope, Q, is governed by the following equation

$$Q = (ELA)C_d\sqrt{2\Delta P_r / \rho} \qquad (4)$$

where

Q = predicted flow rate, ft^3/s (= cfm/60)

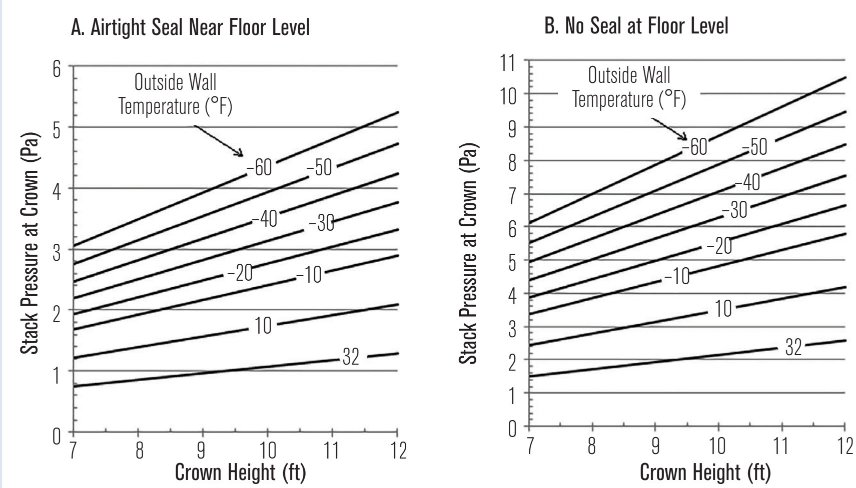
C_d = discharge coefficient (varies between 0.6 for small sharp-edged openings and 1 for large openings).

ELA = equivalent or effective leakage area, ft^2 (= in.^{2}/144)

ρ = mass air density, 0.002313 slug/ft^3 (= 0.07451 lb/ft^3/g) at 11.02 psia, −60°F

ΔP_r = reference pressure difference (lb/ft^2) or customarily in units of Pa (= 47.88 × lb/ft^2)

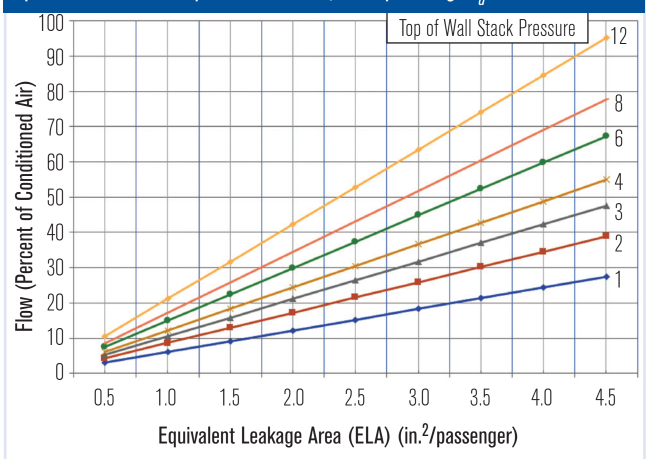
FIGURE 2 Effect of a floor level envelope flow blocker on stack pressure.



Using *Equation 4*, *Figure 3* shows the percent of cabin air passing behind the insulation at stack pressures ranging up to those at cold soak (−60°F [−51°C]) for a range of envelope ELAs per passenger at ¾ atmosphere cabin pressure (11.02 psia [75.98 kPa]) at C_d = 0.6. This C_d represents the flow coefficient for an envelope that has an air space between the walls and the insulation.

Tests on an older B737-200 with the wall sealed at the floor found a equivalent leakage area in the cabin liner (sum of the leaks), as defined in *Equation 4*, of 1.65 in.^{2} (1065 mm^2) per passenger, with a crown stack pressure of 4 Pa (0.02 in. w.g.) at cold soak. This equates to 20% or more of the cabin conditioned air supply passing behind the cabin insulation at cold soak,* depending on the actual envelope flow blocker leakage at the cabin floor or between windows.

FIGURE 3 Percent of a 20 cfm/passenger conditioned cabin air supply drawn behind the insulation at cold soak versus ELA per passenger and top of wall stack pressure ΔP. Cabin air pressure = 75 kPa, envelope leakage C_d = 0.6.



For example, the envelope might have some leakage around the edges of the flow blocker. The stack pressures and floor vent pressure differential create high velocities around the flow blockers (*Figure 4*). Note that the pressures and temperatures within the envelope are lower than in the adjacent cabin area for this example.

