Hdb Env Chem Vol. 4, Part H (2005): 3–24
DOI 10.1007/b107234

Aircraft Environmental Control Systems

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Abstract The external environment at 41 000 ft (12 500 m), a typical cruise altitude for modern civil aircraft, is hostile to human life. Aircraft environmental control systems are designed to ensure the survival of the aircraft occupants as well as providing them with a comfortable atmosphere. Major design drivers for the environmental control system are thermal comfort, pressurisation and cabin air quality. However, these parameters cannot be considered independently. They interact between themselves and with other parameters, which may or may not be controllable by the system designer. These interactions occur in a highly complex manner. Research has led to a good understanding of the basic functions to allow safe and comfortable aircraft environmental conditions. Future research efforts will be increasingly focussed on identifying and elaborating the interdependency of factors in order to further enhance the aircraft cabin environment.

Keywords Environmental control system · Thermal comfort · Cabin air quality · Pressurisation · Humidity control

Abbreviations

APU	Auxiliary power unit
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
ASICA	Air management simulation for aircraft cabins
CDC	Centers for Disease Control
CFD	Computational fluid dynamics
cfm	Cubic feet per minute
CPCS	Cabin pressurisation control system
DIN	Deutsches Institut für Normung (German Standardisation Institute)
ECS	Environmental control system
FAA	Federal Aviation Administration
FACE	Friendly aircraft cabin environment
FAR	Federal Aviation Regulations
FL	Flight level
HEACE	Health effects in aircraft cabin environment
HEPA	High-efficiency particulate arrestor
IFE	In-flight entertainment
JAA	Joint Aviation Authorities
JAR	Joint Aviation Requirements
LF	Load factor
MAK	Maximale Arbeitsplatz-Konzentration (German Maximum Workplace Concentrations)
MIL	Military standard
ppm	Parts per million
RH	Relative humidity
SARS	Severe acute respiratory syndrome
SVOC	Semi-volatile organic compounds
VOC	Volatile organic compound
WHO	World Health Organisation

1
Introduction/Summary

The necessity to provide aircraft occupants with not only survivable but also comfortable conditions for work and relaxation drives ECS design. Due to the hostile environment outside the aircraft during flight conditions this aim requires the control of several interdependent factors. The analysis of cabin environment factors is mainly limited in this discussion to the major design requirements for air conditioning systems, e.g. air contaminants, thermal comfort and cabin pressure, however, a short discussion of the interdependency of factors will be revisited at the end of this paper. Where possible, measurement results as well as calculations are shown and related to aircraft system design methods; specifically the Airbus design philosophy. Gaps in knowledge surrounding the perception of the cabin environment by unhealthy, very young or elderly aircraft occupants are identified. Where appropriate, reference to current and future technology developments is made to show how the design process is evolving as these knowledge gaps are closed.

2

Regulatory Requirements and Guidelines

The conditions outside the aircraft during flight are hostile for humans. An artificial climate must be established within the cabin to support life under these conditions. Additionally, the cabin environment is an important influence on crew performance and passenger comfort.

Although there are certification requirements for at least some of the cabin environment factors [1, 2], air quality in particular is the subject of investigation by governmental organisations [3–5], as well as standardisation committees established by ASHRAE (SPC161), DIN (DIN6032) and CabinAir, an EU funded research programme. The reason for this interest is the increasing sensitivity of the public and press to potential health threats and the recognition that a set of new information generated through recent research may require inclusion in the certification requirements. Existing standards also do not address the specific environment of the aircraft cabin in detail, if at all. The aircraft cabin environment is unique when compared to other indoor spaces due to the combination of elevated cabin altitude, low humidity, high passenger density, the long sedentary position of the passengers and flights across time zones.

