Environmental Control Systems

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Summary
At cruise altitudes between 36,000 and 43,000 feet, conditions of very low temperature and pressure , elevated ozone concentrations and the lack of humidity constitute a hostile environment to human beings. In order to create a life-supporting atmosphere inside the aircraft, environmental control systems provide appropriate regulation of pressure, temperature and air exchange in the cabin. As aircraft cabins become increasingly part of the normal habitat for humans in addition to these basic life sustaining conditions, pax & crew expectations for the cabin environment are increasing, leading to additional challenges for environmental control systems.

Introduction
The Environmental Control System (ECS) has to provide an artificial climate in the aircraft cabin. Air from the outside has to be pressurized and temperature controlled. Relatively small cabin volumes and high heat loads result in comparatively high air exchange rates, which could lead to high air velocities. These factors confront the designer of the air distribution system with extraordinary challenges. A multitude of sometimes conflicting requirements drives the system design process. Besides safety and maintainability requirements for reliable operation, main design drivers are performance requirements to meet health and comfort criteria and optimisation of the technical realisation. Certification requirements established by regulatory authorities such as FAA and EASA have to be followed and additional guidelines and industry standards established by other organisations like WHO, SAE, ASHREA, VDI, ISO or CEN provide the framework and the basis for an aircraft manufacturer to set the benchmark in ECS design. This paper explains the state of the art architecture of Environmental Control Systems and main design drivers are addressed.

State of the Art
During flight outside air is taken from the compressor stage of the engines ("bleed air") passing a pre-cooler unit and entering the "air conditioning pack" with a temperature of approximately 200°C. The air conditioning pack cools the air to the required temperature using outside air ("ram air") as the cooling medium and air cycle machines for compression cooling. In principle this represents a two-stage compression process with subsequent cooling after each compression and finally the expansion cooling of the supplied outside air which enters the pressurized fuselage passing a check valve in the pressure bulkhead. The energy for the second compression stage is recovered by expansion of the air via the air cycle machine turbine. This basic architecture is still the best proven technology for aircraft airconditioning systems with regards to efficiency, flexibility, reliability, installation space, and maintenance costs. Sophisticated design solutions comprise a second turbine to better adjust conditions for water separation, which is indispensible during operation in humid environments, and overall pack performance.

A mixer unit, installed below the cabin floor in front of the centre wing box, mixes outside air with cabin air. The cabin air, which has entered the underfloor area, is drawn through recirculation filters by recirculation fans. The recirculation fans blow the air through check valves to the mixer unit. The quantity of recirculated cabin air mixed with outside air varies from 40% to 60% in normal operating conditions and improves efficient removal of heat loads at a moderate temperature gradient between incoming and outgoing air. As outside air itself is extremely dry, an additional benefit of the recirculation approach is the increase in humidity by making use of the more humid cabin air. An innovative airflow management system was introduced with the A340-600/-500, which regulates outside airflow, for the first time allowing for the layout and the actual load factor of the aircraft. This also contributes to reduced fuel burn and improved cabin comfort as a result of higher humidity levels even at low load factor. This airflow management system has become standard on new aircraft developments at Airbus since the introduction of A340-600/-500.