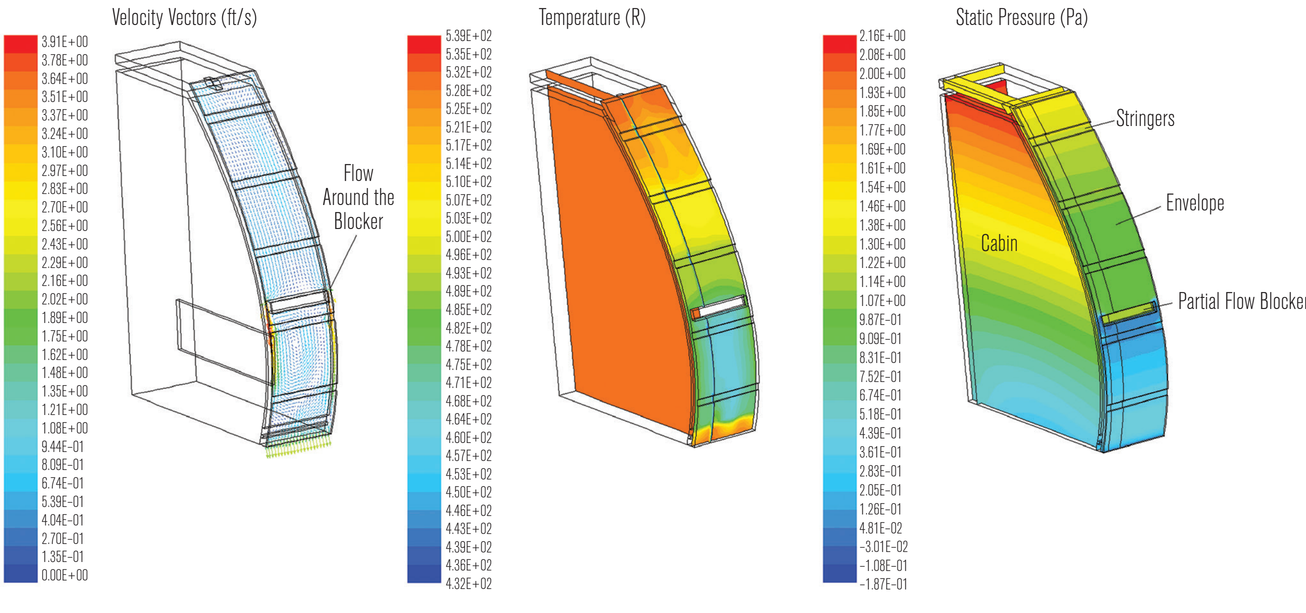
Measures That Affect Envelope *ELA*

More than two decades ago, following the elimination of tobacco smoking on the airplane, the outdoor air ventilation rate in commercial aircraft was reduced by 50%. This reduction effectively doubled occupant-sourced airborne pollutants, so a HEPA filtration rate equal to the reduction in outdoor air supply rate was introduced so pathogen levels in theory would not be any higher. In addition, the amount of humidity condensation on the cold fuselage behind the insulation increased dramatically. To address the increased humidity condensation, the following steps were considered by manufacturers:

Controlled Drainage Path. As water freezes on the outer skin during flight, large amounts of water as ice could accumulate in the insulation envelope on any part of the cold structure over many flights if the airplane is operated in cold climates. As soon as the airplane encounters an environment warm enough to melt the ice, this water will begin to flow downward to the cabin

*When the temperature between the insulation and the skin reaches its lowest value.

FIGURE 4 Conditions in the cabin and envelope with a partial flow blocker.



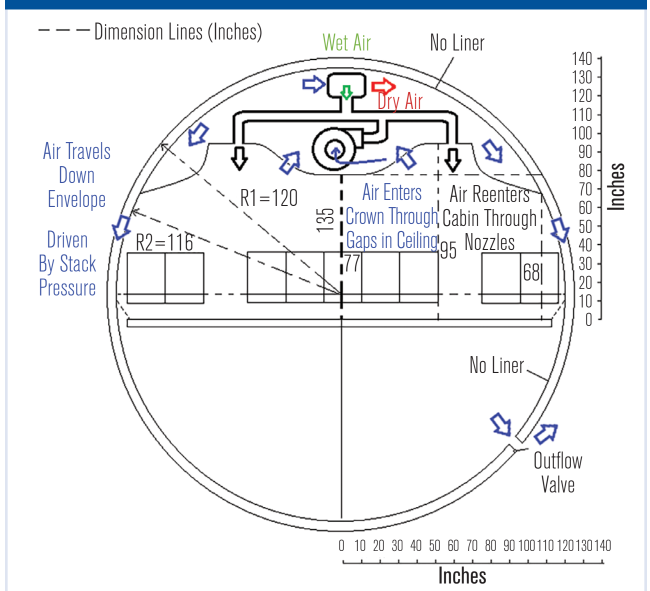
if not redirected. Similarly, an airplane operated in humid climates on short routes with open-air passenger loading will condense water as the structure cycles from cold in flight to warm on the ground.

To try to prevent this, water-absorbent felt was placed in areas where the structure passing through the insulation was exposed beyond the insulation, and layers of plastic were placed on various surfaces to redirect the water flow to areas that would not drip into the cabin. The insulation blankets overlay each other much like roofing shingles, so that the water flows downward on overlapping layers. The blankets are fiberglass, so they are placed in waterproof bags to allow water to flow over them. The water then flows around the cabin through the walls to underfloor drain holes on the belly of the airplane. Of course, this doesn't prevent the buildup of water over time if the airplane is operated in cold ground level climates.

Note: These measures do not affect envelope ELA or change the amount of cold fuselage condensation.

Other Types of Insulation. Some have proposed foam-in insulation within the walls in a way that's similar to building use. But airplanes require periodic inspection of the structure for corrosion. They also require access to ducting and wiring that pass through the walls. The airframe flexes with static weight load on the ground and aerodynamic load in flight, which affects the adhesion of the foam, including mechanical degradation if

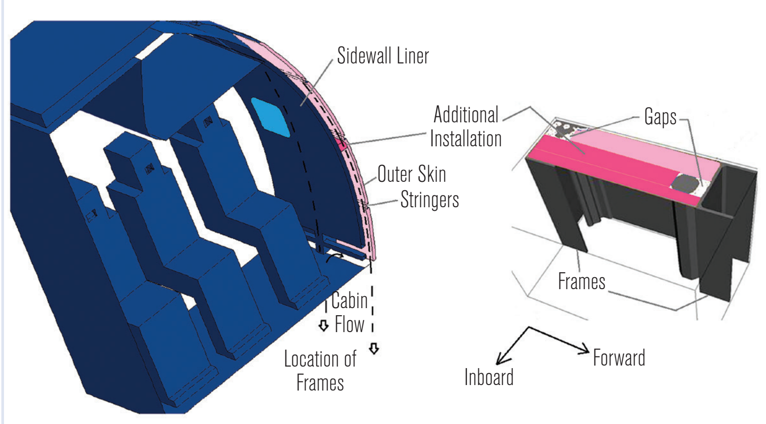
FIGURE 5 Stack pressure driven flows including the flow of dehumidified cabin air and open crown insulation associated with the CCDS and the downward airflow in the insulation.



rigid. Fiberglass blankets are used because of the above and because they have the advantage of lower weight for the same heat loss and acoustic properties and low flammability.