3

Environmental and Occupant-Related Constraints

Due to the specific external environment, the primary function of the ECS is to preserve the lives of the occupants of the aircraft. At a cruise altitude of 41 000 ft ambient pressure may be as low as 200 hPa, the temperature lower than – 60 °C and the water content of the air almost zero. Without life support systems humans would not be able to survive under these conditions. The ECS encompasses the air conditioning packs, consisting of heat exchangers, compressor, water extraction and turbine, and the air distribution, recircu-

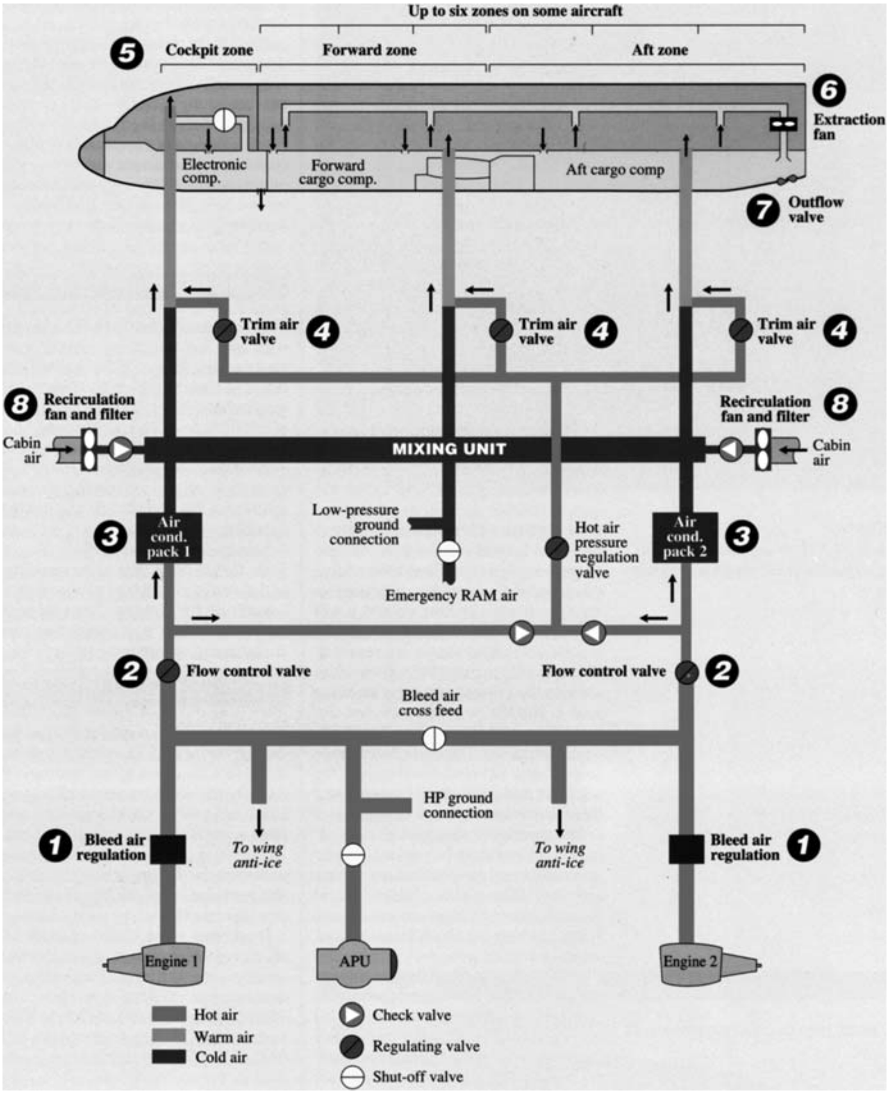

Fig. 1 The environmental control system – Airbus Library

lation and pressurisation systems, including the associated fans, valves and ducting. The bleed system delivers hot air from the engines, APU or external sources to the ECS, and a trim system taps some of this hot air off before it passes through the air conditioning pack to be added in the distribution ducting for temperature control reasons. These systems, and how they are interconnected are shown in Fig. 1.

