

Controlling Cabin and Envelope Air Flows and Pressure Differentials to Prevent Envelope Condensation, Enable Cabin Humidification, Improve Fire Safety, and Decrease Fuel Use

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ABSTRACT

The uncontrolled flow of cabin air into the aircraft envelope caused by indoor-outdoor temperature gradients and associated stack pressure differentials causes cabin air to circulate between the cabin and the envelope, producing condensation on the cold fuselage behind the insulation with a number of adverse consequences. These include an inability to practically maintain cabin humidity at normal levels, a reduction in ventilation effectiveness, microbial growth, metal corrosion and structural failures, insulation performance degradation, thermal discomfort, increased engine noise transmission, additional fuel consumption and electrical failures and fires. This paper explains the origin of these stack pressures and the air flows they create between the cabin and the envelope, and indicates means to control the flows and associated cabin-envelope pressure differentials and thereby minimize condensation and its associated problems, improve thermal comfort and fire safety, and coincidentally decrease fuel use.

INTRODUCTION

ENVELOPE CONDENSATION

Aircraft are subjected to sub-zero temperatures (e.g., -50 C) when flying at cruising altitudes. While the aircraft skin is slightly warmer than outside air due to air friction, temperatures behind and within the insulation blankets (particularly adjacent the skin) cool to between 0 C and -40 C, depending upon flight duration and altitude. Moisture in cabin air that penetrates the aircraft envelope will condense as liquid water or ice on the skin, in the insulation, and on

any cold sink with a temperature below the dew point of the incoming air

Air from behind the insulation envelope surrounding the cabin is drawn through cracks and openings by pressure differences created when the cabin is depressurized during ascent. During descent, it is circulated behind the insulation from the cabin as the cabin is being pressurized. During flight and on the ground air is continuously circulated between the cabin and the envelope driven by natural stack pressures (buoyancy effect). Stack pressures are created by density differences between the cooler air behind the insulation and the warmer air in front of the insulation (cruising flight condition). The density difference creates a slight negative pressure in the envelope (relative to the cabin) near the ceiling of the cabin and a slight positive pressure in the envelope near the floor of the cabin if the envelope circumferential flow is blocked there.

The frost that forms while the aircraft is at altitude will melt as it descends and while it is on the ground, depending upon ambient temperatures. Drainage systems can take moisture away, but may not always be perfect and moisture can accumulate, trapped in crown and side panel areas. The glass fiber insulation blankets typically used may have tears that allow moisture to penetrate and be sorbed into the material.

The adverse effects of this condensation range from a simple nuisance through increased operation costs to decreased aircraft life. The more an airplane is used, the more time it spends in cruising flight, the greater its occupancy density (spatial volume per occupant), and the lower its outside air ventilation rate per person, the higher its potential for

condensation problems. Cases have been reported of water dripping from the cabin paneling. Wetting of insulation increases thermal conduction and, over time, can add hundreds of kilograms of dead weight on surfaces and sorbed in the insulation material, increasing operating costs.

Envelope condensation increases the potential for electrical failure and fire; it can lead to the growth of bacteria and fungi; it causes corrosion, leading to earlier fatigue failure and reduced aircraft life. Unexpected fatigue failures have involved sections of the aircraft aluminum skin at the crown breaking off during cruising flight, accompanied by sudden cabin depressurization and emergency decent and landing.

CABIN RELATIVE HUMIDITY

Relative humidities above 65 percent, which commonly occur in aircraft envelopes for even relatively low cabin humidities, can support microbial growth under appropriate conditions. Such growth can include Gram-negative bacteria, yeasts and fungi. Where sludge builds up, anaerobic bacteria may grow, producing foul smelling metabolites. Saprophytic microorganisms provide nutriment for Protozoa. Exposure to aerosols and volatile organic compounds (VOCs) from such microbial growth can result in allergenic reactions and illness.

The relative humidity of outside air at typical cruising altitudes is frequently less than 1- 2% after heating and pressurization to cabin conditions. Consequently, since cabin air normally is not humidified, on longer flights some passengers may experience dryness and irritation of the skin, eyes and respiratory system, while asthmatics may suffer incidences of broncho-constriction. High air circulation velocities compound this problem. While humidification of the cabin air during flight would alleviate the “dryness” problem, it would also exacerbate the potential for microbial growth and damp material off-gassing in the envelope, unless ingress is prevented

Thus, although it would be of benefit for health purposes to maintain higher cabin air relative humidity, say 30% which is the typical limit for Canadian homes in winter for example, this will be impracticable until the envelope condensation problem is resolved.

While some private jets and crew quarters in some commercial passenger jets may have humidifiers to maintain cabin air at comfortable and healthy levels, commercial passenger cabins avoid such devices to maintain low humidity which is best¹ for the ‘health’ of the airplane. Computers, avionics systems and corrosive metals like aridity; people don't: they don't find it particularly comfortable. More importantly, medical authorities agree that physical comfort is a minor inconvenience compared to the

potential health hazards of an excessively dry environment, which may include:

- Aggravation of respiratory problems, such as sinusitis, asthma, bronchitis.
- Increased susceptibility to influenza infections² and the common cold.³
- Skin irritation and itching due to evaporation of natural skin moisture.⁴
- Eye itching due to evaporation⁵.