Crown Cavity Dehumidifier Systems (CCDS). Crown cavity dehumidifier systems (CCDS) are added to reduce condensation in the crown of the aircraft. Since this involves leaving the insulation open to the airflow, the effectiveness is limited by the humidity reduction the system is able to achieve. Larger airplanes frequently use the crown space as a recirculation duct, and large amounts of cabin air pass through it. These flows are additive to the stack pressure flows. The CCDS must be capable of humidity reduction down to the dew point of the outer skin with more than 1,000 cfm (472 L/s) of flow capacity to eliminate condensation (*Figure 5*, Page 36).

FIGURE 6 Cabin wall "fire stop" between frames showing the air leakage gaps that allow air to flow through it.

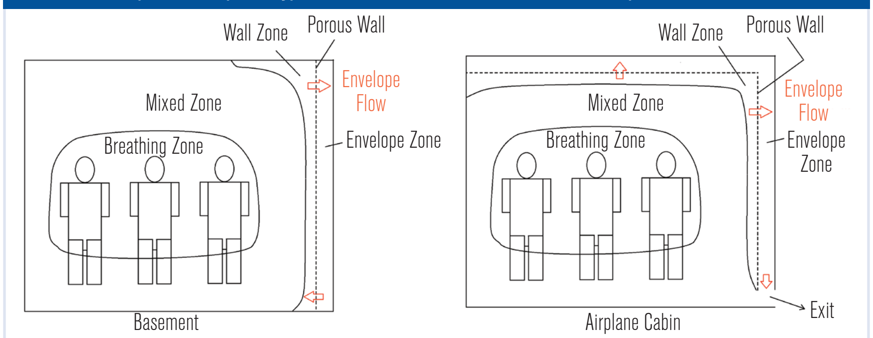


Fire Stop as a Flow Blocker

Airplanes have a flow blocker (fire stop) that is typically located between the windows. The purpose is to prevent smoke and fire from rising up the envelope during an emergency. The fire stop requirement may be met by sealing with additional insulation (*Figure 6*).

Although the blockage is more than sufficient for fire or smoke, it does allow some flow of air to pass through it and also the envelope over the cold outer skin and structure of the airplane.

FIGURE 7 A simplified example of bypass ventilation flow loss for basement and airplane cabin.



Percent Ventilation Air Passenger Bypass

Examples of Envelope Air Ingestion

In *Figure 7* a simplified diagram is used to convey the physical aspects of the ventilation zones that best describe a room with a sealed wall (concrete wall of a basement) and a room with a porous ceiling and wall with a floor exit (airplane cabin). The inlets are not shown because the human effluent (humidity, particulate and gaseous contaminant) levels are supply location dependent.

There is no bypass ventilation flow for the basement, but odors and water vapor will have the same effect on condensation within the envelope as in the airplane.

The breathing zone will have the highest water vapor concentration if the inlet circulates the ventilation air around the occupants rather than over them.

The mixed zone represents the concentrations of effluents that are expected in a well-mixed system.

The wall zone extends over the room side and ceiling surface of the wall. This zone could have the lowest effluent levels in the room, also depending on the location of the sources and the circulation pattern in the room.

The envelope zone is bound by the cold outer wall and a porous inner wall (and/or ceiling). The cold outer wall removes heat from the zone, lowering its temperature relative to the room. Buoyancy effects lower the pressure within the zone, drawing air from the room through the porous wall. The zone contains insulation that impedes the flow somewhat. Unlike a basement masonry foundation wall through which outside water passes via capillary action as well as any cracks, the airplane outer wall is impervious to outside moisture. If the envelope is filled with air that is cleaner than the air in the mixed zone (also the exit), outdoor air is bypassing the room.

The following equation is used to quantify the amount of ventilation air bypass loss. The rise in CO_2 above that of ambient outdoor air, which is assumed to be at 400 ppm, rather than the CO_2 level is used to keep the calculation compatible with other human effluents like water vapor, germs, etc.

FIGURE 8 Flow pattern for a single aisle cabin with under bin nozzle from CFD.

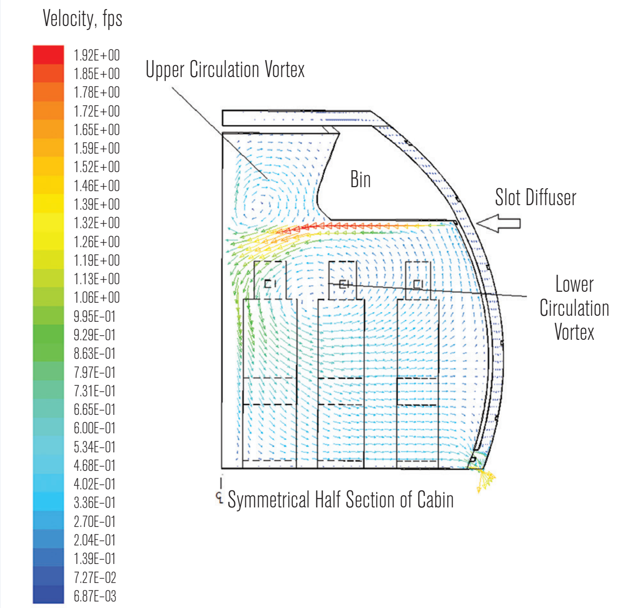


FIGURE 9 Surface CO_2 for a single aisle cabin with under bin nozzle from CFD.