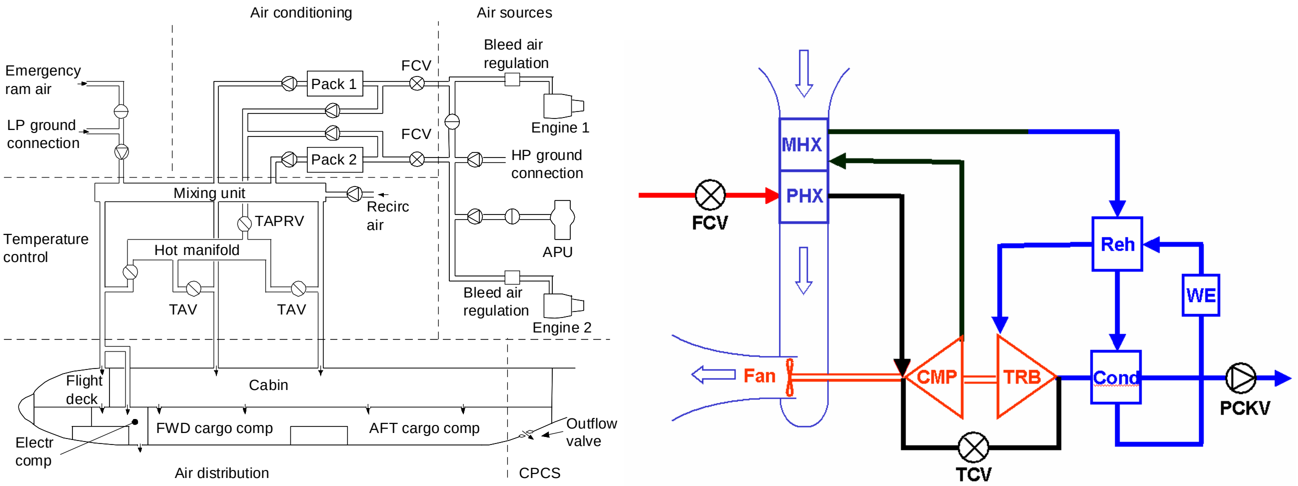

Figure 1 – simplified ECS and pack architecture scheme

After leaving the mixer unit the air is distributed to different cabin zones. For each cabin zone a different temperature can be selected. Trim air valves regulate the cabin outlet temperature by injecting small amounts of hot bleed air from the pre-cooler outlet (“trim air”).
The conditioned air enters the cabin through outlets on both cabin sides at ceiling level leading the flow from upper parts of the cabin downwards. The outlet definition and positioning is crucial to ensure good ventilation to the seat area as well as to persons standing or working in the aisle.
The cabin pressure control system regulates the cabin pressure by two outflow valves continuously releasing excess air. Since the maximum pressure difference between cabin and environment is important for the structural integrity of the aircraft, failure to prevent excessive pressure difference would be hazardous. Therefore this function is of highest priority for the cabin pressure control system and additional mechanical valves provide a backup to prevent excess differential pressures from inside (positive) or outside (negative).

In order to determine the required cooling performance of the aircraft air conditioning system, heat loads have to be balanced with the airflow requirements, which is also a statutory airworthiness requirement, in the most challenging operating conditions. Such conditions can be constant (e.g. hold case at low flight level on a hot and humid day) or transient (e.g. pull down and pull up cases at hot and cold days respectively). Main influencing factors are heat loads contributed by passengers and electrical devices, but also solar radiation, outside temperature (with alternating impact) and optional systems to increase cabin comfort or operating revenue such as galley cooling systems or cargo temperature control. Additional driving factors are hot and humid environmental conditions on the ground or at low flight level. As the temperature supplied by air conditioning packs under such humidity is substantially lower than the dew point temperature of the incoming air, a considerable cooling performance is needed for water condensation and removal.
Considering the above factors and challenges, it might be assumed that environmental control systems are the most energy demanding systems besides the propulsion of the aircraft itself. Today’s aircraft needs 2-4% of the total fuel consumption for supply and conditioning of outside air. An efficient and reliable environmental control system hence reduces the operational costs for an aircraft significantly.

Design drivers

The prime function of environmental control systems is the provision of a life-sustaining environment. Consequently, besides the oxygen supply, the basic factors that have to be controlled are pressure, temperature, and appropriate atmospheric composition.