Several species of bacteria and viruses survive best at low or high, rather than intermediate humidities. Humidities above 50% have been found to increase the population size of fungi and mites that cause allergies. An ideal relative humidity in terms of general health considerations would be in the 40-50% range for individuals to reduce the incidence of upper respiratory infections and to minimize adverse effects on people suffering from asthma or allergies.⁶

Degrees of comfort vary with factors such as age, health, activity, clothing, body characteristics and even gender. But according to Carnegie Mellon University's Lycos Internet site, “By increasing the relative humidity to above 60 percent within [the 71- to 77 deg F range], 80 percent or more of all average dressed persons would feel comfortable.” In fact, according to Lycos, “An apparent comfortable temperature can be maintained with a thermostat setting of 75 deg F with 20-percent relative humidity, or with a 70-deg F setting with 80-percent humidity.”

ENVELOPE CONDENSATION MITIGATION

Conventionally, passive measures have been used to cope with the envelope moisture problem. These include anti-corrosion coatings, drainage systems, deliberately maintaining cabin humidity well below minimum levels recommended by health authorities and the (costly) replacement of water-soaked and deteriorating insulation.

Nordstrom *et al* proposed a method for preventing moisture problems by injecting dehumidified cabin air into the envelope.⁷ Liebherr have a system for injecting bleed air into the envelope crown. Both methods have been used by CTT AB and Liebherr in various aircraft including the Airbus 320 and Boeing 737, 767, 777 and 787's.⁸

However, while these methods undoubtedly mitigate, they offer partial relief only and can never eradicate the moisture problem because they do not address the underlying issue of stack pressures that naturally drive air flow between cabin and envelope. Further, they can be energy wasteful compared to the alternatives available.

FIRE MITIGATION

In the case of a fire, thermal and electrical insulation systems in the envelope as well as other materials in the cabin can undergo pyrolysis and burning, generating toxic smoke and combustion products. Conventionally, this problem is addressed by employing fewer combustible materials, and using hand-held containers with non-toxic fire suppressants. Under any cabin fire emergency, the objective is to exhaust the smoke from the cabin while suppressing the fire. There is currently no method in place to directly suppress or extinguish fire and/or pyrolysis within the envelope. Nor is there any effective means of preventing smoke within the envelope from penetrating the cabin. Furthermore, exhaustion of air from the cabin is usually via grilles at the floor, which undesirably enhances smoke circulation throughout the cabin.

Miller *et al* proposed a method of fire extinguishment in aircraft cabins using ventilation ducts in communication with the cargo fire extinguishment system.⁹ However, this system does not address envelope fires and/or pyrolysis, or the health and safety problems associated with exposing passengers to potentially lethal combinations of fire suppressants and their combustion products together with fire and smoke.

SOLVING THE CONDENSATION PROBLEM

The injection of dry air into the envelope, as employed in the Nordstrom or Liebherr countermeasures, cannot of its own solve the condensation problem. It can *only* be solved by preventing the ingress of cabin air into the envelope through the suppression of stack pressures and back diffusion with a sufficient injection of dry air, liner tightness, flow blocker placement and tightness, and leakage pathway depth to ensure liner air outflows throughout. This can be done practically by the installation and strategic placement of effective flow blockers, together with a tightening of liner joints, controlled distributed air injection to pressurize the envelope and minimization of opening leakages.¹⁰

The root of the envelope moisture problem is stack pressures between the cold and warm side of the insulation that, even though they are only a few Pascals, inevitably circulate cabin air behind the insulation where it condenses on the cold fuselage. These stack pressures are largest during cruising flight when indoor-outdoor air temperature differences are greatest. They are also present on the ground after landing

while the fuselage is still relatively cool. In both cases, the objective is to inject dry air into the envelope at a rate that pressurizes the envelope relative to the cabin by a fraction of a Pascal or more and so prevents humid air entry via convection flows. This approach will solve the problem provided back diffusion rates of humid cabin air flow through cracks into the envelope carry in less moisture than outward convection air flow rates from the envelope remove it.

STACK PRESSURES

Stack pressure differentials are created by the temperature difference between the cabin air and the air behind the envelope insulation next to the aircraft skin. This pressure varies with height h above and below the neutral pressure differential plane and is predicted by¹¹

$$dp = (\rho_2 - \rho_1) * g * h \quad (1)$$

Substituting

$$\rho = p/RT \quad (2)$$

Gives

$$dp = p_1 (1/T_1 - 1/T_2) * g * h / R \quad (3)$$

Where

- ρ_1 = air density in the cabin (kg/m^3)
- ρ_2 = air density behind the insulation (kg/m^3)
- h = height above the neutral plane (m)
- p_1 = cabin pressure (75,000 Pa at a cruising cabin pressure of 8,000 ft altitude)
- T_1 = temperature in cabin ($^{\circ}\text{K}$)
- T_2 = temperature behind the insulation ($^{\circ}\text{K}$)
- R = individual gas constant for air ($286.9 \text{ Joules.kg}^{-1}.^{\circ}\text{K}^{-1}$)
- g = acceleration due to gravity (9.8 m.s^{-2})