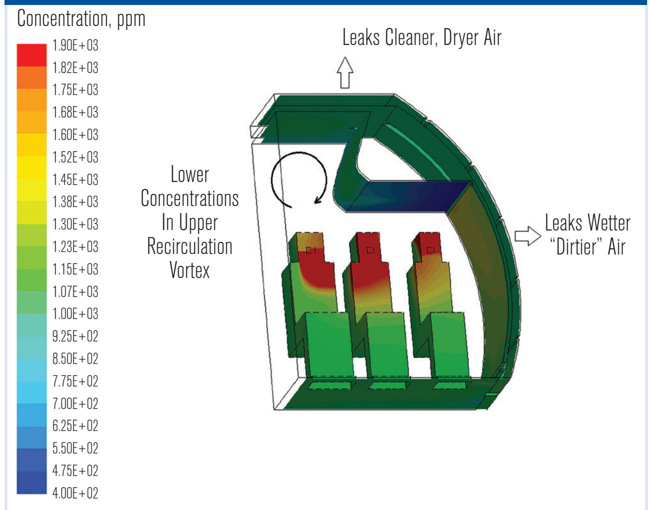
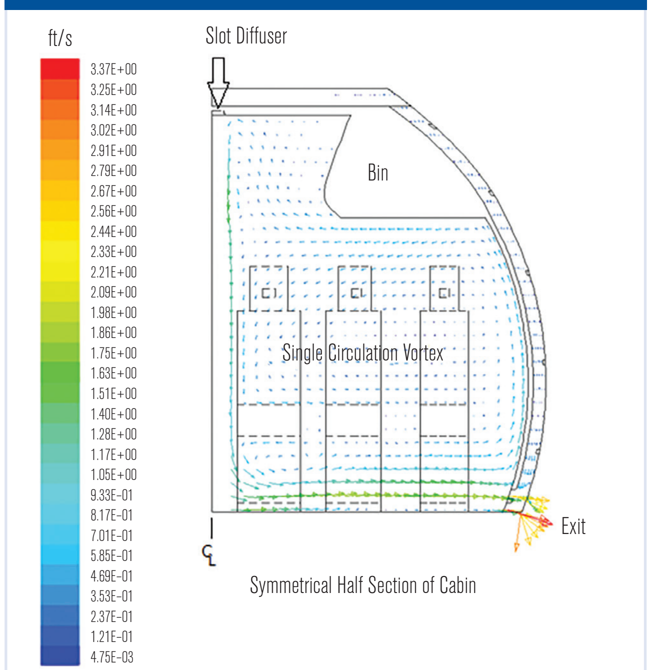


FIGURE 10 Flow pattern for a single aisle cabin with overhead supply nozzle from CFD.



$$Effective\ Bypass\ \% = (actual\ bypass)\% \frac{dilution\ CO_2\ flow}{envelope\ CO_2\ flow}$$

$$= (actual\ bypass)\% \frac{(\Delta C_{exit} - \Delta C_{envelope})Q_{envelope}}{\Delta C_{envelope} Q_{envelope}} \quad (5)$$

$$= (actual\ bypass)\% \frac{(\Delta C_{exit} - \Delta C_{envelope})}{\Delta C_{envelope}}$$

In ΔC_{exit} references the cabin floor exhaust grilles and $Q_{envelope}$ references the bottom of the envelope. If the effective bypass is greater than zero, it is important to note the water vapor levels are also lower in the envelope when the occupants are the only source of water vapor as some of the drier ventilation air will have entered the envelope above the occupants breathing space. More importantly, there is no effective bypass loss if the cabin air is well mixed and the envelope concentration increase at the base of the envelope equals the cabin concentration increase at the cabin exhaust.

Case 1 Single Aisle Airplane Under-Stowage Bin Supply Nozzle

With a slot diffuser located on the sidewall flowing inboard, the slot produces a wall jet. The wall jet stays attached to the underside of the bin, then separates from the inboard edge, producing an upper circulation vortex inboard of the bin and a lower circulation vortex below the bin. Since ceiling panels are typically resting on panel support (channels), and flow blockers are usually at window height, the following models assume 25% leakage only through the ceiling (*Figure 8*).

The wall jet and upper circulation vortex isolates the bin and ceiling from the CO_2 and water vapor produced by the passengers. These concentrations along the surface are lower than the seated area below (*Figure 9*).

As a result, stack flow through upper part of the cabin will divert outdoor air from the cabin. The good news is that the air is drier in the ceiling cavity and condensation is reduced.

For a 25% bypass flow through the ceiling panels, there is 25% of the total 60 cfm = 15 cfm (28 L/s = 7.1 L/s) as

FIGURE 11 Surface CO_2 concentrations for single aisle with overhead supply nozzle from CFD.