Pressure: The human body needs oxygen to produce energy in the mitochondria of the tissue cells by oxidation of carbohydrates in order to maintain vital function. To promote this energy production process, oxygen has to be supplied to the tissue and the produced carbon dioxide has to be removed. With increasing altitude and decreasing pressure, even though the oxygen concentration of the air is nearly constant, its partial pressure will fall leading to reduced blood oxygen saturation. Whilst the partial pressure of oxygen is linearly dependent on total pressure, the saturation of blood with oxygen is not and there is only a moderate decrease in oxygen saturation of haemoglobin up to an altitude of 10,000 feet [1, 2]. There can be individual variation in oxygen saturation, which may be exacerbated by medical conditions. Advisory guidelines exist to identify medical preconditions, for which supplemental oxygen is advisable [3, 4, 5]. Even though there are no US and European statutory requirements to operate an aircraft below a pressure equivalent to an altitude of 8,000 feet, there are certification requirements that aircraft must be able to maintain this pressure at maximum operating altitude under normal operating conditions [6, 7]. There are on-going discussions and investigations within the whole aircraft industry to determine if lowering maximum cabin altitude could be of benefit, especially for passengers with adverse medical conditions. A position paper of the Aerospace Medical Association concludes that for the time being there is insufficient evidence to recommend a change in current rules and practices in this regard limiting the overall aircraft design [8]. Further research is recommended, although results from the European ICE study have not shown any detrimental effects even in those passengers with cardiopulmonary disease up to cabin altitudes of 8000 ft. In the same study the lower pressure environment was not associated with any discomfort. It is a matter of fact that cabin altitude in Airbus Long Range aircraft varies with flight level and is maintained substantially below the certification limit for all flight levels, and below 7000 feet for most parts of any flight. Even at the highest cruise altitude, which may be reached at the end of the flight, cabin altitude is still well below the 8,000 feet limit. Figure 2 shows a typical flight schedule for a north-Atlantic route, with only 13% of the flight time the cabin being at a pressure altitude of 6500 ft, and more than 85% being at or below 6000 ft.

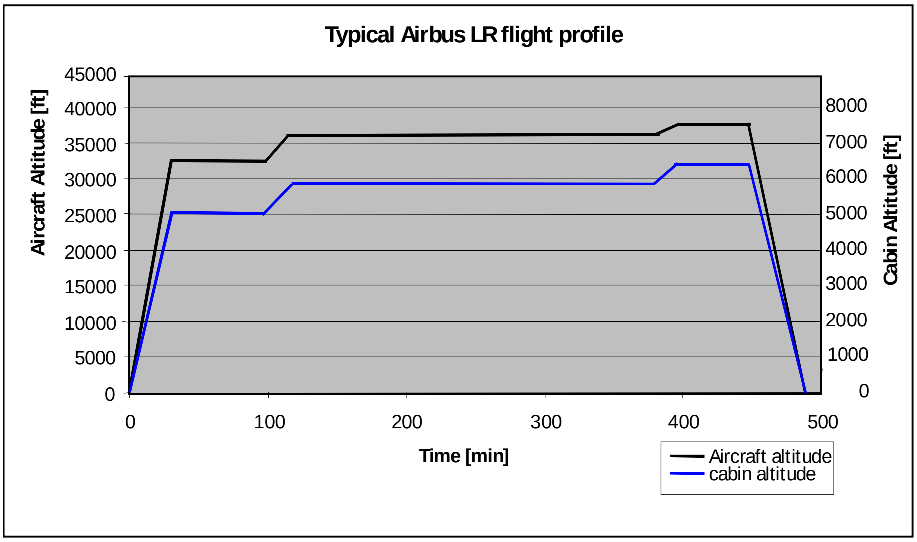

Figure 2 – Typical Long Haul Flight Profile

With the A330/340 family, Airbus was the first manufacturer to introduce a reduction in cabin altitude for the entire flight envelope setting the maximum cabin altitude well below the regulatory maximum. The aircraft manufacturer has to balance the investment of technical progress improving passenger and crew comfort and simultaneously promote efficient overall aircraft design. As a process of continuous improvement, Airbus followed this approach with the introduction of the A380, which offers lower pressure altitude levels than A330/340 at currently unbeaten aircraft efficiency. The new A350XWB will be the next milestone to follow this philosophy with again a reduced cabin altitude and further improved efficiency.

