AIRCRAFT ENVIRONMENTAL CONTROL

ENVIRONMENTAL CONTROL SYSTEM IN AIRCRAFT

Introduction

In general, the environmental control system (ECS) refers to equipment in charge of maintaining a comfortable close environment for a given payload (goods, living matter, and people), i.e. keeping temperature, pressure, and composition, within acceptable limits, usually by circulating a fluid for thermal control and for life-support, if required (the term ECLSS, for environmental control and life support system, is also used to make the latter explicit). The ECS for vehicles in hostile environments is most demanding: submarines, aircraft and spacecraft. The ECS usually focuses on the inside part of the vehicle, whereas the environmental control of the outer side is usually named environmental protection system (EPS).

Aerospace engineering (aeronautical and space) is high-tech transport engineering, involving vehicles, infrastructures and payloads. Aviation refers to activities involving man-made flying devices (manned and unmanned aircraft), and the people, organizations, and regulatory bodies involved in their use.

- Vehicles (aircraft and spacecraft; aircraft=aerostats (balloons and airships) and aerodynes (airplanes and rotorcraft), manned or unmanned).
  - Structure (frame): fuselage, wings and appendices.
  - Propulsion: engines and propellers.
  - Other systems
    - Energy systems for propulsion and control: fuel, mechanical, hydraulic, pneumatic, and electrical systems.
    - Flight control systems: sensors and actuators, electronic systems (avionics).
    - Communications: air traffic control (ATC), radio-navigation, intercoms.
    - Start and stop systems (for engines and other systems): undercarriage (landing gear), APU, ground starter, ram air turbine.
    - Environmental control system (**ECS**, internal)
      - Cabin air conditioning: pressure, temperature, ventilation, humidity (e.g. windows defogging), and fire protection.
      - Water and sanitation. Flexible hoses are used, and cold water pipes must incorporate thermal sensors and electrical strip heaters to guarantee $T_w>0$ ºC even with $T_{ext}=-40$ ºC, in spite of the hose being resistant to water freezing. Hot water is electrically heated to $T_{max}=50$ ºC.
      - Food, and solid waste.
      - Others: fuel tank inertization, cabin furniture ergonomics, noise (70 dB typical in a cruising airliner), lighting, entertainment…
    - Environmental protection system (**EPS**, external)
      - Against high temperatures (rarely against cryogenic temperatures).
      - Against high winds or turbulences.
      - Against water and ice.
      - Against radiations and electrical shock.
      - Others: against biological attack (from micro-organisms to beasts) either through openings or by impact in flight.
  - Infrastructures: base, tracks, navigation aids, telecommunications, operations and payload management.

We here focus on aircraft thermal systems aside of propulsion, i.e. ECS and EPS. Engine thermal problems are basically different to ECS because of the very hot working parts involved (e.g. turbine blade refrigeration to keep $T<1700$ K). There are other environmental impacts on flight that cannot be fight out, like jetlag (discomfort by distortion of circadian rhythm). Others, like mobility restriction, may be alleviated within large planes.

In addition to providing thrust, the engines also have to deliver electrical, pneumatic and hydraulic secondary power to the systems in the aircraft. Among these systems, the ECS is the main power consumer (75 % of non-propulsive power on cruise, which is 1 % of propulsion), and it generates the most important extra consumption of fuel. With engines off on ground, the auxiliary power unit (APU, a

smaller turboshaft engine of some 1 MW) provides electrical power, and bleed air for air conditioning and the start of main-engines.

The pneumatic system of an aircraft includes:
- Bled air at 250 kPa and 450 K for:
    - The internal ECS (cabin air).
    - The external EPS (anti-icing, anti-rain windscreen air-curtain).
    - The pressurization of some hydraulic systems (non-power, like in lavatories).
    - Cross-engine coupling for start-up.
- Additionally, it may include a pneumatic power system, at some 2 MPa (obtained on an additional compressor), but this is only used by some European manufacturers (Americans use hydraulic or electric systems).

Cabin air conditioning

Cabin air conditioning must provide comfort conditions (i.e. some 22±2 ºC, 90..100 kPa, and 50..70 % RH) within a closed container (the cabin), under all foreseeable circumstances (−60..+50 ºC, 10..100 kPa, 0..100 % RH, ozone, etc.), i.e. it must provide ventilation, pressurization, heating, cooling, humidification, deshumidification (demisting), and disinfection. One may split air conditioning factors in: physical, chemical, and biological. Besides, cabin air monitoring provides the basic smoke detection means for fire warning.

Air conditioning is the second power-consuming system, after propulsion; e.g. for an A320, propulsion takes $\dot{Q}_{prop} = \dot{m}_f LHV = 40$ MW and ECS $\dot{Q}_{ECS} = \dot{m}_f LHV = 200$ kW; all the rest (instruments, lighting, entertainment, kitchen…) account only for a few tens of kW.

Conditioned air enters the cabin from distribution ducts by wall-floor and ceiling grilles and directional outlets above the seats, and goes out through other grilles and collecting ducts (Fig. 1). About half of this exiting air is exhausted from the airplane through an outflow valve in the underside, and the other half is drawn by fans through special filters (for trapping microscopic particles, bacteria and viruses) and then recirculated On some flight decks there is no recirculation, to have more margin for avionics cooling.
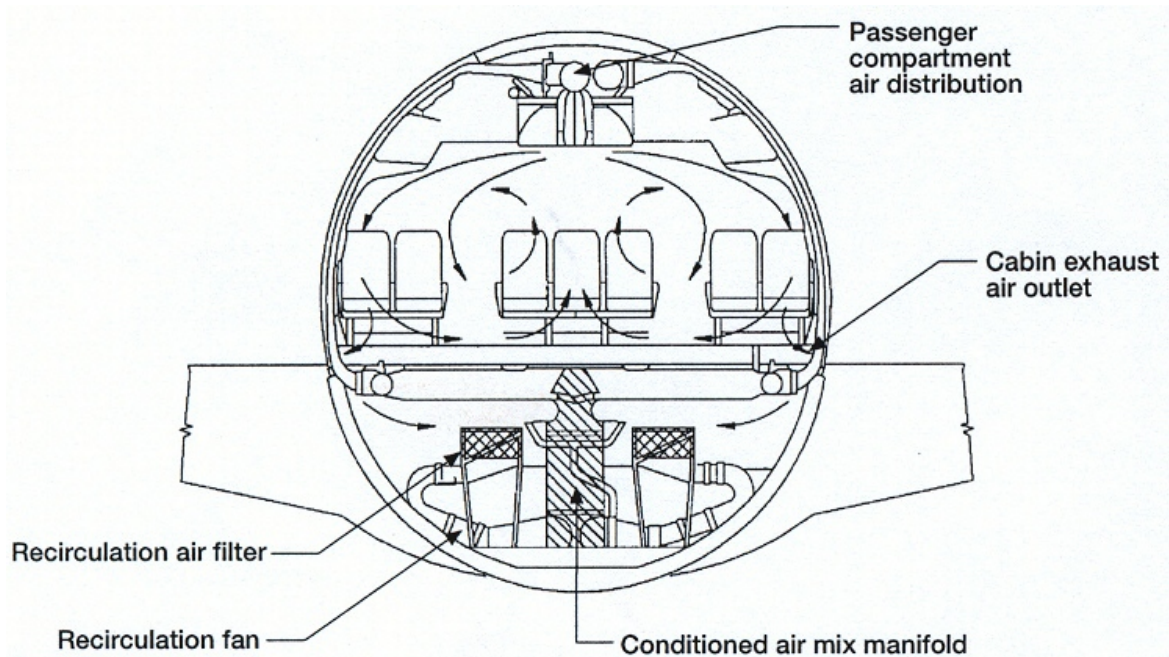
Fig. 1. Air flow inside an aircraft cabin.

Ventilation governs air supply. Air quality (as well as blood oxygenation) is primarily measured by CO_2 concentration (instead of oxygen availability), according to ANSI-ASHRAE Standard 62-1989: Ventilation for Acceptable Indoor Air Quality, Appendix D:

$$\dot{V}_{air,STP} = \frac{\dot{V}_{CO_2,gen}}{x_{CO_2,cabin} - x_{CO_2,outside}} = \frac{4\% \cdot (0.5 \text{ L/(breath)}) \cdot (1/3 \text{ breath/s})}{(1700 - 380) \cdot 10^{-6}} = 5 \ \frac{\text{L/s}}{\text{pax}}$$

Normal breathing. An adult breathe some 0.5 L of air in normal conditions 20 times per minute (up to 2 L in deep gasps, and the rate varies from 12 breath/min at rest to 120 breath/min on panting). Intake composition (fresh air) is 77 % N_2 + 21 % O_2 + 1 % H_2O + 1 % Ar + 0.04 % CO_2, and exhalation is 74 % N_2 +17 % O_2 +4 % H_2O +1 % Ar +4 % CO_2. Maximum environmental CO_2 for comfort: 0.17 %vol (1700 ppm). Design condition for any habitable space is to guarantee an air flow of 10 L/(s·cap), to have enough oxygen (0.15 L(s·cap) would be enough: 0.5 (L/breathe)·(1/3 breathe/s)), but mainly to sweep odours, microorganisms, and heat release.

A person metabolism processes a minimum of $0.1 \cdot 10^{-3}$ kg/s of air in respiration, consuming a minimum of $5 \cdot 10^{-6}$ kg/s de O_2 and generating a minimum of $7 \cdot 10^{-6}$ kg/s de CO_2 and a minimum of $3 \cdot 10^{-6}$ kg/s de H_2O. Skin transpiration (dry) and perspiration (sweat) contributes in an even greater amount of H_2O vapour release.

Disinfection may range from applying an aerosol repellent to insects, to inertization with CO_2 (fumigation is banned) to kill rodents and reptiles that enter with the payload (in the pallets) or doors. An A340 requires 2500 kg de CO_2 each time. Rodents die in half an hour, but reptiles may take half a day, and cockroach larva even longer).

In days gone by, it was not unusual for people to smoke in any public place and a commercial airplane was no exception. At that time, the ECS was additionally required to get rid of tobacco smoke present in the cabin.

Exercise 1. How long does it takes for the ECS to change all the air in the cabin?
Sol.: In a full loaded plane, each passenger may be allocated some, let say, 1 m^3 of air, so that, at 5 L/(s·pax) of minimum fresh-air ventilation rate, it takes 1000/5=200 s to renovate the air. A further check is to divide actual cabin-air volume by the air-supply for a given aircraft; e.g. for B747-400, V_{air}=886 m^3, 416..524 pax, and 5 L/(s·pax), the typical renewal period is 886/(500·0.005)=350 s (i.e. a few minutes).

Pressurization and oxygen control

- Typical ventilation. Before cabin pressurization in the 1950s, ventilation was by infiltration as for buildings. Pilots used oxygen mask since WWWI reconnaissance flights (pressure suits were developed in the 1930s). Early jet liners (in the 1940s) pressurized the cabin with 10 L(s·pax) of fresh air, but modern jets (since 1970) only supply and renew 5 L/(s·pax), forcing another 5 L/(s·pax) of cabin air recirculation (otherwise, the primary jet engine would deteriorate too much in large bypass turbofans; e.g. each of the two A320 engines uses 80 kg/s primary air, and cabin air is 0.006·200=1.2 kg/s minimum, up to 2 kg/s usual, 1 kg/s from each engine). According to the European Aviation Safety Agency (EASA), each passenger and crew compartment must be ventilated with enough fresh air (but not less than 0.3 m^3/min STP = 6 g/(s·pax)), with CO<50 ppm, CO_2<0.5 % (it was 3 % up to 1997), O_3<0.25 ppm, and particle filter for >10 nm (for virus; tobacco particles are much larger, some 10 μm). Cabin air is renewed every 2 or 3 min. The cockpit has a larger air supply to keep a little overpressure against the main cabin (to avoid gases in). Air speed flow near people must be in the range 0.05..0.3 m/s.