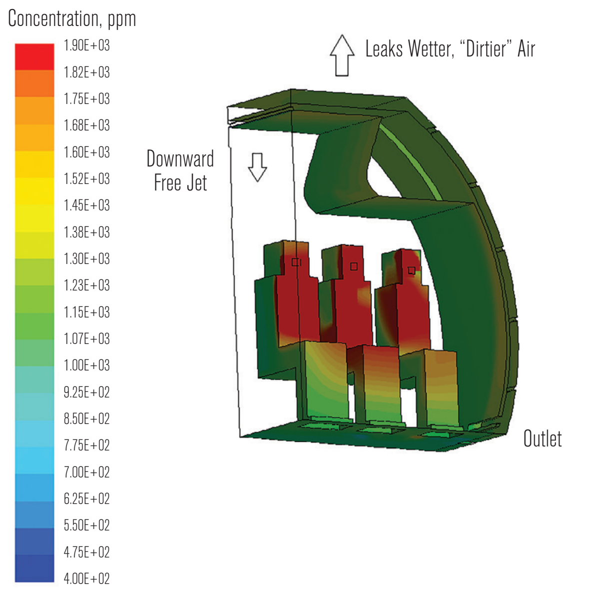
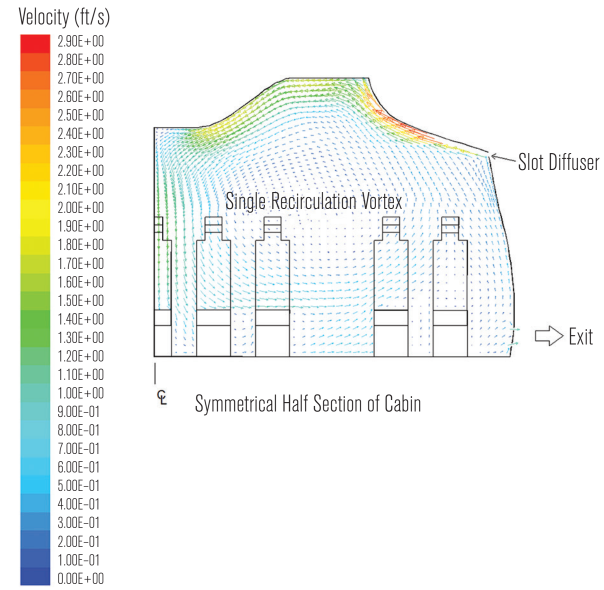


FIGURE 12 Flow pattern for a double aisle cabin with under bin supply nozzle from CFD.



ceiling flow, $C_{ceiling}$. The exit rise in concentration at the floor grille is ΔC_{exit} = 1,100 ppm – 400 ppm = 700 ppm. The concentration rise on the ceiling is $\Delta C_{ceiling}$ = 878 ppm – 400 ppm = 478 ppm. Using *Equation 5*, the effective ventilation air bypass of the occupants is 11.6%

This number applies directly to particulate levels. For gaseous effluent some of this air is salvaged by the recirculation system, and some is lost to the outflow valve. The outdoor air effective bypass for systems recirculating 50% of the cabin air should be about half of the particulate bypass value (about 5.8%, a little more than half that value).

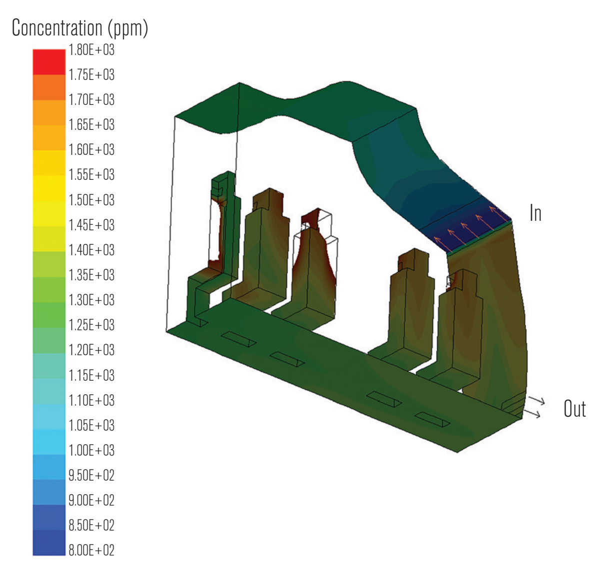
Case 2 Single Aisle Airplane Overhead Supply Nozzle

With a slot diffuser located on the ceiling flowing downward, the slot produces a free jet. The free jet flows downward at the centerline of the airplane cabin, producing a single vortex on each side of the cabin (*Figure 10*).

Here, stack flow through the upper part of the cabin will divert less outdoor air from the cabin. The bad news is that the air is wetter in the ceiling cavity and condensation is increased (*Figure 11*).

For a 25% bypass flow through the ceiling panels, there is 25% of the total 60 cfm = 15 cfm (28 L/s = 7.1 L/s) as ceiling flow, *Ceiling*. The exit concentration rise at the floor grille is ΔC_{exit} = 1,100 ppm – 400 ppm = 700 ppm. The concentration rise on the ceiling and bin is $\Delta C_{ceiling}$ =

FIGURE 13 Surface CO_2 concentrations for a double aisle cabin with under bin nozzle from CFD.



1,270 ppm – 400 ppm = 870 ppm rise. Using *Equation 5* the effective bypass is about –4.9%.

Case 3 A Double Aisle Airplane With Under-Bin Sidewall Supply

With a diffuser located on the sidewall under the bin flowing inboard, the slot produces a wall jet attaching to the contour of the overhead stowage bin and ceiling with a single recirculation vortex on each side of the cabin (*Figure 12*).

FIGURE 14 Flow pattern for a double aisle cabin with overhead supply nozzle from CFD.