The ECS designer must also ensure that the rates of change of pressure and the minimum pressure within the cabin are controlled in such a way as to prevent physiological damage to the occupants. Once the basic life preservation functions have been fulfilled the ECS designer must then consider the system performance for heating and cooling as well as comfort control systems for the occupants. Comfort control design is much more difficult than design of the life preservation functions since individuals have varying ideas of what acceptable comfort is. Additionally, the requirements of both passengers and cabin crew must be fulfilled within the same cabin conditions. Flight crew comfort, with its own attendant requirements must also be carefully considered.

The comfort requirements for the cabin crew and passengers are not generally analogous. While passengers are mainly sedentary, cabin crew may combine periods of activity with periods of inactivity, which may be within the galley, cabin, or special crew rest areas completely separated from the cabin. Equipment in these specific areas may also have an effect on comfort, such as the temperature effect of ovens or chillers in the galleys. The cabin crew may also have specific uniform requirements regarding the clothing they have to wear for each activity, whereas passengers are free to remove or add clothing or blankets to improve their personal thermal comfort.

The flight crew comfort requirements may be considered to be similar to passengers, although temperatures may generally be controlled to lower levels during periods of high workload, such as take-off. There are however some additional design constraints that must be considered carefully when designing for cockpit occupant comfort. One consideration is the amount of heat-generating electrical equipment that is installed in the cockpit. This significant heat load requires high air exchange rates to ensure equipment cooling and prevent occupants overheating. Additionally, the large expanse of windows can be a significant source of either heating or cooling, depending on the outside conditions. Due to the cockpit's small volume, high heat loads and the effect of radiant heat loads it is a significant design challenge to prevent temperature stratification and drafts and ensure a good thermal comfort level.

4

Cabin Pressurisation

The pressure outside the aircraft is hostile to human life at cruise levels of modern aircraft. To assure a habitable environment for the occupants the fuselage has to be pressurised during flight. As the cabin pressure is slightly reduced from ground level pressure during flight conditions, appropriate pressure gradients have to be considered for the CPCS design.

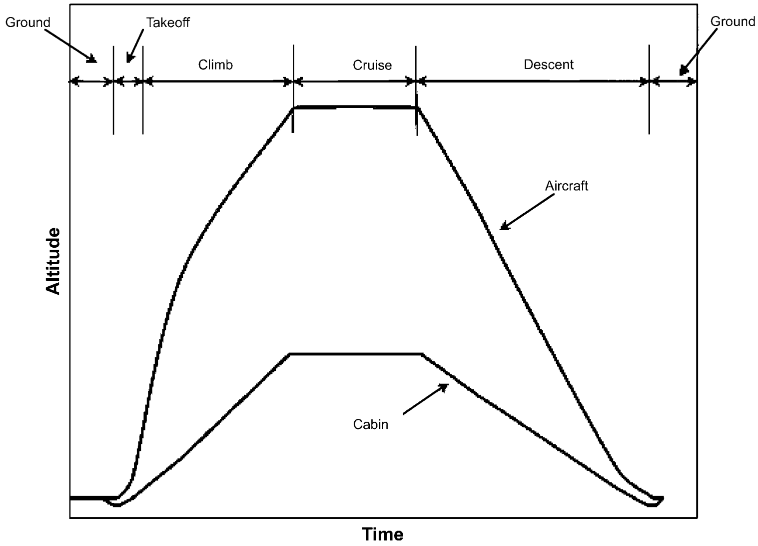

Fig. 2 Typical pressure schedule – SAE ARP1270

4.1
Absolute Cabin Pressure

The current certification requirement is to keep the cabin altitude lower or equal to 8000 ft, equivalent to 2440 m [1]. This is seen as the best compromise between the occupant health and comfort on one hand, and the aircraft structure weight, which would increase with a higher pressure difference between cabin and the outside, on the other. However, the maximum cabin altitude is only seen at the highest certified flight altitude of Airbus aircraft. Many flights are operated substantially below this altitude with cabin altitudes controlled lower than the 8000 ft maximum. The maximum cabin altitude for the Airbus long-range aircraft (A330/A340) is set to 2240 m (7350 ft) for longer flights, providing an additional margin (see Fig. 2 for a typical pressure schedule used by the pressurisation control system).