The neutral pressure plane is mid-height between top and bottom envelope circumferential air flow blockages, the location elevations at which air is free to circulate around the top and bottom of the insulation. Such flow blockage locations in the extreme would be at the cabin crown and the bottom of aircraft. Creating envelope air flow blockage at the cabin floor will reduce stack pressures by 50%. Thus the addition of longitudinal flow blockers is critical. Placement of a flow blocker near head height will ensure that dry air injected into the envelope to pressurize it will exit at the

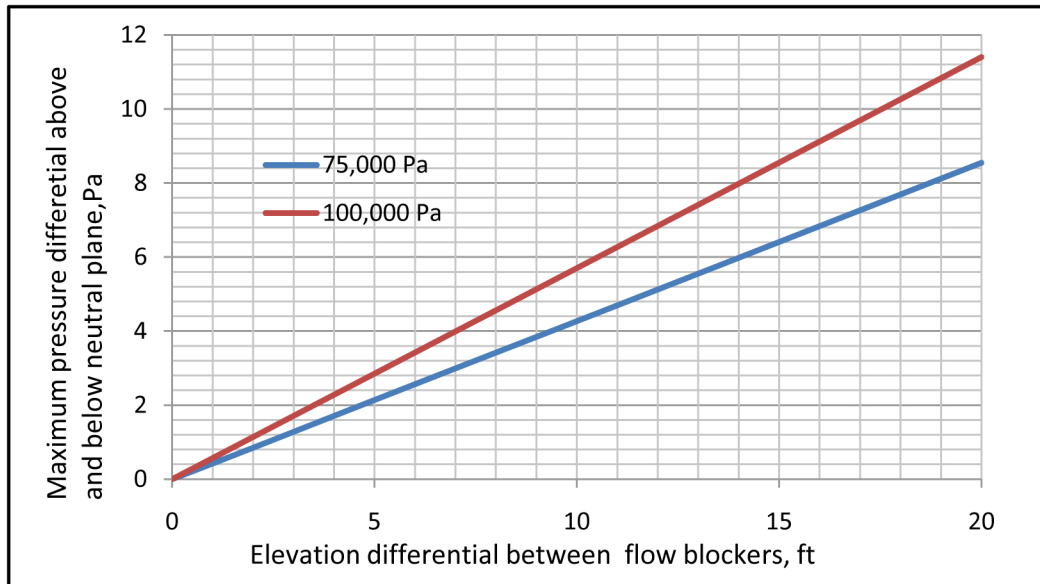


Figure 1. Maximum stack pressure differentials across the insulation (22C to -50C) versus vertical distance between flow blockers at 75,000 Pa (8000 ft) and 100,000 Pa (sea level) cabin pressures.

passenger breathing zone and be useful as cabin ventilation air.

Solving for various elevation differentials between flow blockers at 75,000 Pa (8000 ft) and 100,000 Pa (sea level) cabin pressures, a cabin temperature of 22°C ($T_1 = 295^\circ\text{K}$) and a temperature between the insulation and the aircraft skin at cold soak of -50°C ($T_2 = 223^\circ\text{K}$), yields dp vs h linear correlations for each dry air ambient pressure, as shown in [Figure 1](#).

Stack pressures can be offset to prevent circulation of cabin air into the envelope either by convective air flow entry or back diffusion from the cabin by injecting dry air at a sufficient rate. An example of this offsetting is provided in [Figure 2](#) showing how convective outflows are created over the entire liner surface at all leaks for a maximum stack pressure of 4 Pa.

Stack pressure profiles for different flow blocker locations and plane attitudes are illustrated in [Figures 3 and 4](#). From [Figure 4](#) it can readily be visualized that if the nose of the plane is down, the air in the envelope will flow towards the cockpit - a potentially dangerous situation if there is an envelope fire.

EQUIVALENT LEAKAGE AREA (ELA)

The tighter the liner is constructed, the lower the ELA and the lower the injection ventilation rate required to achieve a particular envelope versus cabin pressure differential target.

For typical construction leaks, the liner ELA can be calculated by measuring air flow versus pressure differential and using¹²

$$ELA = (Q / C_d) * (\rho_a / 2 * dp)^{0.5} \quad (4)$$

where

- ELA = equivalent leakage area (m^2)
- Q = flow (m^3/s)
- C_d = discharge coefficient = 0.6 for small openings
- dp = pressure difference (Pa)
- ρ_a = air density (kg/m^3)

ELAs and pressure differentials are calculated for a range of envelope injection air flows during cruising flight at 8000 ft, 75,000 Pa cabin pressure (air density is $0.9 \text{ kg}/\text{m}^3$) in [Table 1](#) and [Figure 5](#).