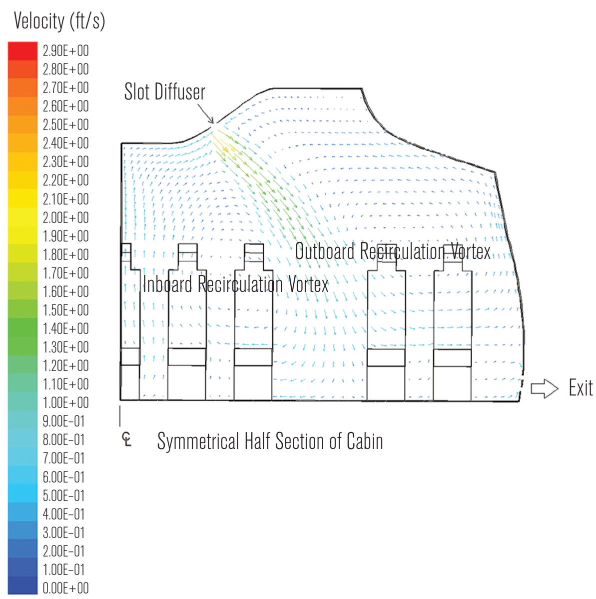
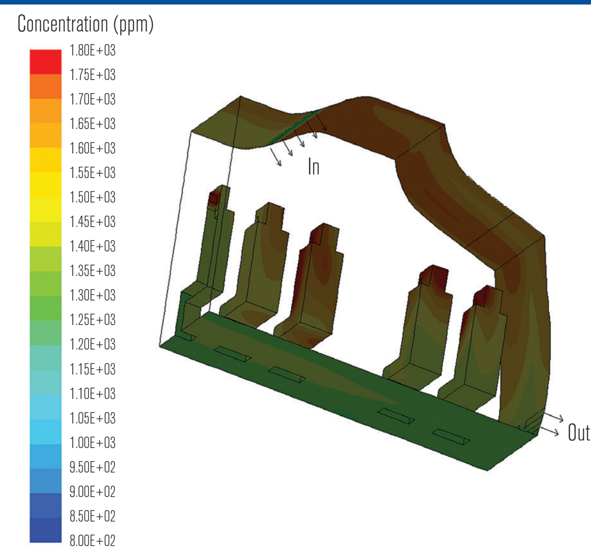


FIGURE 15 Surface CO_2 concentration for a double aisle cabin with overhead nozzle from CFD.



The stack flow through the ceiling panels will divert outdoor air from the cabin and increase the cabin contaminant levels. The ceiling panel is exposed to cleaner, drier air, so condensation would be reduced at the expense of the (reduced) air quality (*Figure 13*).

For a 25% bypass flow through the ceiling panels, there is 25% of the total 90 cfm = 22.5 cfm (42 L/s = 10.6 L/s) as ceiling flow, $Q_{ceiling}$. The exit concentration rise at the floor grille is ΔC_{exit} = 1,400 ppm – 400 ppm = 1,000 ppm. The concentration rise on the ceiling and bins is $\Delta C_{ceiling}$ = 1,145 ppm – 400 ppm = 745 ppm. Using *Equation 5*, the effective bypass is 8.6%.

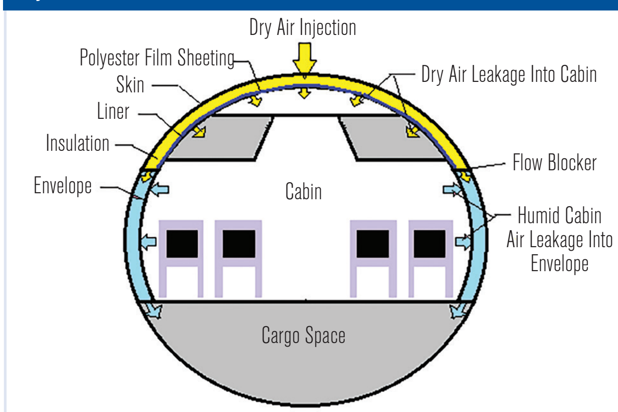
Case 4 Double Aisle Airplane With Overhead Supply Nozzle

With a slot diffuser located on the ceiling flowing downward and outboard, the slot produces a free jet. The free jet produces two vortices on each side of the cabin (*Figure 14*).

The stack flow through the ceiling panels will divert less outdoor air from the cabin and improve the air quality. Unfortunately, the air is wetter in the ceiling cavity and condensation is increased (*Figure 15*).

For a 25% bypass flow through the ceiling panels, there is 25% of the total 90 cfm = 22.5 cfm (42 L/s = 10.6 L/s) as ceiling flow, $Q_{ceiling}$. The exit concentration rise at the floor grille is ΔC_{exit} = 1,400 ppm – 400 ppm = 1,000 ppm. The concentration rise on the ceiling and bins is $\Delta C_{ceiling}$

FIGURE 16 Cabin airflows with a crown air sealing liner and the dehumidified air injection behind the crown insulation seal.



= 1,575 ppm – 400 ppm = 1,175 ppm. The effective bypass is –3.7%.

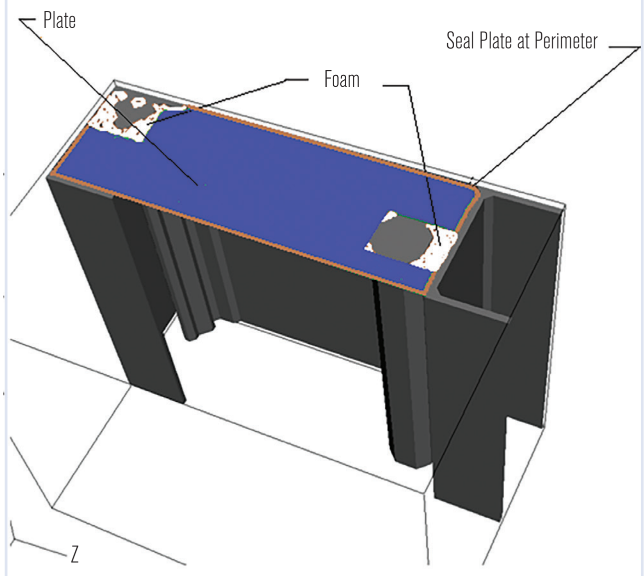
The cases with a negative effective bypass show that the stack flow can improve cabin air quality but at the expense of an increase in water condensation.