The percentage of oxygen in the atmosphere remains constant at around 21% for the altitudes at which modern aircraft fly. What is of greater concern for the definition of the cabin pressure requirement is how much of that oxygen the body is able to absorb. Therefore the major driver defining the cabin pressure requirement is the required oxygen saturation of the blood to keep crew performance high and prevent passenger health problems.

The blood oxygen saturation is dependent on the oxygen partial pressure of the cabin air, which is dependent on the cabin pressure itself. As the cabin pressure reduces (with increasing cabin altitude) the oxygen partial pressure decreases. The oxygen partial pressure is however only one factor for the actual oxygen saturation of the blood. The pH-value, occurrence of carbon monoxide and personal constitution also play roles, the exact details of which have not been fully investigated. The effects of elevated cabin altitude on children, elderly or sick people could be derived from chamber studies with their population groups but ethical concerns have up until today prevented such studies. However, study programmes are increasingly highlighting this area as a high priority and research programmes are starting to be set up which could address some of these issues.

4.2
Cabin Pressure Rate of Change

Furthermore, since the maximum cabin altitude increases in comparison to airport altitudes (with some exceptions, such as take-off or landing at Mexico City at 2237 m (7341 ft), Quito at 2808 m (9213 ft) and Lhasa at 3570 m (11 712 ft)) the cabin pressure must be reduced during aircraft climb to cruise conditions and raised during aircraft descent to the external conditions at the landing field. The rate of pressure change is noticed by many passengers through natural physiological phenomena, such as pressure discomfort at the eardrum, frontal sinuses or in the intestines. The eardrum is especially sensitive to pressure changes. These effects are amplified if illness is pending or, for instance, nasal cavities are blocked or cavities in the teeth are present. The pressure adaptation is easier with decreasing pressure (equivalent to aircraft climb).

The cabin pressure rate of change is therefore limited by the CPCS for these physiological reasons; the cabin altitude should not increase at more than 150 m/min (500 ft/min) and as the adaptation is more difficult during the aircraft descent (re-pressurisation of the cabin), the cabin altitude should not decrease at more than 90 m/min (300 ft/min). These gradients are appropriate for healthy people, but may not prevent problems for occupants with deteriorated health, such as ear problems or a severe cold.

5
Thermal Comfort

Thermal comfort is often seen as a matter of temperature alone. However, thermal comfort is actually an agreeable combination of temperature, air velocity, rate of velocity fluctuations and humidity. These four control parameters are further related to the flow pattern achieved within the cabin. The flow pattern is a critical parameter to ensure that the ventilation air supply is correctly distributed throughout all areas of the cabin.