An additional comfort aspect when considering pressure is the rate of pressure change. Occupants may be aware of air exchange between the cabin environment and body cavities. The eardrum is particularly sensitive to pressure changes. Such effects are exacerbated if, for instance, the Eustachian tube or sinus cavities are blocked or cavities in the teeth are present. The cabin pressure rate of change is therefore limited for physiological reasons. The cabin altitude should not increase at more than 500 ft/min (sea level equivalent) and as the pressure equalisation in the ear is more difficult during descent (pressurisation of the cabin), the cabin altitude should not decrease at more than 300 ft/min (sea level equivalent) [9]. These gradients are appropriate for healthy people. Occupants with impaired health, such as ear problems or an upper respiratory tract infection, might experience problems, but may alleviate symptoms by using decongestants. Due to the safety relevance of differential pressure on the structural integrity of the aircraft, the pressure rate of change of course depends on the altitude schedule of the aircraft. However, during normal flight schedules modern Airbus aircraft keep the pressure rate of change well below the above-mentioned limits.

Temperature control and thermal comfort: There are few requirements for temperature control established by regulatory authorities [10], which are aimed at safe operation of the aircraft rather than creating a comfortable environment. These requirements cover limited exposure times between 90 to 10 minutes for temperatures from 35°C to 60°C respectively and would not be acceptable from a comfort point of view. In terms of comfort, design targets for an acceptable cabin temperature, depending on outside conditions and passenger adaptation, cover a range from 21°C to 27°C. One important point that has to be considered is the difference in heat loads in the different cabin sections due to different classes or seat loads. Airbus LR aircraft provide more temperature zones than any other manufacturer in order to allow for adaptation to those differences.

Thermal comfort is not only a function of an averaged temperature alone. The temperature perceived by the individual is influenced by the direct air temperature, the wall temperature (radiation), the air velocity and, to a limited extent, humidity. In addition disparate individual preferences and different activity levels between passengers and crew have to be considered. Relatively small cabin volumes and the necessity to remove high heat loads lead to comparatively high air exchange rates.

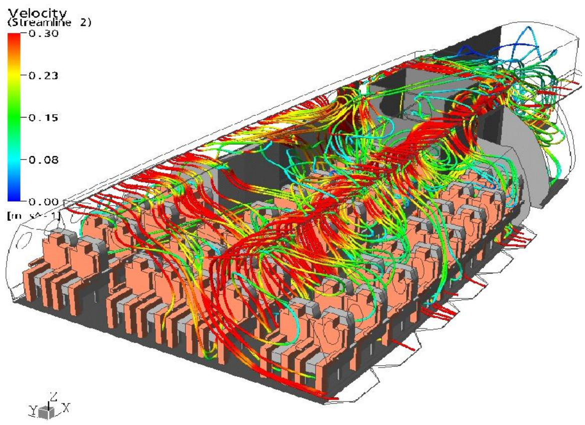

Figure 3 – Flow Simulation for Thermal Comfort Prediction (Twin aisle cabin)

The outlet definition ensures good ventilation to the seat area as well as to individuals standing or working in the aisle. Equal air distribution in a longitudinal direction gives comparable air quality and cabin comfort in all cabin sections. Airbus pioneered the introduction of double air outlet design and applies advanced comfort modeling methods based on Computational Fluid Dynamics (CFD) and different thermal comfort models to set high comfort standards very early in the design process (Figure 3). In order to validate predictive computational design, highly sophisticated mock-ups are used, in which any given condition can be simulated eperimentally. Hence those demonstrators enable a proper verification of high end ventilation design even before First Flight.

Contaminant control: With the exception of Ozone as a natural constituent of the atmosphere at high altitudes, the most prevalent source of contamination inside an aircraft cabin during flight relates to passengers and their activities. Besides carbon dioxide as a natural respiration product, negligible concentrations of organic components can be found on revenue flights using sophisticated analytical procedures. Analysis shows the main component to be ethanol followed, in significantly lower concentration, by acetone [11, 12]. Both substances are human metabolic products and alcoholic beverages are assumed to be the main source for ethanol. The main and most powerful approach to removing contaminants on current aircraft is air exchange. Outside air is conveyed into the pressurized fuselage and approximately the same amount is discarded overboard. An additional approach to effectively reduce odorous contamination - continously followed by Airbus - is to extract odors at their origin in galleys and lavatories and discard them overboard via the cabin air extraction system. With current flow rates for outside air and the appropriate treatment of recirculated air by filters, concentrations of carbon dioxide and other gaseous and particulate contaminants measured on aircraft in numerous in-flight studies were significantly below limits set by regulatory bodies and other health related organisations. Since 1988 on single aisle aircraft and since 1994 for the entire fleet, Airbus installs HEPA filters providing 99.99% filtration efficiency (for 0.3 microns particle size at sodium flame test) while the capture mechanisms ensure the detainment of larger and smaller particles to an even better extent. Independent studies within the last ten years have shown that microbiological and particulate contamination of cabin air for a/c with HEPA filters is much lower than found in the most common ground environments including those environments with high air purity requirements such as hospital operating theatres.