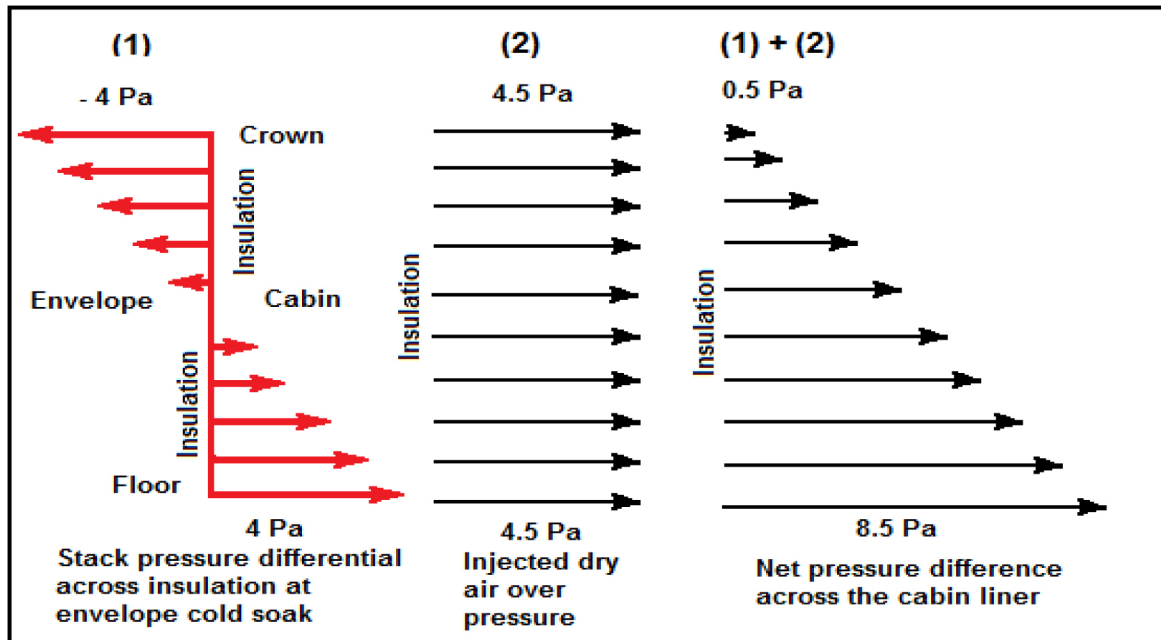


Figure 2. Offsetting stack pressures (1) with an injection flow at a rate that creates an offsetting higher pressure throughout (2), such that the net pressure ensures envelope air outflow at all cracks and openings.

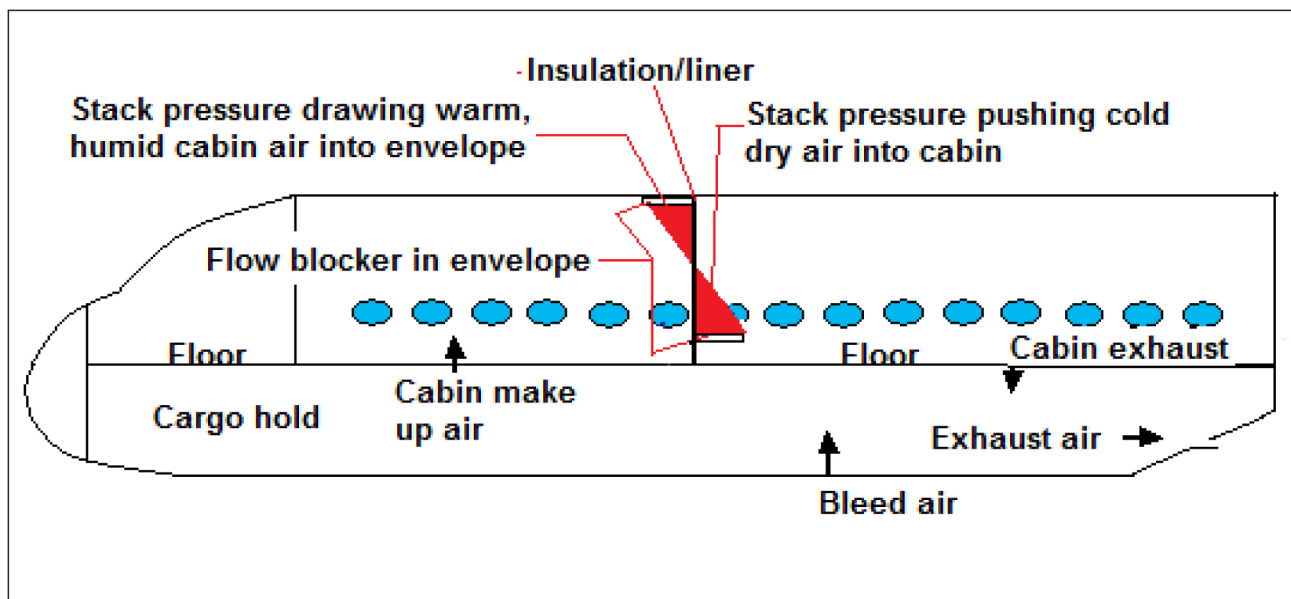


Figure 3. Illustration of the stack pressure profile with longitudinal flow blockers in the envelope near the ceiling and below the windows. This profile will be the same throughout the length of the plane when flying at level attitude.