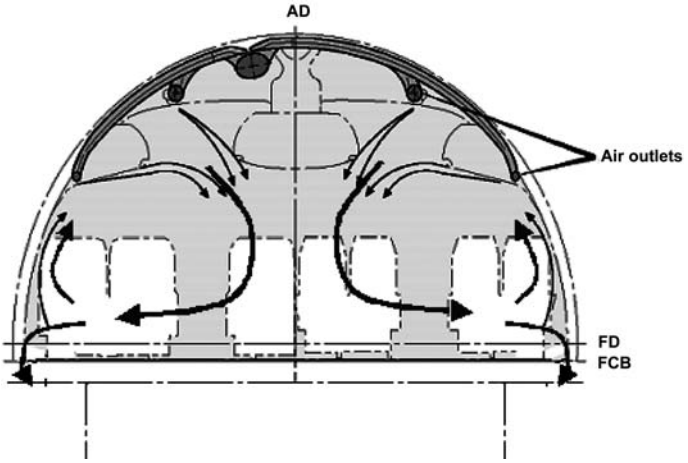

Fig. 3 Typical circular flow pattern within cabin – Airbus Library

5.1
Flow Patterns in the Cabin

The ventilation system is designed such that the air is adequately distributed throughout the length of the cabin. It is just as important to distribute the air appropriately in each temperature control zone (the cabin is divided into temperature control zones to allow temperature control with respect to the cabin section layout). Thus the allocation and design of the cabin outlets are the main tasks to be carried out during an air conditioning system design process. There are several different philosophies regarding how best to achieve optimal flow patterns in the cabin. Large commercial aircraft tend to have a circular flow pattern within the cabin where the ventilation air enters at the top of the cabin and circulates as two counter-rotating advection rolls before being exhausted at floor level (see Fig. 3 for a typical example).

The number of air outlets per side may be optimised, depending on the specific requirements of the aircraft cabin layout. Airbus designs the air outlet positions so as to achieve the necessary air exchange rate of air within the cabin. Lateral outlets significantly improve air movement at the window seats and in co-flow with upper ceiling outlets establish a stable, quasi two-dimensional, advection flow.

The circular advection flow pattern which develops as a result of this design is seen as being an optimal solution to ensure homogenous air distribution through the cabin for the majority of operating conditions. It is important, however, to note that the design of the air outlets and their blowing characteristics is very much dependent on cabin lining. A smooth lining contour can allow only one air outlet installation per side, which creates two counter-rotating fluid flows in each semi-section of the cabin. However, as the