- Oxygen concentration needs. Both, pressure and oxygen-fraction are important because what matters for the flow of matter is chemical potential, depending on the product $x_{O2}p=p_{O2}$ (oxygen partial pressure). Safe range for prolonged exposure is p_{O2}=18..40 kPa at the intake. As atmospheric pressure decreases with altitude, either cabin pressure or oxygen fraction should be increased to keep p_{O2} within range. Although we just focus on oxygen needs, breathable air quality imposes many other constrains on air composition: <0.5 % CO_2 mole fraction (i.e. <5000 ppm; up to 1997 the limit was 3 %), <50 ppm CO, <0.25 ppm ozone, limits in volatile organic compounds (lubricating oils and hydraulic fluids can enter the aircraft cabin via the ECS system), limits in particle concentration, etc. Air composition control is also known as air revitalization.

- Emergency oxygen can be supplied from:
  - Gas bottled at 15 MPa (heavy, and might be dangerous).
  - Liquid cryogens at cabin pressure (continuous loss, and might be dangerous).
  - Solid 'candles' of lithium perchlorate ($LiClO_4$=LiCl+2O_2) that releases O_2 when 'ignited' (locally heating above 400 ºC) by pulling a pin on the cartridge; in an airliner, when oxygen masks drop down, you have to give a pull on it to actuate the igniter pin. Lithium perchlorate is most used in aerospace applications as a last resource since it gives the highest quantity of oxygen for its weight and for its size, in spite of its high price (cheaper sodium perchlorate, $NaClO_4$, and even sodium chlorate, $NaClO_3$, are used in mines and submarines). A typical 2.2

kg cartridge used in spacecraft supplies enough oxygen for one person per day. Some metal peroxide is added to the perchlorate (about 5 % by mass) to scavenge possible chlorine gas formed ($Cl_2+Li_2O_2=2LiCl+O_2$). Oxygen candles have a long shell life, but they cannot be stopped after ignition, and the heat release must be properly evacuated.

- Gas separation from ambient air in a molecular sieve (the lightest and most modern way).

- Pressurisation needs. Ambient air at 10 km altitude is at 26 kPa (Table 1) and −50 ℃ (too thin for oxygenation, and too cold for thermal comfort). Airliners fly up to 12 km altitude (above that, air density falls faster), where p=19.4 kPa → p_{O2}=4 kPa → 50 % people would die in 5 minutes. Aircraft must keep p_{O2}>16 kPa (ICAO), what implies p_{air}>75 kPa → z_{cabin}<2.5 km (EASA CS-25 requires z_{cabin}≤2440 m); the tendency is to decrease z_{cabin}<2 km. The larger the cabin overpressure, the heavier the structure must be; that is another reason why airliner cannot fly over 12 km; e.g. when flying at 12 km with 20 kPa outside pressure and 80 kPa cabin pressure, a typical 0.5·0.5 m^2 aircraft skin panel must withstand a force, when the 50 % safety factor is included (f_s=1.5), $F=A\Delta p f_s$=0.5·0.5·(80-20)·10^3·1.5=22.5 kN. Although pressure may have no influence on inert payloads, cargo compartments are usually pressurised (although perhaps at a smaller overpressure, e.g. at 50 kPa, 5000 m boot-altitude). Combat aircraft keep a lower cabin overpressure: 35 kPa instead of 50 kPa. Only the landing-gear boot and some technical-system boots nearby or at the tail are un-pressurised. The pressurised cabin is not airtight (there are too many through-wall openings), but uncontrolled air loss is small compared to 5 L/(s/pax) renewal. Cabin pressurization cycling may cause structural fatigue; many early pressurised aircraft, like piston-engine Avro Tudor in the 1940s, and Comet in the 1950s (the first commercial jet), cracked in flight. Controlling the rate of change in pressure to avoid ear pain is particularly important during ascent and descent.

- Pressurisation control. Cabin air is just compressed outside air. In the conventional air-cycle air-conditioning system, the whole aircraft is pressurised by bleed air (bled at 250 kPa from engine compressor, upstream of combustion chambers) supplied to the conditioning packs at some 450 K (180 ℃) with a pre-cooler. Cabin pressure is controlled by outflow valves (controlled by redundant electric motors) to keep cabin pressure above 75 kPa (equivalent to 2400 m altitude), and never below 5 kPa underpressure or 500 kPa overpressure to outside air. Pressure control is based on outflow valves (Fig. 2) and safety valves:
  - Safety overpressure is limited by a positive pressure-relief valve to $\Delta p \equiv p_{int} - p_{ext}$=65 kPa for structural reasons.
  - Overpressure during normal operation is limited to Δp<55 kPa by the main outflow valves (i.e. SLP cannot be maintained at z>6 km).
  - Sonic valves at lavatories and kitchens provide a constant independent outflow at those locations, avoiding odours to mix with cabin air.
  - Safety underpressure is limited by a negative pressure-relief valve to Δp=−7 kPa to avoid structural collapse (controlled by a spring loaded flapper valve).
  - A dump valve quickly releases cabin pressure difference when landed.
  - A sudden change in cabin pressure Δp>3 kPa (equivalent to Δz=300 m near sea level) cause pain and vertigo.

o Rate of change in cabin pressure is limited to $\Delta p/\Delta t = 1$ kPa/min (equivalent to $\Delta z/\Delta t = 1.5$ m/s) to avoid ear problems (one may relieve it by swallowing).

o The pressurisation control system is all pneumatic for reliability.

Table 1. Pressure-altitude correspondence in ISA model (with this model, temperature at sea level is 15 ℃, drops 6.5 ℃/km up to 11 km, and remains at −56.5 ℃ up to 20 km).

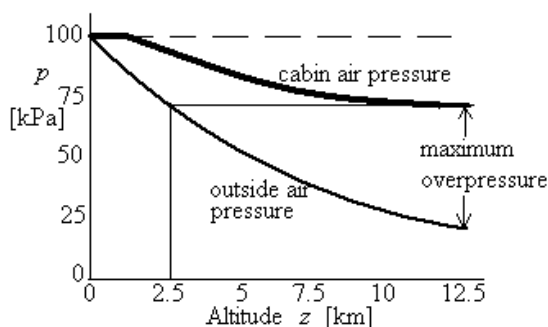| z [km]	p [kPa]	p [kPa]	z [km]
0	101.32	100.	0.111
0.5	95.46	95.	0.539
1.	89.87	90.	0.986
1.5	84.55	85.	1.454
2.	79.50	80.	1.945
2.5	74.69	75.	2.461
3.	70.12	70.	3.006
3.5	65.78	65.	3.584
4.	61.66	60.	4.198
4.5	57.75	55.	4.855
5.	54.04	50.	5.563
5.5	50.53	45.	6.331
6.	47.21	40.	7.171
6.5	44.07	35.	8.101
7.	41.10	30.	9.146
7.5	38.29	25.	10.343
8.	35.65	20.	11.805
8.5	33.15		
9.	30.80		
9.5	28.58		
10.	26.50		
10.5	24.54		
11.	22.70		
11.5	20.98		
12.	19.40		
12.5	17.93		

Fig. 2. Cabin pressure regulation as a function of altitude, and a photo of an outflow valve (below the fuselage) that regulates it.

Pressure sensors are most important in aviation. Two air data computers (ADC) receive total and static pressure from independent pitot probes (Fig. 3) and static ports on each side of the fuselage (must be placed where free-stream disturbance is minimum), and the aircraft's flight data computer compares the information from both computers, checks one against the other, and compute pressure altitude, Mach number, and vertical speed.
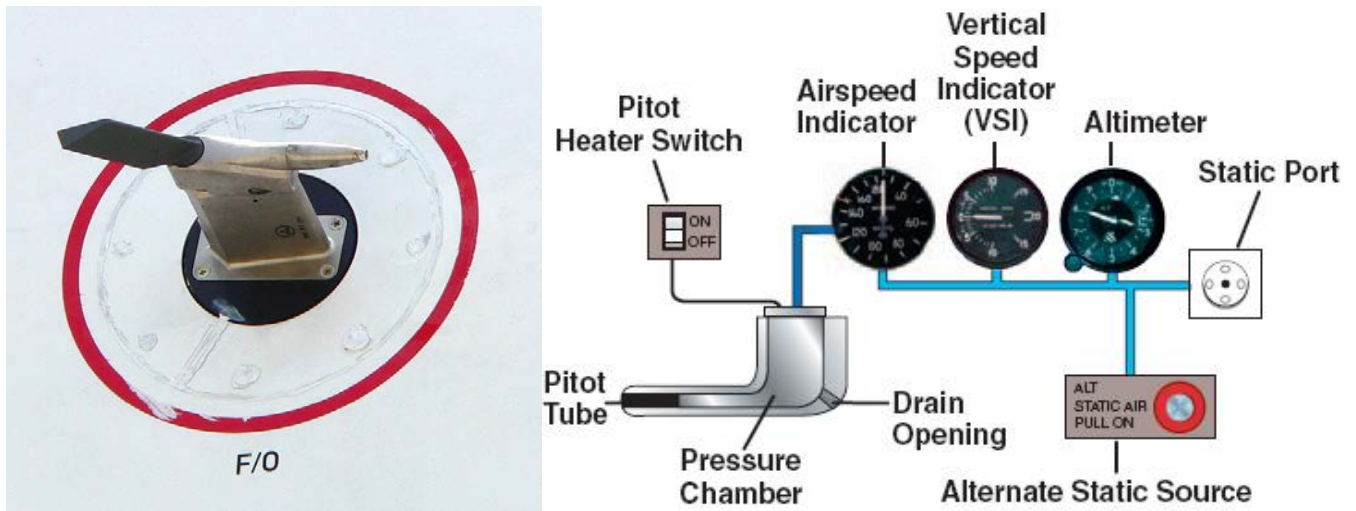
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Fig. 3. A flight-officer side pitot probe in Airbus A380, and generic diagram for a pitot system.

Air source. Bleed air circuit

The air source in aircraft ECS is ultimately outside air (in spacecraft it must be produced). Most ECS, up to now, take compressed air from main engines (before the combustion chambers, of course), instead of having dedicated compressors to pump outside air (but B787 is based on the latter).

Bleed air systems should bleed at compressor interfaces (HP, LP-HP or LP-MP-HP) because bleeding at intermediate stages may cause unwanted flow deflections.

- One bleed, from HP (exit).
- Two bleeds, from HP and LP, for better regulation.
- Three bleeds, from HP, LP and fan (the latter to cool the hot air (which is at >200 ℃ if compressed from 24 kPa to >250 kPa). This is the usual choice in airliners (Fig. 4).
- On ground, bleed from APU (must be closed for main engine start-up), or direct air supply from ground-based air-conditioning units.

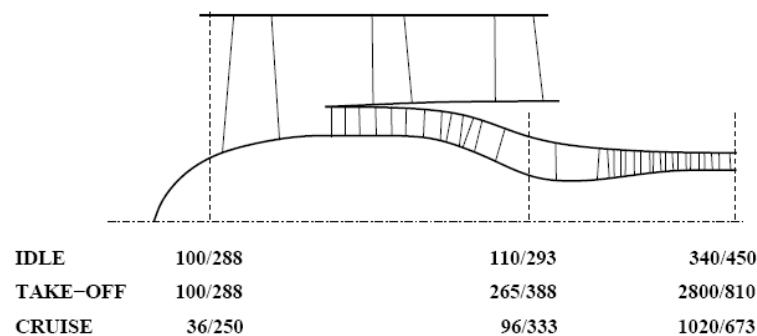|			
IDLE	100/288	110/293	340/450
TAKE−OFF	100/288	265/388	2800/810
CRUISE	36/250	96/333	1020/673

Fig. 4. Pressure (in kPa) and temperature (in K) at engine inlet (e.g. 100/288 means 100 kPa and 288 K), at the end of the low pressure compressor (around the 6th stage), and at the end of compression (around the 16th stage). The LP and HP bleedings from main-engine compressor are blended to provide the nominal 250 kPa air-conditioning input pressure, and cooled, if needed, by an additional pre-cooler, to the 450 K nominal input temperature. A typical 30:1 pressure-ratio main-compressor is assumed, with a 5:1 bypass ratio. The primary flow follows into the combustion chambers and then drives the turbine (of some 5 or 6 stages) before exiting the engine.