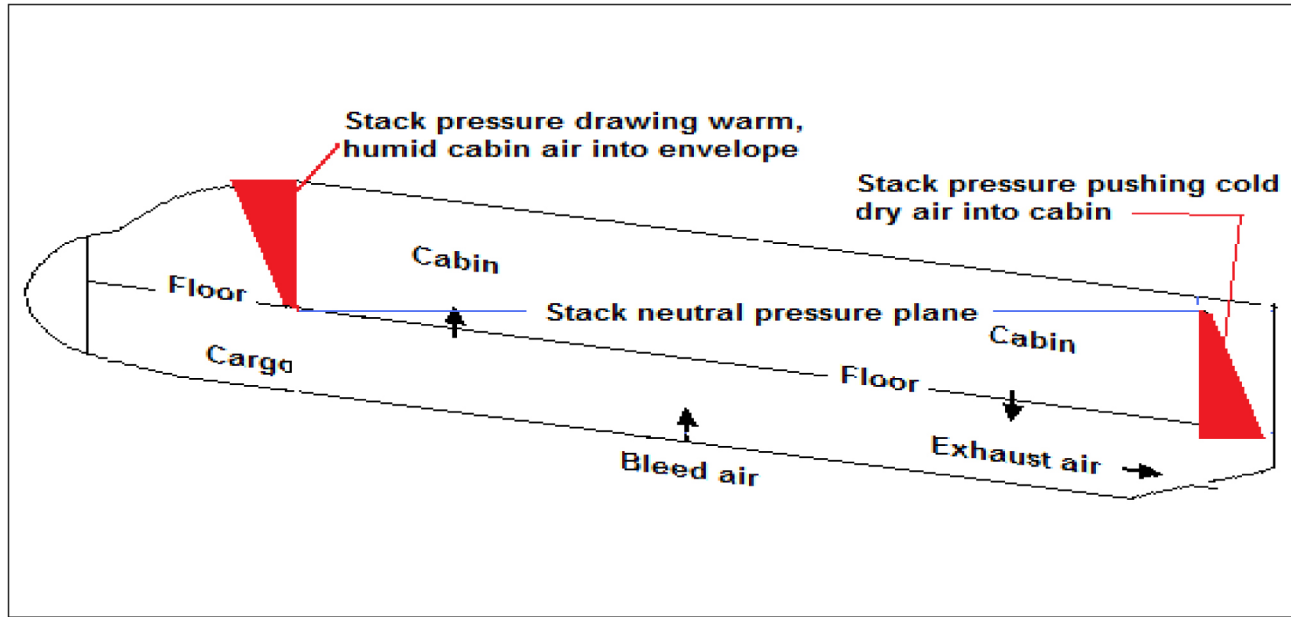


Figure 4. Illustration of the different stack pressures acting in the fore and aft sections of the cabin as a result of a nose-up attitude

Table 1. ELA and pressure differentials for a range of envelope air flow injection rates

Pressure differential across liner (Pa)	Envelope injection air flow rate, L/s							
	5	10	25	50	75	100	125	150
	Liner equivalent leakage area (ELA), cm ²							
0.5	79	158	395	791	1186	1581	1976	2372
1	56	112	280	559	839	1118	1398	1677
1.5	46	91	228	456	685	913	1141	1369
2	40	79	198	395	593	791	988	1186
2.5	35	71	177	354	530	707	884	1061
3	32	65	161	323	484	646	807	968
3.5	30	60	149	299	448	598	747	896
4	28	56	140	280	419	559	699	839
4.5	26	53	132	264	395	527	659	791
5	25	50	125	250	375	500	625	750
6	23	46	114	228	342	456	571	685
8	20	40	99	198	297	395	494	593
10	18	35	88	177	265	354	442	530
12	16	32	81	161	242	323	403	484

To achieve the allowable leakage areas, the integrity of the cabin liner paneling must be maintained throughout and any openings at the overhead compartment must be sealed. With this degree of sealing, during a sudden aircraft depressurization event (for example, if a cargo door opens in flight), one or more panels of the cabin liner will “pop” to equalize the pressure difference between the cabin and the envelope. Additionally, the damper of the return air control units can be designed so that both the envelope opening and

the cabin opening will open automatically in a sudden depressurization event. When insulation continuity is maintained, envelope ventilation air entering the cabin from behind the insulation will be warmed by dynamic insulation heat recovery.

MOLECULAR DIFFUSION

Trace amounts of gases can escape from the cabin into the pressurized envelope through a phenomenon known as