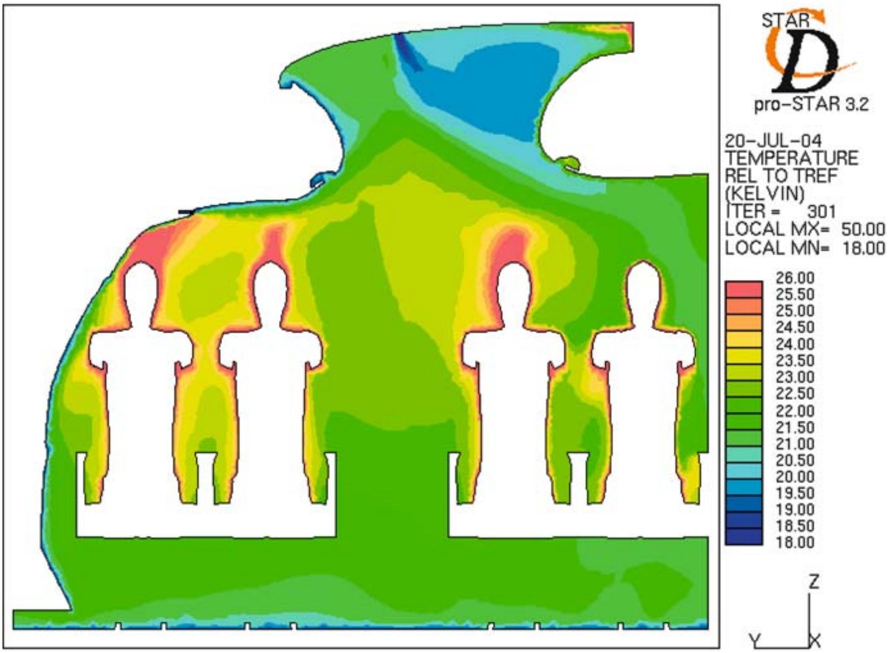

Fig. 4 Typical CFD calculation result for temperature – Airbus Library

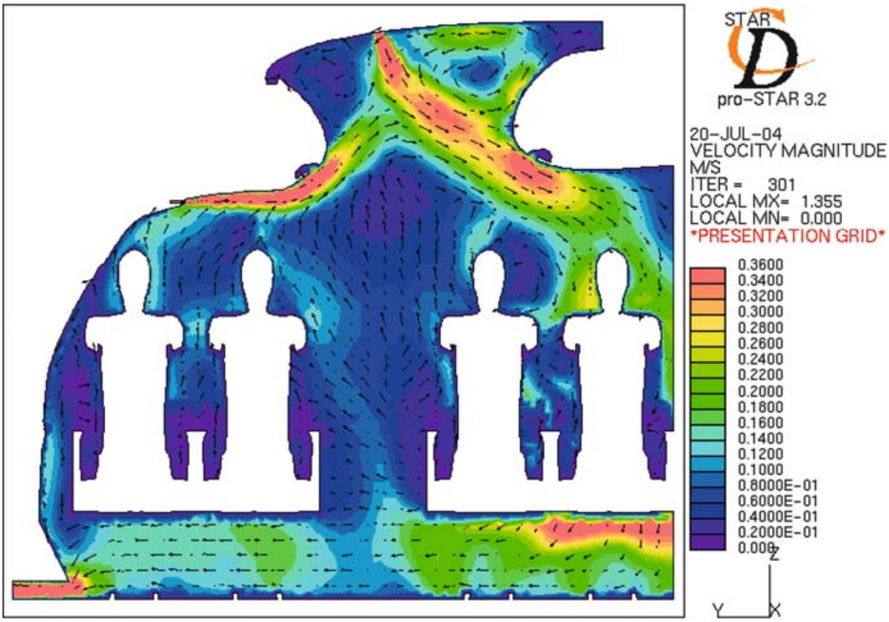

Fig. 5 Typical CFD calculation result for air velocity – Airbus Library

trend to flexibility and customisation of the cabin interior increases, the challenge for the ECS engineer is to ensure that regardless of the cabin interior layout an optimal flow pattern remains. For the A380, for instance, several air outlet configurations have been developed, and would be applied depending on the individual airline's cabin interior layout choice.

Systems providing a flow pattern from bottom to top (air inlets at floor level, outlets at head level) have been suggested from time to time but major disadvantages of this type of flow pattern include the downward convection flow direction, with the subsequent difficulty of achieving the cooling demand, and the negative influence of high momentum air flow in the vicinity of seated passengers. Additionally, contamination on the floor will be carried up into the faces of the passengers. Another major factor in the difficulty of designing bottom up flow designs is the effect that the cabin furnishings may have on the flow patterns. In top down flow designs the outlet is positioned to leave the flow free from disruption by the overhead storage compartments. The seats and seat-back tables only influence the flow once it is distributed and therefore low momentum. With a "floor up" flow, the air flow will be disturbed before reaching the heads of the sitting or walking passengers and crew. This would therefore make it much more difficult for the designer to develop stable, quasi two-dimensional flow patterns within the cabin.

CFD simulations are used for new aircraft programs to optimise the flow pattern within the cabin in the early phases of the design process. This has an added benefit of easing the validation of the ventilation and distribution systems during rig and aircraft tests. Both the temperature distribution and air velocities can be predicted by CFD (see Figs. 4 and 5 for example output). Good flow patterns within the cabin will ensure good temperature distribution, preventing hot spots occurring and ensuring a uniform temperature throughout the particular temperature control zone.

5.2
Temperature and Air Velocity

Just as temperature control is linked to correctly calibrated flow patterns, so is temperature perception interdependent on air velocity. One difficulty with designing temperature control systems is that temperature perception depends on individual preferences. Every individual has a particular sensitivity to temperature. This may create difficulties for airlines in meeting the differing comfort expectations of the passengers.

Additionally, working flight attendants have different temperature requirements than the seated passengers, typically requiring cooler temperatures while they are working and more elevated temperatures during their rest breaks. Temperature control is typically limited to the occupied cabin areas, with the galleys drawing air from the cabin, or being incorporated into the adjacent cabin temperature zone. There are however increasing moves towards introducing temperature control possibilities into the galleys with the installation of heated floor panels, dedicated heaters and individual air outlets being studied industry wide.