A nominal bleed-air condition is defined to facilitate interfacing with the ECS.

- Bleed pressure is regulated to some 250 kPa (from 200 kPa to 300 kPa, depending on manufacturer). Lower values may be insufficient to force the air through the two heat exchangers in the air conditioning machine, and higher values may be a waste of resources (the higher the bleed-pressure, the higher the cost on fuel).
- Bleed temperature is regulated to some 450 K (some 180 ℃) by cooling the bleed air with ram air (or better with fan air, to avoid a fan at the heat exchanger). The air bled from the compressor may be very hot (e.g. at >200 ℃ if compressed from 24 kPa to >250 kPa). Lower temperature values (<180 ℃) may be insufficient for the anti-icing system, and higher values may cause damage to composite structures and plastic materials in the neighbourhood of ECS ducts (the ducts are made of heat-resistant fibreglass or aluminium tubes). To notice also that the air-conditioning packs are always close to fuel tanks.

Most often, there are two air-conditioning packs for safety (3 packs on B747 and DC10), nominally supplying 50 % of air needs, but able to operate at their 180 % nominal flow rate in case of one failures. On twin-engine aircraft, each engine bleeding is designed to supply half the total air flow (although the two bleedings are connected). On three-engine aircraft, the third engine bleed is on stand-by for redundancy. On 4-engine aircraft each bleeding only supplies ¼ of the total design flow.

Control valves in all the bleed system (Fig. 5) protect against flow reversal, and maximum bleeding (e.g. in case of a break).
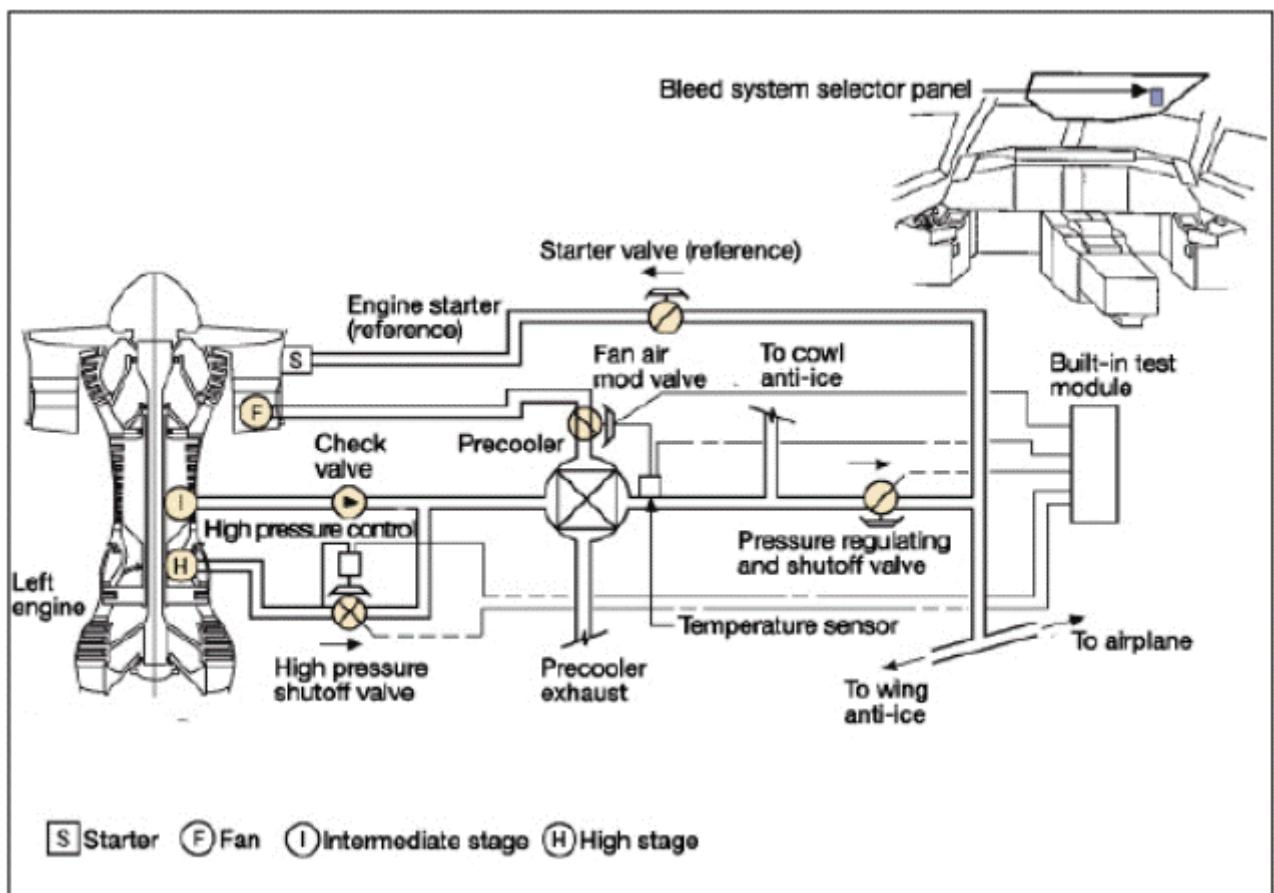

Fig. 5. Some of the control valves in the bleed system (from Boeing).

<u>Flow rate multiplier</u>. If only hot air is needed, a small amount of bled air at 250 kPa and 180 ℃ may be used to pump the necessary total flow rate (5 L/(s·pax)) from outside air (at 25 kPa, 250 K) with:

- A jet pump.
- A compressor, driven by a turbine in the bled stream.

Humidity control

Human comfort demands relative humidity in the range 50..70 %, but this is not maintained aboard aircraft to avoid condensation problems on cold walls and equipment, which tends to corrode metals and boost micro-organism growth. Relative humidity is kept in the very low range, 10..20 % RH, in spite of some discomfort (it is highly recommended to drink during flight, to compensate for evapotranspiration in such a dry environment) and electrostatic build-up (a person with leather shoes and wool suits may grow 15 kV of electrostatic charge on carpets without carbon treatment). At cruise altitudes there is practically no water in the air, so it is natural to have dry cabin air (but see the example below to account for passenger evapotranspiration). On ground and during ascent, the air conditioning system must dehumidify the fresh air introduced into the cabin, particularly in tropical climates when doors are still open.

There are water sinks at the cabin wall bottom to cope with liquid condensate dripping down the external envelop walls. The condensate frosts on the very cold walls on cruise (at some −30 ℃), but it is being melted by circulating air between the outer skin of aluminium and the insulating wall that protects passengers and cargo (cabin wall usually has three layers. fuselage, insulation panel, and lining). Notice that the air flow from the cabin interior to this surrounding air curtain (drained at the bottom) is a continuous source of humidity, whereas if the air conditioning system directly discharges the dry air in this envelop, it acts as a humidity barrier.

Outside humidity is very small at high altitudes, and is kept very low inside the plane to minimize problems of condensation and frost on the cold structure (there are water sinks at the cabin wall bottom). Water vapour released by passengers, some $m_{w,gen}$=50 g/(h·pax) (a third or so by respiration and the rest by transpiration), and recirculation already yields some 10 % RH within the cabin. New aircraft using more corrosion-resistant composites in their construction, are being designed to operate with a cabin relative humidity of 15..20 %, providing more comfort on long flights.

Cabin relative humidity may vary from 90 % (on tropical zones on ground, with doors open) to less than 2 % (in flight with low passenger occupation). In some cases, mist may form inside windows, and hot air is used to demist the windshields, as in cars (outside defrosting is covered below under Environmental Protection System). After 3 or 4 hours of exposure to relative humidity in the 5–10 % range, some passengers experience discomfort, such as dryness of the eyes, nose, and throat, but there is no conclusive evidence of extensive or serious adverse health effects of low relative humidity on the flying population that would justify recommending a regulation to add supplementary humidification systems to aircraft.

Sometimes, the injection of cold air over passenger seats on ground or at low altitudes may yield small condensation clouds by the mixing of cold dry air with warm humid air in the cabin (not on cruise).

For humidity calculations, one must recall Clapeyron's equation of liquid-vapour equilibrium of a pure substance for the vapour pressure of a pure substance, p_v^*:

$$\left.\frac{dp_v^*}{dT}\right|_{LVE} = \frac{h_{LV}}{Tv_{LV}} \quad \rightarrow \quad \ln\frac{p_v^*(T)}{p_{v,0}^*} = \frac{-h_{LV}}{R_v}\left(\frac{1}{T}-\frac{1}{T_0}\right)$$

(with $p_{v,0}^*$=0.6 kPa for T_0=0 °C, h_{LV}=2.5 MJ/kg, and R_v=462 J/(kg·K)), and Raoult's equation of liquid-vapour equilibrium of an ideal binary mixture:

$$\frac{x_{v,LVE}}{x_{l,LVE}} = \frac{p_v^*(T)}{p} \quad \xrightarrow{x_{l,LVE}\to 1} \quad p_{v,LVE} = x_{v,LVE}\,p = p_v^*(T)$$

where x_v and x_l stand for the molar fraction of water in the vapour phase and the liquid phase (the latter assumed unity because of the low solubility of air in water), and $p_v \equiv x_v p$ is the partial pressure of water in the vapour phase. Relative humidity, ϕ, is defined as $\phi \equiv x_v/x_{v,LVE}=p_v/p_{v,LVE}=p_v/p_v^*$, and absolute humidity by:

$$w \equiv \frac{m_v}{m_a} = \frac{M_{va}}{\dfrac{1}{x_v}-1} = \frac{M_{va}}{\dfrac{p}{\phi\,p_v^*(T)}-1} \approx \frac{M_{va}\,\phi\,p_v^*(T)}{p}$$

Dew point temperature, T_{dew}, is defined by $\phi p_v^*(T)=p_v^*(T_{dew})$, i.e. the condensation temperature when a given unsaturated mass of humid air is cooled at constant pressure and constant absolute humidity. For solid-vapour equilibrium, the only change is to substitute h_{LV}=2.5 MJ/kg by h_{SV}=0.33 MJ/kg, and the dew point is then called frost point.

Example 2. Find the condensate production by the air conditioning system on a hot and humid ground place, 35 °C, 80 % RH, to supply cabin air at 22 °C and 50 % RH.

Sol. Absolute humidity values are $w_{ext}=M_{va}\phi p^*(T)/p=0.622\cdot0.8\cdot5.6/100=28$ g/kg and $w_{in}=0.622\cdot0.5\cdot2.6/100=8$ g/kg, so that, for a 2 kg/s ECS flow rate, the required condensation is $\dot{m}_a\Delta w = 2\cdot(28-8) = 40$ g/s (i.e. 2.4 kg/h).

Example 3. Find the cabin humidity at cruise, if air renewal is dry (it is always <5 % HR).

Sol.: For an air renewal of 5 L/(s·pax), 30 g/(h·pax). Mean cabin humidity $w=m_{w,gen}/m_{out}=(0.03/3600)/0.005=1.7$ g/kg (ϕ=1.7/16=11 % HR). Recommendation: drink, and don't wear contact lens.

Note: (0.5 L/breath)·(1/3 breath/s)·(0.0012 kg/L)·(0.040 kg/kg)=8·10⁻⁶ kg/s=30 g/h. w_{sat37}=40 g/kg.

Thermal loads

There are two basic thermal control requirements:

- People comfort demands air supply at T=18..26 °C depending on heating or cooling needs, without thermal chocks, i.e. $|T-T_{cabin}|<5$ °C, and without drafts (i.e. $v<0.2$ m/s close to people and <2 m/s

anywhere). Floor, lateral walls and ceiling are also heated/cooled to enhance temperature uniformity and help comfort (eliminate high radiative couplings).