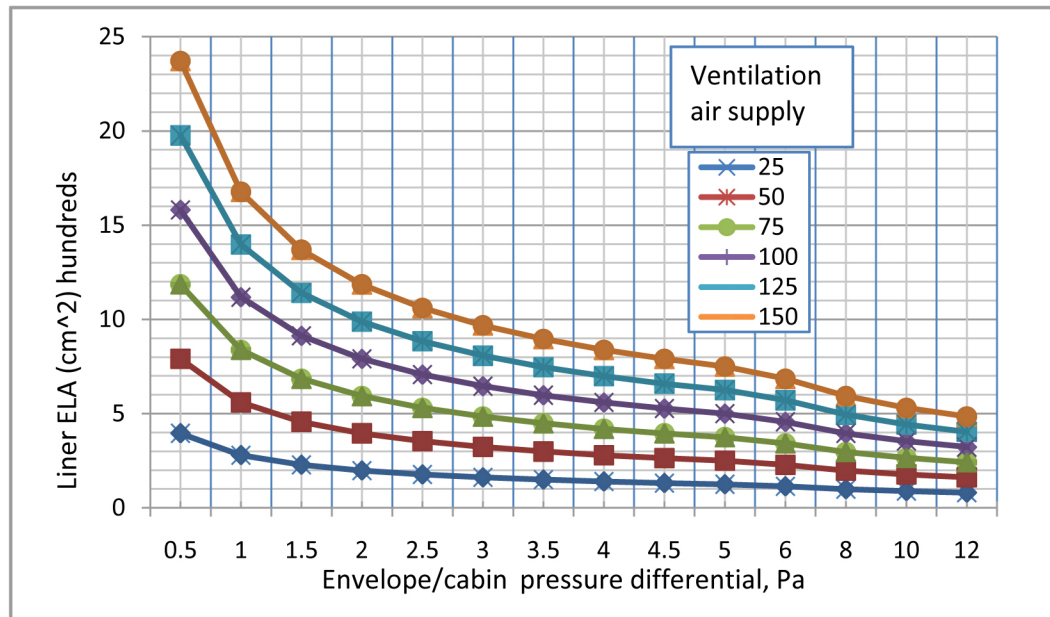


Figure 5. ELA and pressure differentials for a range of envelope air flow injection rates and $C_d = 0.6$

molecular diffusion. Molecular diffusion, often called simply diffusion, is a net transport of molecules from a region of higher concentration to one of lower concentration by random molecular motion. The result of diffusion is a gradual mixing of material. In a phase with uniform temperature and the absence of external net forces acting on the particles, the diffusion process will eventually result in complete mixing and a state of equilibrium. The quantities of moisture entering the envelope from the cabin via diffusion depend upon the concentration differential between the two spaces, the envelope air supply rate and the liner ELA and joint thickness.

Molecular diffusion of a gas in air is calculated from

$$M_d = D * (\rho_2 - \rho_1) * A/L \quad (5)$$

where

- M_d = mass transfer of a gas or vapour due to diffusion, mg/s
- D = mass diffusivity for the gas in air, m^2/s
- $\rho_2 - \rho_1$ = partial density gradient of the gas, mg/m^3
- A = cross sectional area over which diffusion takes place (ELA), m^2
- L = length over which diffusion occurs (liner thickness), m

According to Chapman-Enskog theory the mass diffusivity of a gas increases with temperature as $T^{3/2}$, it varies inversely

with pressure and it varies inversely with the square root of its molecular weight.¹³ At atmospheric pressure and 293K, D for water vapor is $2.42 \times 10^{-5} m^2/s$; for radon it is $0.6 \times 10^{-5} m^2/s$; for ethanol it is $1.19 \times 10^{-5} m^2/s$; and for methane it is $1.6 \times 10^{-5} m^2/s$.

Diffusion of a gas into the pressurized envelope is countered by its convective mass transfer from the envelope into the cabin. Convective transfer is calculated using

$$M_c = C_1 * Q \quad (6)$$

where

- M_c = mass transfer from the pressurized envelope through liner leaks due to convection (mg/s)
- C_1 = concentration of the gas in the envelope (mg/m^3)
- Q = air flow injection rate into the envelope (m^3/s)

The weight of water vapor in air for any given air temperature, relative humidity and altitude can be calculated using ASHRAE psychrometric charts. Some values of interest for the cabin and behind the insulation are provided in Table 2. Humidification of commercial passenger cabins to 30% would bring them to comparable levels maintained in Canadian homes in winter and might be a reasonable target for commercial passenger aircraft cabins; hence the inclusion of water vapor weights at this level as well as lower 20% and higher 40% levels for comparison. Maintenance of relative

humidity below 65% is a target for preventing fungal growth in the envelope.

As noted earlier, the required injection rate of dry air into the envelope depends upon the stack pressures to be overcome and the liner equivalent leakage area (ELA). The stack pressures in turn depend upon the vertical distance between top and bottom longitudinal flow blockers in the envelope, as also noted earlier. Assuming flow blockers at the crown and seated passenger head height, maximum stack pressures across the cabin liner typically might be 4.5 Pa or less, depending on whether the envelope has reached cold soak or not. Placing an additional longitudinal flow blocker half way between these two might reduce stack pressure to less than 2.25 Pa. Using [Table 1](#), a 75 L/s injection flow will produce envelope pressurizations relative to the cabin of 2.5 and 5 Pa for ELAs of 530 and 375 cm², respectively, while an injection flow of 125 L/s will produce these pressure differentials for ELAs of 884 and 625 cm², respectively.

Molecular diffusion depends on leakage area or ELA; it also depends upon distance travelled along the leakage paths. Most liner leakage will occur at the joint of the panels, the thickness of which might be 0.0025 m or less. However, the overlapping at joints makes for leakage pathways of perhaps 0.006 m.