A Method for Preventing Ventilation Air Loss and Envelope Moisture Problems

Crown Air Barrier and Dry Air Injection

The first step in eliminating either increased cabin bioeffluent (e.g., virus) levels or increased envelope condensation is to seal the crown insulation with a membrane liner such as polyester film sheeting and inject the dehumidified air directly into the crown insulation envelope behind this membrane liner as shown in *Figure 16*. The amount of dry air injection required to completely prevent humid cabin air entry depends on the envelope ELA and the tightness of a flow blocker. The injected air will leak back into the cabin above the flow blocker and also, but to a lesser extent, through the flow blocker as illustrated, but now the leakage into the cabin is all in the desired direction.

FIGURE 17 Illustration of an airtight flow blocker.



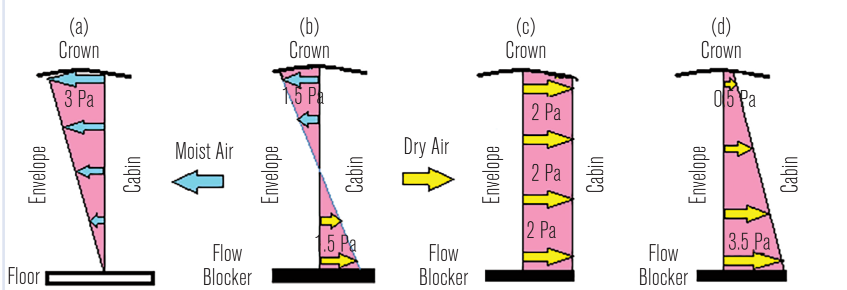
Air Barrier Over the Insulation

Similar sheets could be placed over the insulation and taped together to form a tight air barrier inner seal under the cabin (sidewall) liner and over exposed insulation under the floor. Join this air barrier to the crown air barrier. This will increase liner air tightness and decrease the amount of injection air required.

Flow Blocker

There are any number of ways to create a well-sealed flow blocker. One is to install lightweight, fire-rated plates, which fit tightly into the frame spaces. These plates would have cut-outs for wire bundles and ducts. The gaps could be filled with flexible spray foam or adhesive. This flow blocker sealing is illustrated in *Figure 17*. This seal is designed to fail at high pressures during any sudden cabin depressurization event.

FIGURE 18 Provide sufficient envelope pressure to ensure outward flow.



Pressurizing the Sealed Insulation Envelope

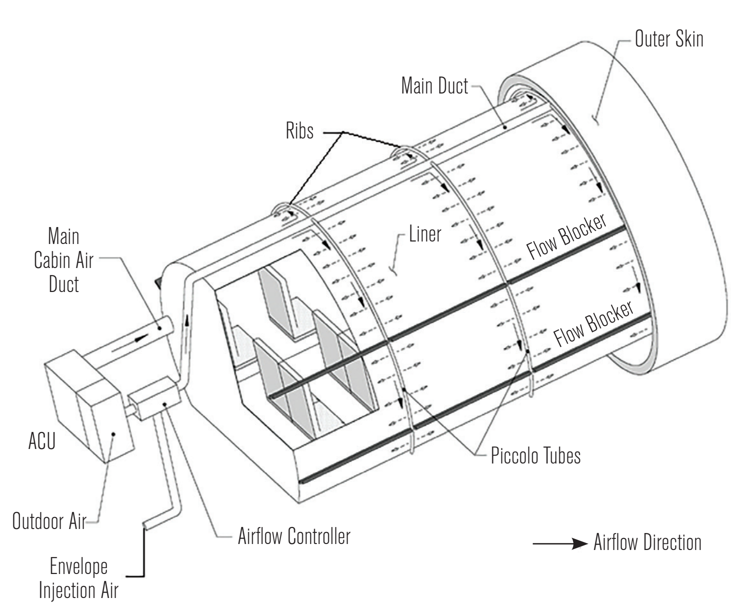
The envelope should be sufficiently pressurized to ensure outward flow over the entire inner surface of the envelope.

If the envelope is pressurized over cabin pressures by the air injection by 0.5 Pa (0.002 in. w.g.) or more throughout cruise level flight, there will be no envelope condensation during this time. The measures taken and their impact on stack pressures and airflows are illustrated in *Figure 18*. The envelope is sealed on the cabin side with polyester film sheeting.

With the three measures—crown and liner sealing, one or more flow blockers, and envelope net pressurization with dry air of 0.5 Pa (0.002 in. w.g.)—in-flight condensation and ventilation air bypass of occupants will be prevented. The tighter the flow blocker(s) and the sealing of the crown and behind the cabin liner, the smaller amount of dry injection air required, perhaps no more than one-tenth of the amount of current CCDS dehumidified airflow rates. Just inserting a flow blocker at the floor could reduce condensation rates by as much as 50% (*Figure 18b*). The 0.5 Pa (0.002 in. w.g.) minimum net pressurization of the envelope relative to the cabin is chosen to minimize any molecular back diffusion of cabin water vapor into the envelope through small leakage openings.