- Avionics cabinets must be kept within $T=-30..70$ ºC for proper operation.

The thermal loads on cabin air may come from outside (positive or negative heat flows depending on environmental conditions, Fig. 5), and from inside (heat dissipation only (from people and equipment). Besides the basic ISA model, other temperature profiles are considered in aircraft design, like ISA−20 (i.e. 20 ºC below ISA values), ISA+20, or the bounds in Fig. 6.
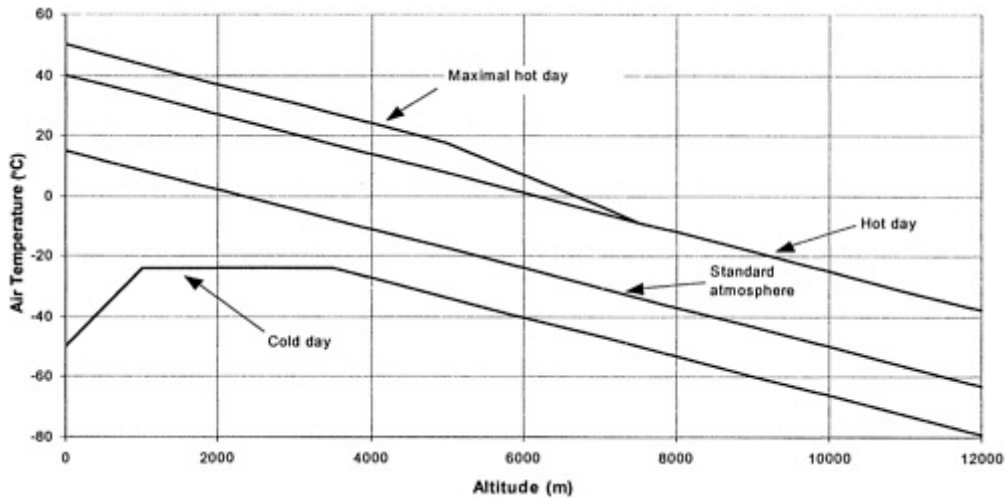

Fig. 6. Outside air temperature range to be considered in aircraft design.

The thermal loads are:

- Heat flow through the fuselage: heat loos on cruise ($\Delta T_{max}=(-60)-20=-80$ ºC, but we must take into account the dynamic temperature recovery of almost 30 ºC at $M=0.85$, so that $\Delta T_{max,sub}=(-30)-20=-50$ ºC), but heat gain on ground ($\Delta T_{max}=50-20=30$ ºC). Taking for the fuselage 3 mm aluminium pressure shell (not structural: frames and beams), 20 mm insulation ($k=0.1$ W/(m·K)), and 2 mm coating ($k=0.1$ W/(m·K)), the overall transmittance is $K=2.5$ W/(m^2·K).

$$K = \cfrac{1}{\cfrac{1}{h_e}+\cfrac{\delta_{Al}}{k_{Al}}+\cfrac{\delta_{in}}{k_{in}}+\cfrac{\delta_{co}}{k_{co}}+\cfrac{1}{h_e}} = \cfrac{1}{\cfrac{1}{100}+\cfrac{0.003}{200}+\cfrac{0.02}{0.1}+\cfrac{0.002}{1}+\cfrac{1}{5}} = 2.5 \ \frac{W}{m^2 \cdot K}$$

- Heat release inside: avionics (10 kW), passengers and crew (200*0.1=20 kW), kitchen (10 kW), lighting and entertainment (1 kW).
- Solar heating. May reach 1 kW/m^2 on lit surfaces, and it may significantly contribute to heating on cruise (but worsens the cooling problem on ground on summer).
- Indirect heat input from engines through inside piping.

Outside air temperature is measured with a Pt-100 probe extending beyond the boundary layer and measuring total air temperature (TAT); static temperature can be computed with $T=T_{TAT}/(1+0.194M^2)$ in K ($T=T_{TAT}/1.124$ for Mach=0.85). Notice that flying through clouds decrease ram heating because part of

it goes to evaporation (e.g. at M=0.7, ΔT=20 ºC in dry air, but ΔT=10 ºC in middle clouds, and ΔT=15 ºC in high-middle clouds at some 6 km altitude).

The heat sink is ultimately the outside air, but in some circumstances the fuel in the reservoirs is used as cold fluid (e.g. to cool the lubrication oil, and the avionics in supersonic flight); this fuel heating is beneficial to its piping and combustion, particularly on cold climates during the early phases of flight (fuel temperature may be <−40 ºC on ground with cold weather, close to the freezing point of −50 ºC for Jet A1, although it gets hot by cooling the lubricating oil and the fuel pump, up to 150 ºC during descent).

Thermal design is driven by the need to match the following extreme requirements:
- Worst cooling case (hottest case):
  - Cooling on ground at a hot and humid place, aircraft full, doors closed, APU power. Refrigeration must be able to cool from 47 ºC to 21 ºC in <30 min. In A320, of fuselage area 350 m^2 (4 m diameter and 40 m length), for the 2 kg/s ECS-air-flow-rate to evacuate the $\dot{Q}_{wall,max} = KA\Delta T = 2.5 \cdot 350 \cdot (47 - 22) = 22$ kW plus some 25 kW from people and lights, the supply temperature to cabin must be T_i=22−(22+25)/2=−2 ºC on hot ground (in practice always >0 ºC to avoid frost). Maximum refrigeration efficiency: (22+25)/150=0.31.
  - Cooling on cruise is only applicable to supersonic flight, where ΔT=v^2/(2c_p)=(2·300)^2/2000=180 ºC and T_{wall}=220+180=400 K (some 350 K in reality because of the lower recovery factor).
- Worst heating case (coldest case):
  - Heating on ground at a cold and humid place, aircraft empty, doors closed, APU power. Heating must be able to heat from −40 ºC to 24 ºC in <30 min.
  - Heating on cruise at night. In A320, for the 2 kg/s ECS-air-flow-rate to supply the $\dot{Q}_{wall,max} = KA\Delta T = 2.5 \cdot 350 \cdot (22 - (-35)) = 50$ kW minus some 30 kW from people and avionics, or just the 10 kW in the worst case of low occupancy, the supply temperature to cabin must be T_i=22+(50−10)/2=42 ºC on (cold) cruise. Maximum heating efficiency is then 40/150=0.30.

The fact that cabin air is recirculated in 50 % of the mass flow rate has no influence on the thermal loads because the entry rate is doubled and the entry temperature difference halved.

A characteristic of aircraft air conditioning is the quick cycling between heating and cooling needs, associated to rapid changes from ground temperature (that may be >40 ºC), to cruise temperature (that may be <−60 ºC). Only spacecraft thermal control has to deal with such environmental jumps (of order 10^2 K in some 10^3 s).

Mass and energy balances

A balance equation is a relation between the change with time of some magnitude in a system, and the causes that motivate it. According to the type of interactions between a system and its surroundings, the balance equation for a generic magnitude can be layout like that (leaving aside radiation exchages):

For an isolated system: Accumulation =   Production

For a control-mass system: Accumulation =   Production   + Diffusion

For a control-volume system: Accumulation =   Production   + Diffusion   + Convection

The mass and energy balances may be written as:

$$\frac{\mathrm{d}m_i}{\mathrm{d}t} = \dot{m}_{i,gen} + \sum_e \dot{m}_{i,e} \ , \ \frac{\mathrm{d}(me)}{\mathrm{d}t} = \dot{Q} + \dot{W} + \sum_e \left(\dot{m}_e h_{t_e} \right) \quad (\dot{Q}_{pax} \ \& \ \dot{m}_{w,pax} h_{vap} \text{ depend on system choice})$$

Some nomenclature details follow. An isolated system has no interaction with the environment. The term 'accumulation' is better than its equivalent 'storage increment' (notice that both terms convey the idea of a relative measure, not an absolute measure as the term 'store' implies). All terms in the balance should be understood as net contributions, i.e., net accumulation (which may be negative if the store decreases), net production (i.e. production minus consumption), and net fluxes for diffusion or convection (and not flux in minus flux out).

Example 4. Find the mass of CO_2 required to fill an A340 (5.2 m diameter by 70 m length) to kill living beings for disinfection, on ground.

Sol.: The cabin air cannot be extracted and then the CO_2 fed because the structure would collapse beyond a 7 kPa vacuum pressure. The common procedure is to pump CO_2 in through the air-conditioning ground-port, while letting the air escape through the outflow valves, until the composition at the exit is largely CO_2. As a minimum the mass of CO2 to fill the aircraft is $m=pV/(RT)=10^5 \cdot 1400/(189 \cdot 288)=2600$ kg, where volume has been estimated as $V=L\pi D^2/4=70 \cdot 3 \cdot 5.2^2/4=1400$ m^3, and $R=R_u/M_{CO2}=8.3/0.044=189$.

As a first approximation, mass and energy balances for cabin air are:
- Dry air balance: $\dot{m}_{in} = \dot{m}_{out}$.
- Water balance: $\dot{m}_{in} w_{in} + \dot{m}_{w,gen} = \dot{m}_{out} w_{out}$, where w stands for absolute humidity, and $\dot{m}_{w,gen}$ is the water vapour released by passengers (50 g/(h·pax)).
- Energy balance: $\dot{m}_{in} h_{in} + \dot{m}_{w,gen} h_{w,gen} + \dot{Q}_{pax,gen} + \dot{Q}_{equip,gen} + \dot{Q}_{wall} = \dot{m}_{out} h_{out}$, where h stands for humid-air enthalpy ($h=c_p(T-T_0)+wh_{LV}$), $h_{w,gen}$ can be neglected if the metabolic heat release is fully accounted in $\dot{Q}_{pax,gen}$ (100 W/pax), $\dot{Q}_{equip,gen}$ accounts for avionics and lighting dissipation (and kitchen ovens), and $\dot{Q}_{wall}$ is the heat flow through the cabin wall (positive when entering, negative if leaving)

Possible solutions: HVAC systems

Cabin air heating may be achieved by:
- Electrical power (resistive or heat pumps). Used in helicopters and some small planes.
- Mechanical power (heat pumps directly driven by the engine, instead of by an electrical motor).
- Burners. Used on large aircraft in the past. Breathable air (from outside or recirculated) is forced to pass through a heat exchanger around the burner exhaust.
- Exhaust heat recovery. Used in some small aircraft. Similar to a car heating system: a flow of breathable air (from outside or recirculated) is forced to pass through a heat exchanger that takes

residual heat from the engine (from the exhaust gases here, since aircraft engine is not water-cooled like in cars).

- Compressor air bleeding (adiabatic heating). This is the system used on most large aircraft.

Cooling below ambient temperature is more difficult to achieve, and it impose peculiar problems: cooling fluids must pass through walls, water condensate must be eliminated, temperature jumps and efficiencies cannot be high, etc. Cooling may be achieved by:

- Vapour cycles (mechanical or absorption): high efficiency, but do not provide air renovation and pressurization. Components: compressor (driven by the engine or a motor), heat exchangers (vaporiser and condenser; fan assisted), expansion valve, piping, insulation, and controls.
- Air cycle (inverse Brayton): low efficiency (worst on ground), but lighter, more compact, reliable, cheap, and provides full solution to cooling/heating plus ventilation and pressurization. This is the system used on most large aircraft.
- Other refrigeration means are only used in special applications: thermoelectric cooling, Ranque tube, etc.

Temperature control is best achieved by partial mixing of an untreated stream with a heated or cooled stream, by using a bypass-control valve governed by a downstream temperature sensor (a single valve shaft may be closing a butterfly valve in one stream while opening another butterfly valve in the other stream, if they are 90º out of phase).

