

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

2011-01-2689

Published
10/18/2011Douglas Stuart Walkinshaw and Keith F. Preston
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doi:10.4271/2011-01-2689

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 descent 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

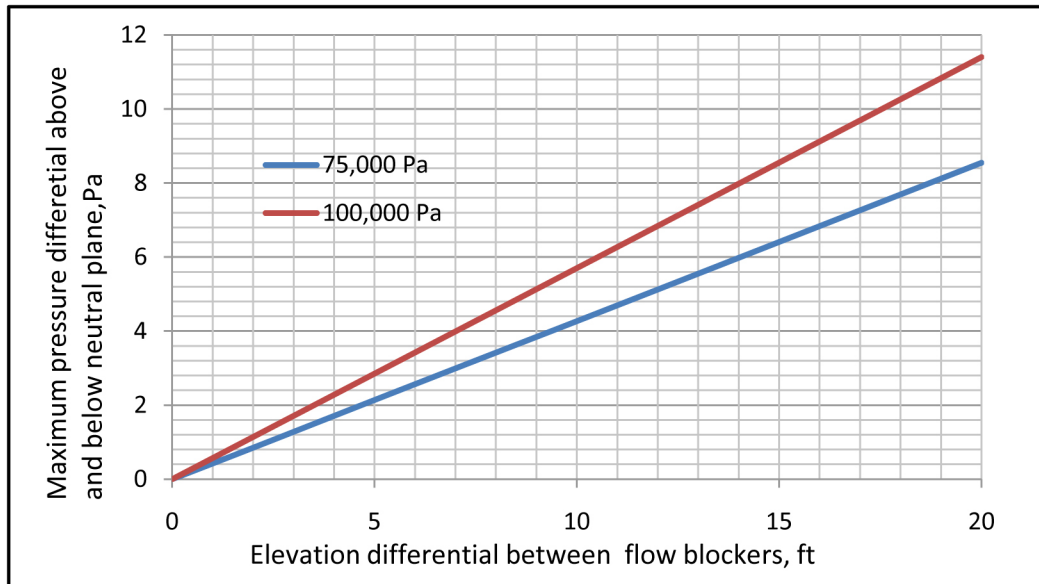


Figure 1. Maximum stack pressure differentials across the insulation (22C to -50C) versus vertical distance between flow blockers at 75,000 Pa (8000 ft) and 100,000 Pa (sea level) cabin pressures.

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](#).