Using these values and the data in [Table 2](#), yields water vapor diffusion rates from the cabin through liner leakage areas totalling 375 to 530 cm², depending upon dp required, to behind-insulation for near cold soak conditions that are significantly lower (between 3 and 5 times) than the vapor removal by convection flows from the envelope through these same leakage areas for a cabin RH 20% condition and a 75 L/s injection rate. Similarly, for a cabin RH 30% condition and a 125 L/s injection rate, water vapor diffusion rates from the cabin through liner leakage area totalling 625 to 824 cm² to behind-insulation for near cold soak conditions are significantly lower (between 2 and 4 times) than the vapor removal by convection flows from the envelope through these same leakage areas. If the leakage areas can be reduced to 125 to 177 cm² then the injection rate of dry air can be reduced to 25 L/s and back diffusion again is not a problem. These input data and calculations are provided in [Table 3](#). Because of the marked temperature dependence of diffusion, the steep temperature gradient at the leakage sites, and our use of a D value for cabin temperature (20C), the calculated rates of diffusion represent upper limits, and the ratios in the final row of [Table 3](#) lower limits.

Table 2. Density of water vapor at various relative humidities and temperatures.

T, °C	RH, %	Water to dry air ratio at sea level, gm/gm	Air density at sea level, mg/m ³	Water vapour density, mg/m ³
20	65	0.0096	1.20E+06	11,520
20	60	0.009	1.20E+06	10,800
20	40	0.0058	1.20E+06	6,960
20	30	0.0044	1.20E+06	5,280
20	20	0.0029	1.20E+06	3,480
0	65	0.00245	1.20E+06	2,940
-40	65	0.00004	1.20E+06	48

IN-FLIGHT FIRE AND/OR PYROLYSIS

If the cabin envelope is sealed well enough to be pressurized relative to the cabin with injection air flows that are significantly lower than cabin fresh air ventilation air flows, it can also be depressurized to a greater extent with cabin exhaust flows. Depressurization can be achieved, for example, by exhausting the envelope rather than the cabin as is normal, into the baggage compartment below, thereby drawing cabin air into the envelope before it passes to the baggage compartment. This could be done during a fire or pyrolysis event in the envelope so that smoke could be vented directly outdoors and not circulated in the cabin. At the same time fire suppressant gases could be injected in the envelope that would not create hazardous conditions in the cabin.

Such a measure could prevent a major catastrophe in a situation where a pilot is obliged to put the aircraft nose down and begin a rapid descent. He might assume that with the cockpit door closed, passenger cabin air cannot enter, but it can by travelling through the length of envelope unless proper envelope flow blockers are in place and the envelope is being exhausted so any leakage through the flow blocker is prevented. Such a fire suppressant envelope injection and ventilation control system might have allowed time for SwissAir Flight 111 to land safely and save 229 lives.¹⁴

Table 3. Ratios of convective vapor flow from the insulated envelope and occupied space vapor diffusion flow into envelope at various cabin RH and envelope dry air injection rates, liner ELAs, a cabin temperature of 20C and an air temperature behind the insulation of -40°C.

	Cruising Cabin RH = 20%, T2 = -40C, 75 L/s injection rate with dp =5 Pa	Cruising Cabin RH = 20%, T2= -40C, 75 L/s injection rate with dp =2.5 Pa	Cruising Cabin RH = 30%, T2 = -40C, 125 L/s injection rate with dp =5 Pa	Cruising Cabin RH = 30%, T2 = -40C, 125 L/s injection rate with dp =2.5 Pa	Cruising Cabin RH = 30%, T2 = -40C, 25 L/s injection rate with dp =5 Pa	Cruising Cabin RH = 30%, T2 = -40C, 25 L/s injection rate with dp =2.5 Pa
Parameter	Mass transfer from cabin through liner leaks to behind insulation via upstream diffusion					
Mass diffusivity D (mm ² /s)	34	34	34	34	34	34
Vapor density gradient (mg/m ³): cabin/behind insulation	3,432	3,432	5,232	5,232	5,232	5,232
ELA (cm ²) for injection flow rate used	375	530	625	884	125	177
Crack depth (m)	0.00635	0.00635	0.00635	0.00635	0.00635	0.00635
Mass flow (mg/s)	0.69	0.97	1.75	2.48	0.35	0.50
Parameter	Mass transfer from behind insulation to cabin through liner leaks via convection					
Vapor density behind insulation at RH 65% (mg/m ³)	48	48	48	48	48	48
Liner air leakage to cabin (l/s)	75	75	125	125	25	25
Mass flow (mg/s)	3.60	3.60	6.00	6.00	1.20	1.20
Flow ratio						
Flow rate ratio: convection from to diffusion into envelope	5.2	3.7	3.4	2.4	3.4	2.4

DISCUSSION

The circulation of dry air throughout the envelope and the prevention of humid air from entering the envelope are both essential since there are times when the envelope may not be pressurized with dry air, for example during descent and on the ground, when moist cabin air can enter and condense. This circulation can only be fully achieved when the envelope is pressurized and even then there may be some envelope areas that will not be penetrated depending upon flow passage resistance. This moisture may be removed during cruising flight, prior to it freezing when the over-pressurization is greater for steady flow systems. Alternatively it may be removed by over-pressurization during ground operations

In some aircraft, a space has been provided between the insulation and the skin to allow condensate water to drain. Where this is not the case, the dry air can be distributed behind or in front of the insulation with piccolo tubes.