To satisfy the air-conditioning needs in flight and on ground (we want a cabin air renovation flow of 5 L/(s·pax) at 75..100 kPa and 22 ºC), different systems can be used, e.g.:

- Up to 1950, only heating was available (from engine heat recovery, electrical heaters, or burners).
- A vapour-cycle system like in car's air conditioning (best with heat-pump capability), supplemented with a separate ventilation system. This is most used in small aircraft.
- An air-cycle system that provides both heating/cooling and ventilation. This is the standard in medium and large aircraft because of its compactness and reliability, in spite of its poor energy efficiency (its operation cost is typically 1 kW/pax at full capacity; some 350 kW for a 400 passenger airliner, about 75 % of allnon-propulsive energy consumption aboard). The ECS packs are typically located close to the wing box section (at the belly, in the vicinity of centre fuel tank).

State of the art:

- All in one solution used in most aircraft: the air cycle machin (ACM) pack (but heating/refrigeration efficiency, $\eta=q_{cabin}/w_{main,comp}=0.5$). A separate electrically-driven ACM would be more versatile and efficient, $\eta=0.7$, but heavier and less reliable.
- Vapour-compression heat pump ($\eta=3$, but no pressurisation, no ventilation) used in many small aircarft.

On ground, instead of using the APU to feed with bleed air the ECS aboard, high-efficiency ground refrigeration systems are being used in main airports. A novel ground-ECS service is based on water chillers with ice storage (ice is made by night, and used on spot to avoid large refrigerators).

The air cycle machine (ACM)

The typical air-cycle conditioner pack works as follows (Fig. 9):

- Air is bled from the main engine compressors through a flow control valve at around 250 kPa; it is very hot (>200 ℃) because of the adiabatic compression-heating. As pressure and temperature of bleeding depends on compressor stage and spinning rate, this pressure is regulated by having two or three bleedings at different stages and control valves (see Fig. 7).

- The hot bled air always requires cooling before entering the cabin, but a simple heat exchanger (HE) with outside air is not efficient (a big HE is needed to cool that amount of air from 200 ℃ to 20 ℃, particularly at low altitudes). To guarantee that bled air can be safely piped from the engine through the fuselage to the air-cycle machine and deicing system, a heat-exchanger (pre-cooler) in the engine cools bled air from the compressor (at >200 ℃) to some 180 ℃ (450 K).

- The air-cycle machine is based on an inverse Brayton refrigeration cycle. Pre-cooled air from the bleed system is further cooled in a so-called primary heat exchanger (Fig. 8) down to some 110 ℃, and then enters a compressor with pressure ratio around π_{12}=1.8 that raises the air to 210 ℃, and a second heat exchanger lowers the temperature again to some 100 ℃. Pressure losses in these compact heat exchangers are high (20..40 kPa). Afterwards, air passes through a turbine and exits at about 5 ℃, to be mixed with some hotter bled air at around 100 ℃ to get the 10..35 ℃ (it depends on operation phase) needed to keep the cabin air at around 22 ℃ at all times, accounting for internal heat release (passengers and equipment), outside heat gain and loses, and air recirculation. The thermodynamic process is sketched in Fig. 9. Additional filters/separators are provided to remove water condensate on ground and low altitudes in humid climates (just after the ACM turbine in most cases, and before the turbine too when very cold cabin air is needed on ground, to avoid the risk of icing inside the turbine); the condensate is injected into the ram air stream to help HE efficiency. Maximum absolute humidity for condenser design is 22 g/kg (saturated air at 26 ℃ and 100 kPa, or 40 % RH and 40 ℃).The common-axis turbo-compressor, of some 0.2 m in size, is made of aluminium, with air bearings.

- Ram air is used as a heat sink in both heat exchangers, which are of the compact type (cross-flow corrugated aluminium-plates). Ram air is captured through an inlet door and a diffuser, and forced by a fan (driven by the ACM turbine) to go through the two heat exchangers mentioned above, a exhaust nozzle, and a louvered exit door. The inlet and outlet doors are linked and driven by the same actuator (one for each pack); these doors remain closed when there is no cooling need (e.g. when the ACM compressor-outlet temperature is <120 ℃ or so). Typical mass flow rate of ram air is two or three times greater than bleed air, in each ACM.

- Two equal ACM nominal systems are implemented, to allow for one failure (Fig. 10).
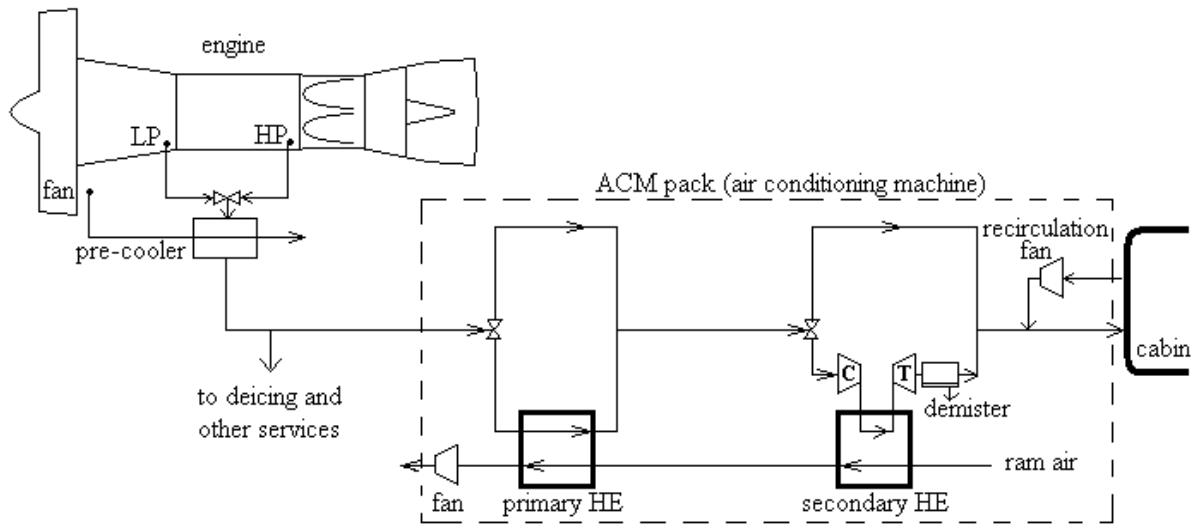
Fig. 7. Environmental control system schematics.

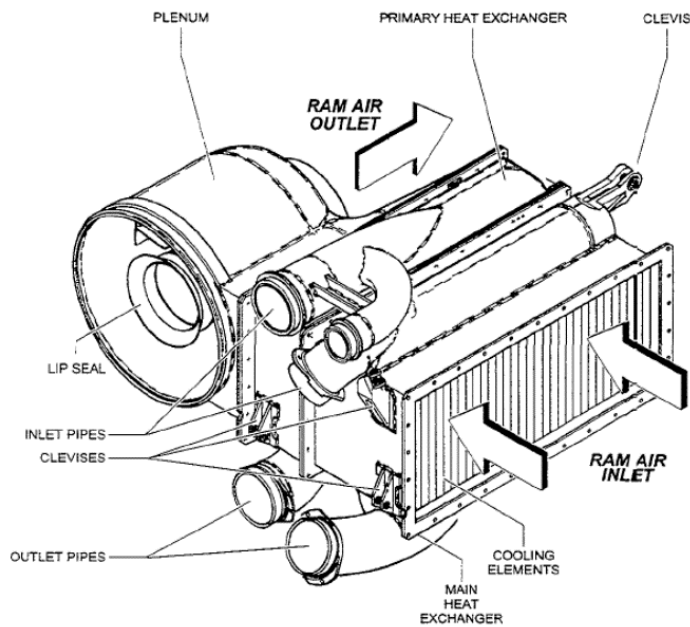Fig. 8. ECS heat-exchanger layout (typical size of each HE is 0.7·0.5·0.3 m³, and 10..15 kg). Photography of one of the heat exchangers.

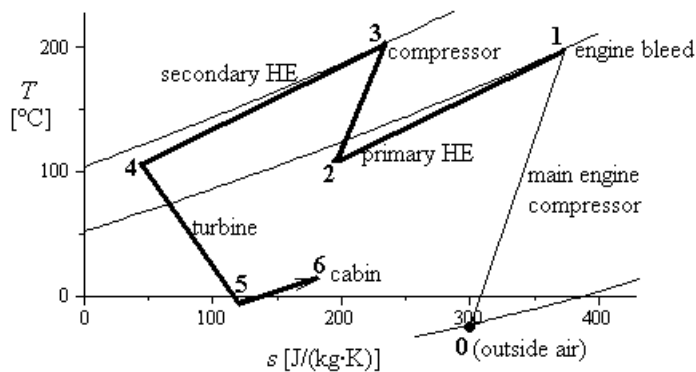Fig. 9. ACM thermodynamic diagram and flow schematics for the cooling case.
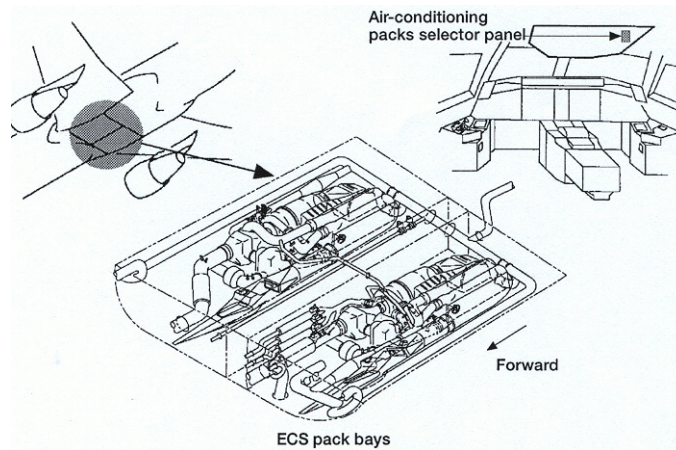
Aircraft environmental control 17

Fig. 10. Typical location of the ACM and cockpit controls.

The ACM controls at the cockpit are:
- A mode knob for each ACM pack with four positions: Auto, Heat, Off, Cool.
- A thermostat knob for each zone in the plane with three positions: Normal, Warmer, Cooler.

ACM working cases

- Heating at cruise level with low occupancy. The ACM must supply air to the cabin at some $T_{cab,in}$=42 ºC (315 K) and p>75 kPa, from bled air at regulated values of 450 K and 250 kPa (from high-pressure compressor), and outside air at 250 K and 22 kPa.
- Heating on coldest ground conditions with low occupancy. The ACM must supply air to the cabin at some $T_{cab,in}$=42 ºC (315 K) and 100 kPa (ambient pressure really), from bled air at a regulated pressure of 250 kPa (from APU or high-pressure compressor, idle) and available temperature of some 30 ºC (300 K), and outside air at 240 K and 100 kPa (ambient pressure really). In this case, using the overpressure to drive a jet pump with outside air, may alleviate the cooling need in the ACM, saving on bleed flow rate.
- Cooling on hottest ground conditions and at low altitudes. The ACM must supply air to the cabin at some $T_{cab,in}$=−2 ºC (270 K) and ambient pressure, from bled air at a regulated pressure of 250 kPa (from APU or idle conditions on ground, or from low pressure in flight) and available temperature of some 100 ºC (370 K), and outside air at 320 K and ambient pressure.

Notice that, because hot bled air (at 350..450 K) is always the input to the air conditioning machine, the ACM must always cool this input air to feed the cabin at −2 ºC in the worst cooling case or at 42 ºC in the worst heating case, and thus, ACM may by understood as either air-cycle-machine or air-cooling-machine.

ACM size and efficiency (energy cost)
The ECS is usually split in one ACM pack per engine. The ACM size is dictated by the ventilation requirement of 6 (g/s)/pax minimum (e.g. 1.2 kg/s minimum for the 200 pax capacity of A320; some 2 kg/s is the typical design value). The A340 ECS weights 720 kg, and has four ACM, each fed with 1 kg/s of air.

On large airliners, some 1 kg/s of compressed air is bled from each engine (from the 80..100 kg/s of primary air used). Each air pack (ACM) weights some 150 kg. Each ACM takes some 3 kg/s of ram air per pack (plus 0.5 kg/s of post-fan air for the pre-cooler at each engine).