Note that pressurizing the envelope with dry air is different than dehumidifying it like a CCDS. In the former case, humid cabin air cannot enter the envelope through leaks and openings, as dry air will be exiting there. In the latter case, the dehumidified air dries wet surfaces and dilutes the humid cabin air that has entered the envelope. The former case is obviously the preferable one in that it uses 10 times less dry air, and it keeps the insulation envelope dry both in the sidewalls and at the crown. Similarly sized sealing building envelopes can overcome winter stack pressures with injection flows of 15 cfm to 30 cfm (7 L/s to 14 L/s) (total for the building) for 2 Pa (0.008 in. w.g.) stack pressures. As aircraft cabin's stack pressures will be 4 Pa (0.02 in. w.g.) at cold soak, perhaps a 60 cfm (28 L/s) (total for the airplane) injection is an achievable target for aircraft envelope pressurization.

FIGURE 19 Sealed envelope dry air injection.



Dry Air Source

While dehumidifiers can be used to produce the dry injection air, engine bleed air or any outdoor ventilation air can also be used without dehumidification since ambient air is dry at cruise altitudes. Using engine bleed air rather than dehumidifiers saves in weight and energy consumption, as the majority of it will circulate back into the cabin as useful ventilation air.

Examples of Dry Air Injection and Flow Blocker Options

The dry air injection airflows into the envelope that pressurize it are illustrated in *Figure 19* with two longitudinal flow blockers, one at the floor and one above the windows.

While circumferential piccolo injection air tubes are shown between each set of ribs, injection could simply be longitudinally at the crown using the main tubing and by tubing below the blocker at the top of the windows. Having a flow blocker above the windows will enable the crown injection air to enter the cabin above the passengers and be used by them as ventilation air. If there is a flow blocker only at the floor, then only crown injection is required, and in this case the injection air will enter the cabin above the floor and be drawn into the cargo space below. In this case only the portion of the air recirculated from the cargo space will be used as a component of the cabin ventilation air.

The envelope can also be depressurized using this system by exhausting it to the outdoors. This could be advantageous to prevent any air contaminant and moisture accumulation while the plane is on the ground from entering the cabin during take-off and ascent while the envelope air is still warm. It could also be used for venting the envelope while the plane is on the ground, with a hot air supply for example.

Summary

The envelope around the airplane cabin has varying degrees of flow porosity, depending upon how tightly fitting the walls, ceiling and bins are and the amount and packing of the insulation. The tightest insulation packing occurs at the flow blockers, which are intended to limit vertical flow through the envelope. The size of the gaps in the blockers affects how much flow passes through the envelope.

The cabin has a slightly elevated pressure relative to the cargo space, which forces flow through the return air grilles to the underfloor recirculation system during thermally neutral conditions (i.e., outer skin temperature equals cabin air temperature). The stack effect created by cold walls in flight or on cold days on the ground causes some flow to bypass the cabin. The stack pressures can be much larger than the pressure drop across the return air grilles.

Depending on the flow pattern relative to the location of the effluent sources (passengers), the air that bypasses the cabin through the envelope may increase or decrease the effluent levels in the cabin.

If the ventilation system is completely mixed (a uniform effluent concentration throughout the cabin), there is no air effectively bypassing the cabin in the sense of cabin effluent levels, even though there may be large amounts of flow through the envelope and condensation still forming in the envelope.

Flow that bypasses the cabin by passing through the insulated envelope affects either the condensation rate or the air quality in the cabin. For example, if one quarter (25%) of the cabin air supply passes through the sidewall insulation envelope, up to 46% of that air (i.e., 11.6% of the supply air) may not reach the cabin occupants for whom it is intended.

The reductions or increases in the effective bypass shown apply to particulate levels (germs, dust, etc.) on full airplanes (with similar flow patterns) and uniform seating. They also apply to gaseous contaminant levels on similar airplanes that don't have recirculation systems. The recirculation system and passenger seating will also affect the bypass air amounts. For gaseous effluents, a full cabin with coach seating throughout would see about 50% of the effective bypass (for example, Case 1, 50% of 11.6% is 5.8%). For airplanes with overhead and underfloor recirculation, it would be between 50% and 100% of what is shown (for example, Case 1, 5.8% to 11.6%).

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Conclusions/Recommendations

- This study consisted of simplified symmetrical short cabin sections with generic supply air locations. The insulation was adjacent to the cabin wall with a gap between it and the outer skin. A real airplane would have some asymmetry, some longitudinal flow, multiple interacting air supply nozzles and varying seating densities. These conditioned air and ventilation air occupant bypass amounts may warrant further study, including measurements on airplanes in service.
- A tightly sealing flow blocker eliminates the actual bypass of ventilation air, but does not eliminate the flow of moisture into the envelope due to the leakage into and out of the envelope through the wall and ceiling porosity. Dry air must be injected into the envelope in sufficient quantity to offset the stack and cabin pressure. The dew point of that air should be below the outer skin temperature. If dry air is not injected, the flow blocker should include a small drainage path whose area is much smaller than the current leakage area. Alternatively, the drainage pathway at the flow blocker can have a P-trap. This solution enables the safe humidification of the passenger cabin to a more comfortable and healthier level without damaging the structure, Such humidification could be enhanced using moisture recovery from the aircraft exhaust air.
- A solution to both the potential ventilation air waste and the cabin envelope moisture problem has been presented. A similar solution has been successfully used for over two decades in buildings to solve these problems.[1]

References

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3. *2005 ASHRAE Handbook—Fundamentals*, 27.12.

4. *2009 ASHRAE Handbook—Fundamentals*, 16.14. ■

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