The injection air must be relatively dry and as such can be generated by a dehumidifier or, alternatively, bleed trim air can be used during cruising flight. Dehumidifiers have the advantage of being a source of dry air throughout the flight cycle, whereas bleed air can only be used during cruise as it can have too much moisture in it when the aircraft is on the ground, as well as during ascent and descent. The use of a dehumidifier increases electrical consumption, occupies additional space, and adds dead weight. The use of bleed air to pressurize the envelope is essentially a no-cost alternative provided it is diverted into the cabin at head height so it can also constitute cabin ventilation air. At the same time it can save fuel by using the skin as a heat exchanger to reduce the bleed-pack cooling requirement. During descent, the bleed envelope supply should be turned off and, if the option is provided, air should be exhausted both from the envelope and the cabin to maintain a neutral pressure across the liner. During taxi and ascent, the bleed envelope air supply should also be off and the envelope exhausted if that option is provided.

Injecting air into the envelope does not automatically pressurize it relative to the cabin. First of all any injection pressurization created has to be adequate to overcome stack pressures which tend to draw in cabin air at the crown. Second, the injection rate has to be sufficient to create pressurization at all liner and flow blocker leaks. Third the injection air has to be distributed so as offset the stack pressure at any location and elevation and this may require a distribution system. Fourth, depending on energy saving and space heating or cooling objectives, the injection air can be optimally distributed on either the cold or warm side of the insulation.

Injection pressurization must be sufficient to prevent the upstream diffusion of moist cabin air into the envelope. Upstream diffusion depends not only on leakage area but also on leak depth. Leak depth at liner joints is the distance from one side to the other accounting for the distance around the overlapping flange at the joint of one liner to another. In the case of the liner panels, this passageway distance might be three times the liner thickness. If this distance is similar to liner thickness, moisture entry to the envelope from the cabin via back diffusion through the leakage areas could be a problem.

Pressure differential across the liner and liner ELA can be assessed at a number of locations when the system is installed and the aircraft is on the ground using a test blower to inject a measured flow of air and a micromanometer to measure pressure differential. Equipment is readily available to measure differentials as low as 0.1 Pa, so that the establishment of flow requirements to offset the stack pressures expected for the flow blocker spacing, and locating areas that are not adequately pressurized because of inadequate air distribution, do not pose technical problems. Similarly, use of a micromanometer during this testing can readily identify flow blocker and liner leakage areas that must be better sealed.

Flow-blocker air tightness, placement and efficiency are critical to the successful elimination of moisture condensation throughout the envelope. They must be designed to accommodate wires passing snugly through them.

Injection flows of 75 to 150 L/s to pressurize the envelope relative to the cabin represent perhaps 5% of the cabin fresh air supply rate and if a longitudinal flow blocker is installed in the envelope at passenger seated head height this injection air is diverted back into the cabin as useful ventilation air and none is wasted.

Pressure differential is sensitive to practical variations in injection flows and ELAs. For example, a 6.7% reduction in flow rate (e.g. from 75 to 70 L/s) will produce a 13% drop in pressure differential across the liner (e.g. 4.6 Pa to 4 Pa) for

the same leakage area (e.g. 391 cm²). Similarly, a 7.2% increase in ELA (e.g. from 553 to 593 cm²) will produce a 13% decrease in pressure differential across the liner (e.g. from 9.2 to 8 Pa) for the same flow (e.g. 150 L/s)

Are cabin liner ELAs of 375 to 884 cm² too tight to be achieved practically? Probably not, but the design must then allow for sudden cabin depressurization. For example, ELAs of 125 cm² can typically be constructed in wood frame and polyethylene barrier sealed insulated basement envelopes of similar areas to aircraft cabins when pressurization systems are required. A principal concern in attaining an envelope tightness that ensures adequate envelope-to-cabin pressure differentials at these injection flows will be the prevention of flow blocker leakage when wires pass through them. This is primarily a design issue.

CONCLUSIONS

- Injecting dry air into the envelope does not eliminate the moisture condensation problem. It can *only* be solved by preventing humid cabin air from entering the envelope and by circulating dry air throughout the envelope and those two objectives can only be achieved through the suppression of stack pressures and back diffusion with an injection of dry air that ensures liner air outflows throughout. This can be done practically by installing a controlled distributed air injection to pressurize the envelope relative to the cabin, with strategically placed flow blockers, by ensuring the tightness of liner joints, and by minimizing opening leakages.
- Pressurization of the cabin envelope relative to the occupied space to prevent moisture condensation behind the envelope insulation by the suppression of stack pressure and molecular diffusion requires the use of perhaps 5% of the cabin ventilation air supply, if liner leakage paths and longitudinal flow blockers are designed and installed properly.
- None of this cabin air or cabin ventilation air will be lost if a head height longitudinal flow blocker is installed in the envelope.
- Cabin humidities of 30% during cruising flight can be maintained without condensation problems once the envelope is pressurized throughout relative to the cabin.
- Pressure differential across the liner is relatively sensitive to changes in ELA and injection flow rates, so system settings at commissioning should allow for this.
- Depressurization of the envelope relative to the cabin and exhausting it directly outside the airplane in the event of a fire or pyrolysis, either in the envelope or the cabin, will prevent or decrease exposure to such fumes both in the cabin and the cockpit. It also permits the use of fire extinguisher materials which can create toxic exposures per se and from

combustion products, and which could otherwise not be used for fire suppression in the cabin.

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