The operation cost in the nominal ECS is the work spent in compressing the bled air, which is $\dot{W}_{ECS} = \dot{m}_{bleed} c_p \left(T_{bleed} - T_0 \right) = 1 \cdot 1000 \cdot (450\text{-}250) = 200$ kW per pack.

Future ECS

Present ECS design is reliable, but expensive to operate (1 kW/pax). There are also some maintenance problems due to overheating on ground and during ascent/descent (when ram air flow must be forced with a fan, the engine fan or a dedicated one). New designs seem to point to a more distributed and electrically-driven system, but different manufacturers follow different trends:

- AIRBUS. For its new born aircraft the A350 XWB, Airbus decided to keep on implementing an engine bleed air driven ECS but combined with advanced engines, the GE GEnx-1A and the RR Trent 1700.
- BOEING. For its new aircraft, the twin-engine 300 seat B787, Boeing has moved to an all-electric ECS (AE-ECS), eliminating any engine bleed. Cabin pressure is increased to >82 kPa (1800 m cabin-altitude). Additional electrical generators on the engines supply the ECS power (hundreds of kilowatts) to drive dedicated compressors that feed on ram air, and electric heaters for de-icing (electro-thermal heater-mats attached to the aircraft slats). There are two ECS compressors on each pack, which are 0.3 m diameter, run at 40..50 thousands rpm on air bearings, and have a total pressure ratio of $\pi=5$ (on each pack), taking ram air (at cruise, from 20 kPa to 100 kPa), and delivering it at 90 ºC instead of the 180 ºC in conventional bleed-air ECS. This AE-ECS adds some 200 kg on airliners (and some maintenance costs), but saves some 5 % fuel (may be 5000 kg). Higher humidity in the passenger cabin is possible because of the use of composites (which do not corrode). Ozone is removed from outside air; HEPA filters remove bacteria, viruses and fungi; and a gaseous filtration system removes odours, irritants and gaseous contaminants.

AIRCRAFT ENVIRONMENTAL PROTECTION SYSTEM

Protection against external actions: ice, rain, high temperatures, and cold temperatures, must be adequately provided. Protection against very low temperatures in aircraft is needed to avoid ice formation, and to avoid freezing of internal liquids (from fuel to sanitary water). Protection against unwanted organism invasion (micro-organisms, insects, rodents, and reptiles, treated under ECS, may be considered EPS too.

Against ice formation

Ice formation may occur:
- On ground, by precipitation of ice particles on upper surfaces. Aircraft take-off is forbidden with ice or snow on wings and controls. They are cleaned by ground means (using propylene glycol).

Icing may cause severe damage also to grid power lines, wind turbines and ship masts and ropes (the oldest problem).

- On flight through clouds (mainly cumuliform), by ice particles and supercooled droplets striking onto frontal surfaces. The worst case is subcooled liquid drops (in metastable state, favoured by the absence of nucleation sites). <u>Warning</u>; we use supercooled and subcooled as synonyms, whereas other authors use subcooled as synonym of unsaturated liquid above its freezing point.

Icing problems in aviation

Falling pellets of ice (hail falling from cumulonimbus clouds with very strong rising air currents) can damage anything, including aircraft and engines. Heavy snow can cause severe icing depending on its temperature and state. Heavy rain may impede visibility and soak critical parts. But flying inside clouds with supercooled liquid droplets (SLD) is most feared because of the degradation it causes on aircraft flight dynamics.

When flying through subcolled droplet clouds, ice chunks a few centimetres thick may form when flying through a 50 km span cloud (some millimetres per minute; it grows linearly with distance and with subcooled water content). An ice thickness around 1 mm near the leading edge of wings and rotors may decrease lift up to 30 %, particularly at large angles of attack, greatly changing the point at which aerodynamic stall takes place (it may decrease the stall angle of attack by 6º). The lift loss is most critical during the descent and approach phases, where speed is reduced and angle of attack is large. The worst occurs when the stall leaves without lift some control surfaces, an a widely unstable flight dynamics develop (e.g. American Eagle Flight 4184 in 1994, or Colgan Air flight 3407 in 2009)

Icing is one of the most dangerous weather conditions for general aviation (icing is involved in nearly 10 % of all aircraft accidents). All aircraft must be able to heat up leading edges (by bleeding hot air, or electrically), or de-ice by other means (ancient rubber bands, or modern electromagnetic striction pulses).

<u>Requirements</u>: airliners must fly in all-weather conditions, thence ice protection is needed on:
- Structure
    - Wings, flaps, tail, and mechanisms (e.g. ram air inlets and outflow valves). In the case of a multi-element wing airfoil, the anti-icing hot air is used to remove ice from the first element, i.e. at the slat only, not on the main body or the flap.
    - Windscreens. They are laminated compounds made of (from outside-inside): a thin tempered glass layer, a transparent heater film of SnO_2 (or fine-wire mesh), a vinyl layer (hot bonded), a structural glass layer, a vinyl layer, and a glass layer; some 30..40 mm thick in total (it must resist the 100 kPa cabin overpressure and the impact of a 2 kg bird at high speed). They incorporate temperature sensors (termistors), and is an expensive item. Windscreens wipers must be often cleaned and never operated dry, to avoid scratches on the outer glass surface.
    - Sensors (pitot and static probes, antenna).
    - Water discharge (sanitary, condensates).

- Engines
  - Nose cowling (the streamlined metal covering fitted around an aircraft engine). Ice particles usually melt on compressor heated air, but sometimes the water freezes again on metal surfaces, and accumulated ice can either break into chunks that damage turbine blades, or melt and douse the ignition system. There have been up to 14 reported cases of in-flight dual-engine flame extinction (all of them were fortunately quickly re-ignited) attributed to ice ingestion (plus many single-engine cases). Although torrential rain and hail were known to shut down engines, icing was not considered a big problem before year 2000.
  - Fan or guide blades. Besides, tiny ice crystals (undetected by pilots and weather radars) may be sucked in great amounts inside jet engines and become a hazard on high-altitude storms because they can coalesce after melting and arrive in liquid form to combustion chambers and douse the flame.
  - Propellers, if any (and old carburettors).

In brief, icing decreases lift, adds resistance, decreases thrust, unbalances rotors, blocks eyesight, sensors, and actuators, and adds weight.

Solution: stages in solving the problem (of icing):
- Detection and warning of risk.
- Action (available tools and procedures) to avoid or repel damage.
- Analysis to solve (predict and avoid, or minimise unwanted effects of) future problems.

Ice detection
- Visual ice detector. Pilot visual clues of ice formation:
  1. Light icing: ice under the windscreen wiper blades. Ice accretion may create a problem if flight is prolonged in this environment over 1 h.
  2. Moderate icing: ice on the wiper nut.
  3. Severe icing: ice on the central windscreen pillar (Fig. 11).

Fig. 11. Severe icing on the central windscreen pillar of an aircraft, formed in under a minute flying at 6 km altitude (FL200).

- Optical ice detector. Based on a protruding acrylic-glass cylinder (the same material used for aircraft windshields). The device works as a combined optical spectrometer and optical switch. A change in opacity registers as rime ice. A change in refractive index registers as clear ice. Ice

thickness down to 0.01 mm can be detected. An internal heater may be added to force the clean-up. The wavelength of the transducer's excitation light is not visible to the human eye so as not to be mistaken for any kind of navigational running light.

- Electrical ice detector. Based on magneto-strictive resonance change in a magnetic cylinder (6 mm diameter and 25 mm long), which is axially vibrated with an oscillating magnetic field, and the extra ice mass lowers its resonant frequency. When $\Delta f > 150$ Hz ($\delta_{ice} > 0.5$ mm), an internal heater melts the ice and a counter is updated; after two heating cycles, the engine-anti-ice system is switched on; after 10 cycles, the wings anti-ice system too).
- Other kind of detectors (acoustic, nuclear) have been tried too.

Anti-icing (prevention) and de-icing (fight) systems:
- Thermal (by hot air). Hot air is bled off the jet engine into tubes routed through wings, tail surfaces, and engine inlets (the hot air is expelled through holes in the piping, and finally vented outside). Ice must be completely vaporised because if it is just molten, the run-off water may freeze downwards; on large airliners it may take up some 100 kW of air bleed. On modern high-bypass airliners, primary air is scarce, and they are being designed to tolerate some icing in non-critical areas (e.g. wing tips and roots). On small aircraft, engine-exhaust heat recovery systems are used.
- Electro-thermal (quasi-steady, or short-pulse). Unlike conventional windshield defrosters that rely on gradual warming to liquefy snow and ice, there are new devices that deliver a pulse (~1 s) of high-power electricity that immediately melts the ice at its interface with an object's surface, and the flow sweeps it away. This system demands less energy (some 20 MW/m^2 during a few seconds instead of some 500 W/m^2 during many minutes) because heat is not wasted warming up the object and the ice.
- Mechanical (inflatable rubber boots). These systems require less engine bleed air but are usually less effective than a heated surface. They must be inflated in small lengths at a time, to avoid large aerodynamic disturbances.
- Chemical (application of a deicing fluid through small holes in leading edges (weeping wing system).
- Electromagnetic (microwaves through composite walls).

Icing tests

Airliners must be able to safely fly through subcooled clouds under the following foreseen extremes (Table 2):
- Continuous regime. Clouds up to 40 km long at any altitude up to 6 km, with subcooled drops characteristics in the envelop shown in Fig. 12a.
- Intermittent regime. In addition to the above continuous regime, the aircraft must cope with smaller but denser clouds: up to 5 km long, with subcooled drops characteristics in the envelop shown in Fig. 12b.
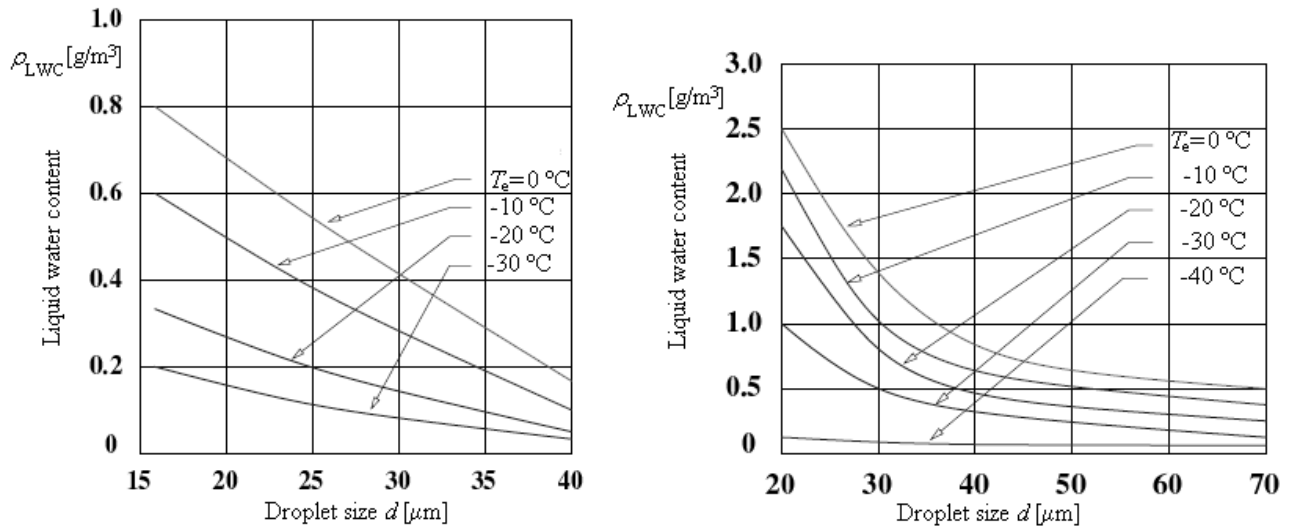
Fig. 12. Fly worthiness on subcooled clouds: a) continuous regime, b) intermittent regime.