The temperature perceived by the individual (the resultant surface temperature) is influenced by the direct air temperature, the wall temperature (radiation) and the air velocity (both the mean value and the fluctuation level). Additionally, humans like the head to be in a slightly cooler environment than the feet. While compensation for individual variability can be made by using blankets and adding or removing clothing, the aim of the designer is to ensure that an acceptable temperature is provided globally when considering the total cabin. Two main requirements have to be considered for cabin air temperature to ensure this desire is met: the temperature selection must be highly flexible and the temperature must be as comparable as possible throughout a cabin zone in all three directions (longitudinal, vertical and horizontal). As discussed in the previous section, temperature stratification and drafts are avoided by ensuring that flow patterns within the cabin are optimised.

6
Humidity

The main source of humidity in the cabin is the occupants. The release of humidity through metabolic processes is fairly predictable and can be calculated depending on the passenger load and in relation to the outside air

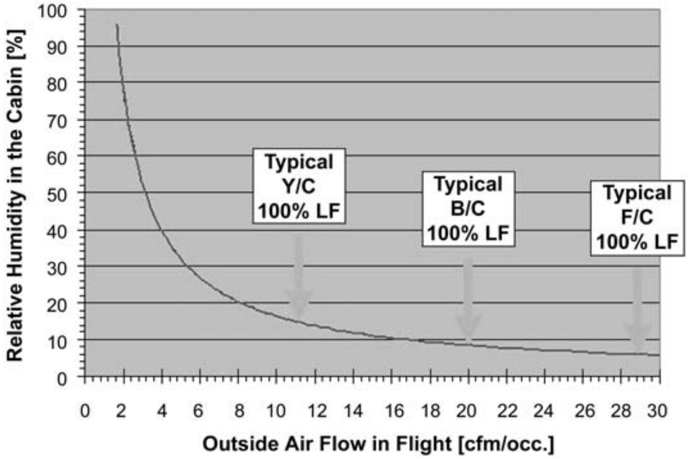

Fig. 6 Calculated decrease of relative humidity – Airbus Library

flow per occupant provided to the cabin. Figure 6 indicates that fairly low outside air flows are necessary to achieve a humidity level usually perceived as comfortable.

During flight, the air entering the cabin from outside is extremely dry (below 1% when the cabin temperature is taken into consideration), even when the aircraft flies through clouds. The reason is the low saturation concentration of water in the cold air outside (– 40 to – 70 °C). As the occupant-released humidity does not increase the level substantially, RH levels between 5 and 20% [6, 7] are usually found in aircraft cabins during cruise. Higher humidity levels may be seen on the ground depending on the climate at the airport.

Comfort standards usually define the lower RH limit at 30% [8, 9]. Low humidity is often perceived as the main comfort degradation for airline passengers from the environment control point of view. However, expert evidence has not confirmed health risks associated with the low level of humidity [10]. Millions of people live in low-humidity environments, either in deserts, e.g. Arizona, or in cold areas with indoor heating during the winter, e.g. Scandinavia. It must be taken into account however that those people are adapted to low humidity levels, which is not necessarily the case for aircraft passengers and crew.

Active humidification systems may be used by airlines to increase humidity levels in the cabin and thus improve thermal comfort. However, due to weight constraints for the equipment and water required for current systems, the RH can usually only be raised to around 20% in specific cabin compartments (crew rest areas, for example). The generally accepted comfort zone for humidity is above 30% which means that the increases possible with today's systems still fall short of optimal comfort.

Another area of consideration, aside from system design and capability, is condensation. During flight the aircraft skin cools below the dewpoint temperature of the cabin air and what humidity there is in the cabin air may condense onto the inner surface of the aircraft skin. During flight this water freezes, but during descent and ground phases this ice defrosts leading to phenomenon such as "rain in the plane" where drops of water may fall into the cabin through gaps around the ceiling panels. As well as having an impact on the airline's image, this free water contributes to electrical faults, particularly as more electronic systems are introduced into the cabin for IFE and other cabin comfort systems. This effect may be seen on aircraft with high density seating layouts combined with high load factors and short turn around times (giving the aircraft less time to dry out). Drying systems, which blow dry air into the ceiling area, are becoming increasingly available and their use to combat the condensation effects of high density layouts and active humidification systems is likely to expand.