Since 1998 Airbus has offered optional HEPA filters combined with activated charcoal for total contaminant protection. These combined HEPA and gaseous filters have been tested in an extensive in-service study to find the appropriate combination of HEPA stage and charcoal capacity to effectively remove minor gaseous contaminations from re-circulated air. Consequently the filters enable airlines to provide an additional upgrade of air quality by removing volatile organic compounds from cabin sources such as bio-effluents, food, drinks, etc. During cruise at high altitudes - in particular on polar routes- the outside air may contain relevant concentrations of ozone. To ensure ozone concentration below the limit of 0,25 ppb (peak) and 0,1 ppb (3h average) as set by the regulatory authorities for a/c cabin air, long haul service a/c and even most of the short haul service a/c are equipped with catalytic ozone converters. The ozone converters are installed after the pre-cooler upstream to the air cycle machine to ensure sufficient temperature levels for the catalytic process. Modern ozone converters as introduced by Airbus in 2004 combine the ozone conversion with the ability to convert VOC during ground operation to prevent unpleasant odours during push back and taxiing. Figure 4 shows the full scope of currently available air treatment technologies on aircraft.

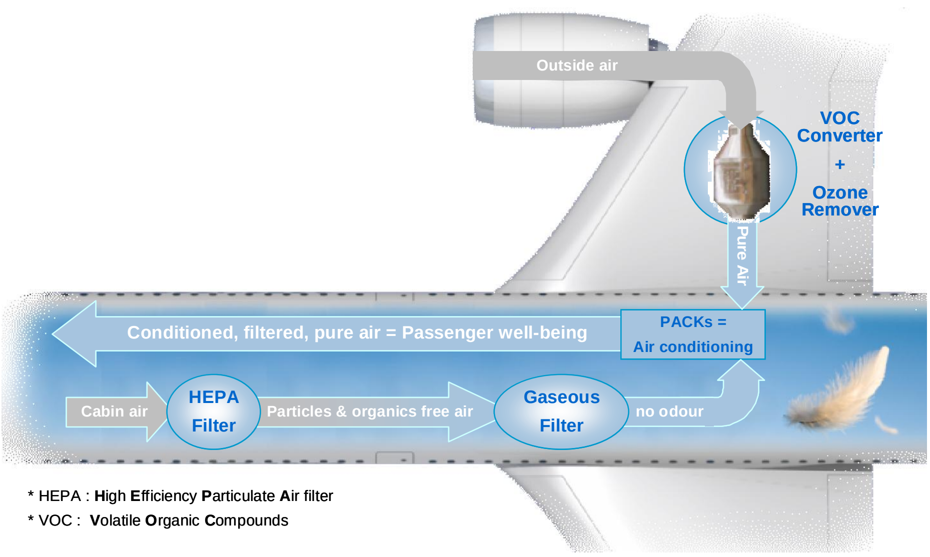

Figure 4 –Air Treatment

Conclusion

Environmental control systems are designed to provide comfortable physiological conditions for passengers and crew aboard an aircraft even in hostile outside environments. Adequate pressure, temperature and oxygen supply must be provided while maintaining an acceptable level of humidity and appropriate ventilation conditions to provide optimal comfort in the aircraft cabin. Very high heat loads contributed by passengers and electrical systems cause the environmental control systems to be the most energy-demanding system besides the propulsion itself. Sophisticated engineering tools are used to carefully balance challenging and sometimes conflicting requirements in order to reach the optimum with respect to comfort, environment and operating costs.

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