Table 2. Conditions likely to be encountered in service operation in icing conditions.

Altitude range [km]	Atmospheric temperature [°C]	Maximum water content [g/m³]	Maximum cloud extent [km]
3..9	0..–20	5	5
		2	100
		1	500
5..12	–20..–40	5	5
		2	20
		1	100
		0.5	500

The main method used by aircraft manufacturers to certify their aircraft is to test a model of the aircraft in simulated icing conditions using an icing tunnel. Another method is to perform a tanker test, where a tanker aircraft sprays water droplets onto a following aircraft, at freezing altitudes. Since both of these tests are expensive and time consuming, computational methods are gaining in popularity.

An icing wind tunnel is a classical closed-loop subsonic wind tunnel, with an air cooler (a refrigeration heat exchanger to deliver air at –20..0 ºC). To initiate icing, a droplet sprayer array injects chilled water (>0 ºC) upstream of the test section to create the amount of water and drop-size desired. NASA's Icing Research Program uses an Icing Research Tunnel (IRT) of 2·3 m² test-section, two Icing Research Aircraft (IRA), and computer codes to predict ice growth.

Those parts of the airframe where the accretion of ice under the conditions of Appendix C is likely to have an adverse effect on the airworthiness of the aeroplane, should be tested for a period of 30 minutes duration at each of the conditions specified in Table 3. The encounters considered with Intermittent Maximum concentrations should include three clouds of 5 km horizontal extent, separated by spaces of clear air of 5 km. At the end of the tests the total ice accretion should be such as not to adversely affect the safety of the aeroplane.

Table 3. Test to be performed on critical airframe parts for icing resistant certification.

Atmospheric temperature [°C]	Continuous maximum liquid water content [g/m³]	Intermittent maximum liquid water content [g/m³]	Mean effective drop diameter (μm)
0	0.8	2.5	20
−10	0.6	2.2	20
−20	0.3	1.7	20
−30	0.2	1.0	20

Ice accretion modelling

The first formulation was by B.L. Messinger in 1953 ("Equilibrium temperature of an unheated icing surface as a function of airspeed", J. Aeronaut. Sci., 29–42), who established the energy balance on icing. Subsequent enhancements have included the addition of an energy source at the substrate for deicing, and a temperature rise due to compressible flow.

Icing models are based on mass and energy balance equations for a heterogeneous flow of air with subcooled liquid droplets, against the aircraft surface: wing, engine cowling, etc. There are several stages in modelling the problem:

1. Specifying the configuration (meteorological and aerodynamic)
2. Computing droplet impacts, for catching rate determination.
3. Solving the energy balance, for freezing fraction determination.
4. Ice accretion rate determination in case of no deicing action.
5. Effect of deicing means.

The factors controlling ice formation and accretion rate are:

- Meteorological: liquid water content, ρ_{LWC} (LWC stands for liquid water content, in the range 0.2..2 g/m³), droplet size, d (in the range 5..50 μm, related to LWC and upward air motion), environmental temperature, T_∞ (in the range −35..0 °C), and longitudinal extent of these conditions (cloud size along trajectory, in the range 5..100 km). Environmental pressure, p_∞ (in the range 45..95 kPa) has a minor influence. Satellite images in the 3.9 μm band are being used to investigate potential icing conditions.
- Aerodynamic: geometry (e.g. airfoil shape and angle of attack), and flight speed (which determines the residence time on clouds, and droplet drift through the flow field). For subsonic aircraft, the flow field at the leading edge can be approximated by the flow field around the front side of a circular cylinder with the same radius of curvature, but for transonic wings this leading-edge equivalent cylinder is so small that most icing takes place downwards in the airfoil. In the former case, the potential air flow velocity in body-fixed axes is:

$$u(x,y) = U_\infty \left(1 - R^2 \frac{x^2 - y^2}{\left(x^2 + y^2\right)^2} + \frac{\Gamma}{2\pi} \frac{y}{\left(x^2 + y^2\right)} \right)$$

$$v(x,y) = U_\infty \left(R^2 \frac{-2xy}{\left(x^2 + y^2\right)^2} - \frac{\Gamma}{2\pi} \frac{x}{\left(x^2 + y^2\right)} \right)$$

where U_∞ is the free stream velocity (i.e. flight speed), R the cylinder radius, and G the circulation that places the stagnation point at the corresponding point in the leading edge of the wing.

Catching factor

If a uniform distribution of droplets in the cloud is assumed with a density ρ_{LWC}, the undisturbed incoming water flux is $j_{w,\infty}=\rho_{LWC}U_\infty$ (normal flux, [(kg/s)/m²]), and we want to find the impacting water flux (per body surface area), $j_{w,p}$ (the 'p' refers to a panel at the wall, and the 'w' to water), which is solved by analysing droplet trajectories.

Droplet trajectories and impact locations are calculated by integrating the momentum equation for each individual droplet, accounting for air drag (air-to-droplet relative speed is 0 initially and close to U_∞ on impact). Droplets are assumed spherical up to the impact, without gravity, and without influencing the air flow field (the potential flow solution $[u(x,y),v(x,y)]$ as given above is good enough, since the residence time in the boundary-layer flow is minimal). Namely:

$$\left.\begin{array}{l} m\ddot{x}_d = -\dfrac{1}{2}\rho v_r^2 c_d \dfrac{\pi d^2}{4}\cos\gamma \\[4mm] m\ddot{y}_d = -\dfrac{1}{2}\rho v_r^2 c_d \dfrac{\pi d^2}{4}\sin\gamma \end{array}\right\} \text{ with } \gamma = \arctan\dfrac{\dot{y}_d-v}{\dot{x}_d-u}, \text{ and } v_r = \sqrt{(\dot{x}_d-u)^2+(\dot{y}_d-v)^2}$$

where $v_r(x,y)$ is the relative drop-to-air velocity at each point, related to droplet velocity $[\dot{x}_d(x,y),\dot{y}_d(x,y)]$, and the free air stream velocity $[u(x,y),v(x,y)]$.

The output of this trajectory analysis yields the upstream region of droplets impacting on the solid, and the spatial distribution of impacts, what is evaluated by a catch factor β such that $j_{w,p}=\beta j_{w,\infty}$ (β can be viewed as the ratio dy/ds, i.e. for a small stream-tube of droplets, the quotient between their undisturbed cross-section, dy, and their striking area at the body surface, ds, Fig. 13).
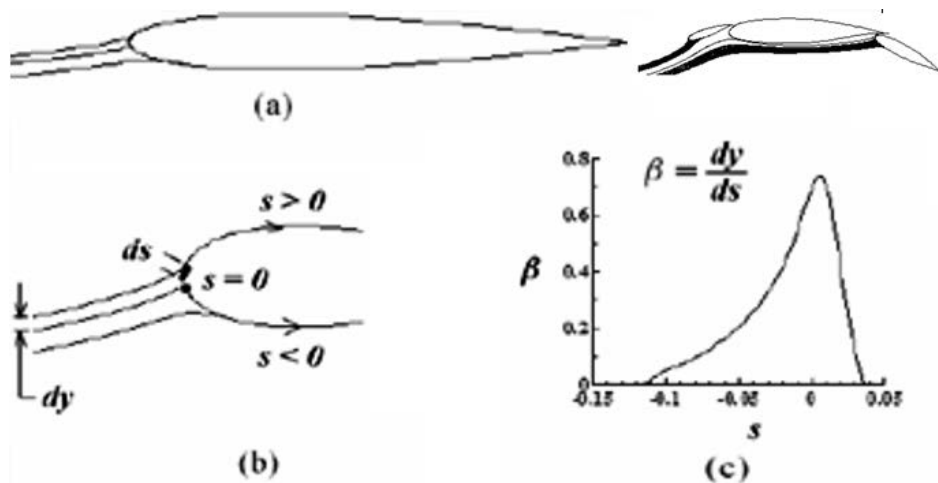

Fig. 13. Impact of water droplets on the leading edge of an airfoil. a) Simple airfoil, and compound airfoil (with slat and flap). b) Close-up view and nomenclature. c) A typical impingement efficiency distribution (catching factor).

Type of ice formed

- Rime ice. Frost formed by the freezing of highly-supercooled small water-droplets onto cold solid objects ($T_\infty < -15\,°\text{C}$, above 4..5 km altitude) is called rime, an opaque white form of ice (with entrapped air) with lower density than glass transparent ice (some 880 kg/m^3 instead of 917 kg/m^3). Light or moderate icing occurs in clouds of type Ac, As, St, or fog, and moderate to severe rime in Ns and Cb. Splashing (droplet bouncing on impact) is never considered, but partial droplet sticking must be considered for large droplets that do not fully freeze, and the remaining liquid part runs away in a liquid layer over the ice layer formed.
- Glaze ice. Under milder conditions ($-10..-5\,°\text{C}$, in strong convective clouds at lower altitudes with larger subcooled drops), glaze ice forms (a transparent wet glossy ice layer under a liquid water layer). In this case only a fraction of the droplet will freeze instantaneously, the rest of the droplet can remain liquid for some time and may flow as runback water. Large drops can only occur in atmospheric upward vertical motion, to compensate terminal velocity (3 mm/s at 10 μm, 70 mm/s at 50 μm; Stokes' law applies up to $d < 50$ μm).

The ice shape formed on leading edges is highly irregular, three-dimensional, and bulky (not a smooth layer).

Thermodynamic analysis. Freezing fraction

Under very cold conditions, all water freezes and dry rime ice forms; the problem reduces then to solving a simple mass balance for ice accretion. In milder conditions, part of the water freezes, forming glaze ice, and the rest runs off along the surface, and now the problem is governed by coupled mass and energy balances, which determine the ice height and water layer thickness. We intend here to model all possible cases, but we neglect the effect of the thickness of the liquid water film formed, if any.

The energy equation determines the droplet temperature after impact, discriminating between droplets that remain liquid and are swept away with the flow, fully solidified droplets that stick to the surface and modify its geometry, or the fraction of droplet mass that freezes (the rest runs away and spreads along the surface). The quasi-steady energy balance at the air-water interface over the solid is:

$$\dot{H}_{w,in} + \dot{Q}_{p,in} = f\dot{H}_{ice,out} + (1-f)\dot{H}_{w,out} + \dot{Q}_{p,out} \tag{1}$$

where $\dot{H}_{w,in}$ is the total enthalpy of the water flow incoming (mind that there is no air flow through the interface), $\dot{Q}_{p,in}$ is the heat flow coming from the panel ('p' is used instead of 'wall' to avoid confusion with 'water', and because numeric aerodynamic simulation is based on the panel method); f is the fraction of water mass frozen, $\dot{H}_{ice,out}$ and $\dot{H}_{w,out}$ are the total enthalpies of ice and liquid water exiting the interface, and $\dot{Q}_{p,out}$ the heat flow lost from the panel to the environment. Notice that a possible evaporation term on the right hand side of (1) has been neglected, in spite of the expected temperature increase.

In more detail, taking the enthalpy origin $H=0$ for liquid water at 0 ºC, and working per unit surface area, dA,

$$j_w\left(c_w\theta_\infty + \frac{U_\infty^2}{2}\right) + \dot{q}_{p,in} = fj_w\left(c_{ice}\theta_p - h_{SL}\right) + (1-f)\,j_w c_w\theta_p + h\left(\theta_p - \theta_\infty - \frac{U_\infty^2}{2c_{p,air}}\right) \qquad (2)$$

where $j_w=\beta j_{w,\infty}$ is the flux of water through dA (the $j_{w,p}$ calculated above), c_w, c_{ice} and $c_{p,air}$ are the water, ice and air thermal capacities, θ_∞ and θ_p the undisturbed temperature and panel temperature (both in degrees Celsius, since we put the enthalpy origin at 0 ºC), h_{SL} the enthalpy of fusion, and h the heat convection coefficient. Notice that a single temperature has been assumed for both the frozen fraction and the liquid remaining, if any.

For a numerical estimation of (2), we start neglecting the heat flux coming from the panel, $\dot{q}_{p,in}=0$ (i.e. adiabatic wall), and assuming that the water temperature after impact is 0 ºC for both the ice formed and the possible run-off liquid; the aim of this exercise is to find the amount of water frozen (i.e. the ice fraction, f). Consider an aircraft flying at some U_∞=150 m/s (M=0.4..0.5, during ascent or descent), through a cloud with liquid water content ρ_{LWC}=0.5 g/m^3 (typical of continuous icing regime, Fig. 10a); the undisturbed water flux is $j_{w,\infty}=\rho_{LWC}U_\infty$=0.5·10^{-3}·150=0.075 (kg/s)/m^2. Consider a leading-edge characteristic length of D=0.2 m (which yields a Reynolds number, $Re_D=U_\infty D/\nu$=150·0.2/(15·10^{-6}=2·10^{-6}), and let assume the catching factor is β=1 to have $j_w=\beta j_{w,\infty}$=0.075 (kg/s)/m^2 in (2), with c_w=4200 J/(kg·K), c_{ice}=2000 J/(kg·K), $c_{p,air}$=1000 J/(kg·K), h_{SL}=334·10^3 J/kg, and h=300 W/(m^2·K), obtained from the high-speed forced-convection correlation:

$$Nu_D = 0.3 + \frac{0.62 Re_D^{1/2} Pr^{1/3}}{\left[1+\left(0.4/Pr\right)^{2/3}\right]^{1/4}}\left[1+\left(\frac{Re_D}{282000}\right)^{5/8}\right]^{4/5} \qquad (3)$$

good for 10^2<Re_D<10^7 and $Re_D Pr$>0.2 [Churchill, S.W. & Bernstein, M., 1977]; which, with Pr=0.7 for air, and Re_D=2·10^{-6} yields $Nu_D=hD/k$=2430, and $h=kNu_D/D$=0.025·2430/0.2=303 W/(m^2·K). Solving (2) we get f=−0.0247·T_w−0.17, which is plotted in Fig. 14, showing that, below T_∞=−47 ºC, all water in the droplet freezes on impact, and above T_∞=−7 ºC no ice forms; for ambient temperatures in between, part of the droplet freezes and the rest runs off as a liquid film.
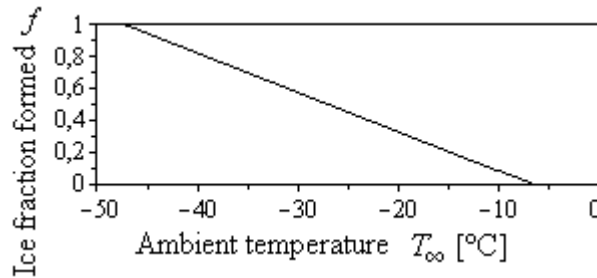

Fig. 14. Fraction of ice formed, f, as a function of droplet temperature (assumed to equal outside air temperature, T_∞). Below T_∞=−47 ºC, all water in the droplet freezes on impact, and above T_∞=−7 ºC no ice forms (water nuns off).

Furthermore, the ice accretion rate would be:

$$\frac{\mathrm{d}z}{\mathrm{d}t} = \frac{fj_\mathrm{w}}{\rho_{ice}} \tag{4}$$

which in our numeric example, in the worst case of $f=1$ (all incoming water freezes), becomes $\mathrm{d}z/\mathrm{d}t=(0.075$ (kg/s)/m^2) / (900 kg/m^3)=0.083 mm/s=5.0 mm/min=30 cm/h, or in other words an ice layer 55 mm thick after a 100 km flight on these conditions (at 150 m/s). This exercise has been an upper-bound analysis (the catching factor is always $\beta<1$), and the ice fraction is usually on the lower range too ($f<1$), but it is not uncommon that icing becomes dangerous in a few minutes of flight in some subcooled clouds.

The heat power needed to vaporize the ice being deposited, in the worst case just mentioned ($f=1$), is:

$$\dot{q}_\mathrm{p,in} = j_\mathrm{w} h_\mathrm{SV} \tag{5}$$

which, in our numeric example becomes $\dot{q}_\mathrm{p,in} =0.075\cdot2.83\cdot10^6=0.21\cdot10^6$ W/m^2. If a strip 0.1 m wide and 10 m long is to be heated with that flux (only part of the wing span is deiced), the total heat flow needed is 210 kW, which, as an upper bound found in this example, is of the correct order of magnitude for the bleed air system used in airliners.

Nowadays, detailed numerical codes are used to find the air flow around the wing, the distribution of the catching factor, and the fraction of droplet mass frozen. Finally, from the solid accretion rate found and ice density jump, the solid deposition may be accumulated into subsequent integration steps, and the transient ice layer growth incorporated to the air flow field around the wing, until wing stall takes place in the simulation (see Fig. 15 for a comparison of numerical simulation with wind tunnel data).
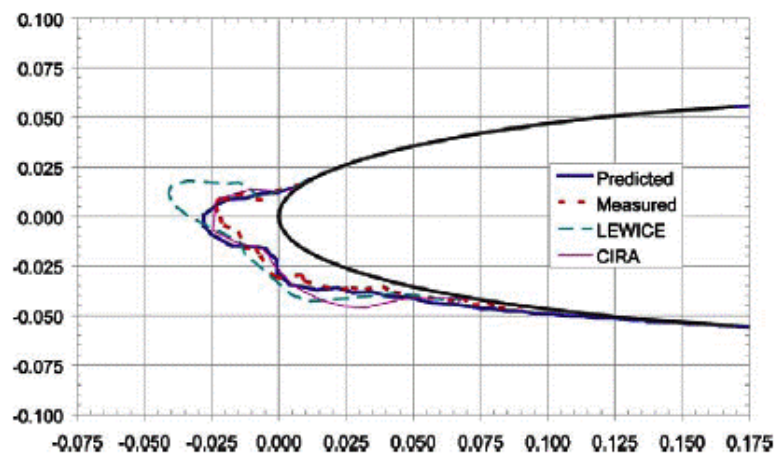

Fig. 15. Icing predictions on a NACA 0012 airfoil at $T_\infty=-10$ °C (horizontal and vertical scales in fractions of the cord) [3].

Against rain

Rain rates are classified by measuring the precipitation collected in one hour interval (Table 4).

Table 4. Rain classification [mm/h].

Very light	<0.5
Light	0.5..2
Moderate	2..15
Heavy	15..30 (d>1 mm)
Very heavy	30..60
Extreme[*]	>60 (d>2 mm, v>5 m/s)

[*]The record is 700 mm/h during 10 s (NASA-1990).

Torrential rain (>15 mm/h, d~1.5 mm, v~5 m/s) prevents visibility, and may shut down an engine by flameout. The same malfunction may occur at take-off by water in the runway being thrown up by the wheels. In all this cases it is convenient to turn the engine igniters on (in some engines this action is automated). The few cases where flameout has taken place in all engines at a time happen to be near landing, when the engines were throttled back.

The windscreen wiper must allow reasonable visibility with rain of 40 mm/h, d~2.5 mm, v~8 m/s. An additional anti-rain system is an external hot-air curtain (bleed air).

Against dust

More dangerous to engines than water precipitation is the effect of clouds of dust or ash created by volcanic eruptions like Mount St. Helens in 1980 and 2006, or Eyjafjallajökull eruption in 2010, where most of Europe airspace was closed for nearly a week, the largest air-traffic shut-down since World War II, causing 10 million passengers to be stranded not only in Europe, but across the world, with over 100 000 flights cancelled and €1300 million losses in the aviation industry.

Against high temperature

Usually due to aerodynamic heating. Total temperature of a (perfect gas) gas flow, $T_t=T+v^2/(2c_p)=T(1+(\gamma-1)M^2/2)$. This total value is attained in stagnation points, and even when decelerated by friction in the boundary layer in the adiabatic-wall case, where some 85 % of the dynamic temperature is recovered at the wall (the recovery factor is $r=\sqrt{Pr}$).

To compute heat transfer flow by convection from a high-speed vehicle to/from the external fluid (i.e. in compressible flows), it is this adiabatic wall temperature:

$$T_{aw} = T_\infty \left(1 + r \frac{\gamma-1}{2} M_\infty^2 \right), \quad r = \sqrt{Pr}$$

which must be used in $\dot{Q} = hA\left(T_{wall} - T_{ref}\right)$ as reference temperature, T_{ref} (recall that it was simply the temperature at the far field for external flows, $T_{ref}=T_\infty$, and the fluid bulk mean temperature for internal flows, $T_{ref}=T_{bulk}$).

- Airliners flying at $M \equiv v/c$=0.85 at 10 km altitude (T=−50 ºC, $c=\sqrt{\gamma RT}$=300 m/s, v=250 m/s) suffer a dynamic temperature jump $\Delta T_{dyn}=v^2/(2c_p)$=32 ºC.

- The Concorde flying at $M=2$ at 17 km altitude ($T=-57$ °C, $c = \sqrt{\gamma R T} =295$ m/s, $v=590$ m/s) suffer a dynamic temperature jump $\Delta T_{dyn}=174$ °C.
- Spacecraft during re-entry are exposed to very hot dissociated ionised air that may reach 10 000 K at the frontal shock wave layer (the rule-of-thumb is to assume the maximum air temperature in kelvin to be equal to the entry speed in meters per second); the outer skin must withstand up to 2000 K at their nose and other stagnation points, either by suitable refractory materials, or most often by ablation.

SUPERSONIC AIRCRAFT

Concorde (1976-2003) has been the only successful commercial supersonic aircraft (the only other one, Tu-144, was cancelled after less than a year in commercial use); it flew at $M=2$ ($v=Mc=2\cdot295=590$ m/s) for 2 h, at 17 km altitude. The other type of supersonic aircraft is the combat aircraft, which may keep supersonic speed only for tens of minutes.

Concorde had unique environmental control and protection needs. To begin with, in spite of the nearly -60 °C outside air temperature at 17 km, the aircraft had to be permanently cooled to keep a cabin temperature of some 20 °C, because the dynamic heating is $\Delta T=v^2(2c_p)=590^2/(2\cdot1000)=174$ °C (measured nose tip temperature reached 400 K, and windows in the cockpit were too hot to touch). However, on ground and during ascent (subsonic) heating was required on winter.

If the outside air was at >100 °C close to the aircraft, how to cool the cabin? Thermodynamics teaches that one may cool a system in a hot environment, by using a refrigerator, but the solution adopted for Concorde was to take advantage of the large thermal inertia of the fuel carried onboard (96 000 kg out of the 187 000 kg at take-off), to use the fuel as the heat sink during the flight for the environmental control system (cabin air, avionics, hydraulics…). At cruise, conditioned air entered the cabin at -25 °C.

Concorde went through two cycles of heating and cooling during a flight, first cooling down as it gained altitude, then heating up after going supersonic. The reverse happened when descending and slowing down.

Designers wanted to keep to aluminium for the aircraft main structure, and, because highest sustained working temperature for aluminium is about 400 K, which limited the top speed to the nominal maximum, Mach 2.02.

The use of aluminium and the supersonic heating caused the 62 m long fuselage to extend some $\Delta L=L\alpha\Delta T=60\cdot20\cdot10^{-6}\cdot200=0.25$ m, the most obvious manifestation of this being a gap that opened up on the flight deck between the flight engineer's console and the bulkhead. It is said that on all Concordes that had a supersonic retirement flight, the flight engineers placed their hats in this gap before it cooled, where the hats remain to this day.

Cabin pressurization was a big concern, and the fuselage had to be narrow (and windows very small) to withstand 82 kPa inside (1800 m cabin pressure altitude) with 10 kPa outside. Sudden cabin depressurization was lethal, so that a compressed air reserve, and a rapid descent manoeuvre was designed to reach a safe flight level before loosing too much pressure (window holes were small).

Ozone had to be reduced from ambient 6 ppm at 18 km altitude to <0.2 ppm, using a Ni-catalyser in the heat-exchangers (working at 580 ºC).

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