A further challenge with respect to design for humidity control in the cabin is during the ground phase in hot and humid environments. To cool the cabin the air conditioning pack air outflow must be cooler than the outside air, which in hot and humid external conditions may lead to free water in the distribution ducting. To prevent condensation, or even icing, in the distribution network, water is removed from the air stream before being cooled in the pack. This is achieved by the introduction of a water extractor in the air conditioning packs before the air passes through the final cooling loop. An energy saving measure may also be obtained by re-injecting this water in to the ram air flow (ram air is used to provide the heat sink for the heat exchangers), which through evaporative cooling further reduces the ram air temperature, leading to increased heat exchanger efficiency. The humidified ram air does not enter the air conditioning pack air stream and is exhausted overboard.

7

Ventilation Rates

As discussed in the section on thermal comfort, a major requirement for the ECS is to provide a well-mixed, uniform temperature environment in the cabin. This must be done without introducing drafts or temperature stratification within the individual temperature control zones. To fulfil this requirement the ventilation flow must be sufficient to remove the heat load in the cabin generated by the occupants, IFE and cabin operations such as food preparation. Heat load dissipation is the main driver for the setting of the ventilation flow rate. A minimum ventilation flow is required to maintain a sufficient level of pressurisation of the cabin at flight altitudes as well as for contaminant dilution. However gaseous contaminant removal can be achieved with relatively low outside air flow rates [11, 12] of around 5 cfm. Flow rates required for heat load dissipation are generally higher than the minimum required to fulfil pressurisation and air exchange requirements.

With current development of equipment to remove gaseous contaminants from recirculation air, complementing the standard installation of particulate filters, it is probable that future aircraft designs will not require outside air flow to manage internally generated contaminants, although some outside air flow may be needed for pressurisation and temperature control reasons.

Recirculation of the extracted cabin air, after appropriate filtering to remove particulate contamination, helps to prevent temperature stratification within the cabin. When the air leaves the cabin at floor level it is well mixed with a stable temperature. A proportion of this air is remixed with cool air delivered by the air conditioning packs. The recirculated air increases the temperature of the pack air towards the lowest temperature demand among the cabin temperature control zones. Where warmer air is required, trim air, drawn from the bleed supply upstream of the air conditioning packs, is added in the individual distribution ducts. An additional benefit of adding recirculation air is a reduced requirement for bleed air, therefore less bleed air is drawn off from the engines leading to better engine efficiency and reduced fuel burn. This helps reduce engine emissions in the atmosphere and therefore offers an environmental benefit.

8
Contaminant Control

Knowledge of air composition and contaminants in the cabin is developed from either measurements or simulations or both. Some of the contaminants of concern are relatively easy to measure, and due to their having a homogenous, unique source are easy to predict. Examples are carbon dioxide and the oxygen content. Others are emitted by several sources or in different quantities, such as VOCs.

8.1
Cabin Operations Contamination Sources

Most of the contaminants can only be measured properly during normal service flights, as either the occupants themselves or the cabin operations are the major emission sources. Cabin occupants are a source of gaseous and biological contaminants through normal metabolic processes. The cabin occupants also introduce particulate contamination with their movement around the cabin (levels of particulates have been found to be significantly higher during boarding than during cruise [13]). Animals carried on board also introduce additional contaminants, as may items brought on board as carry-on luggage. With respect to the cabin operations themselves, food and beverage preparation specifically introduce particulate and gaseous contamination into the cabin, while cleaning procedures in the cabin may introduce other contaminants. Currently gaseous contaminant removal is carried out through high exchange rates of the cabin air. On those aircraft that recirculate air, particles and biological matter are removed by filters in the recirculation system. HEPA filters are recognised as being the current best practise and they are currently installed as standard or optional equipment on all Airbus aircraft.

8.2
External Contamination Sources

Contaminant entry from outside the cabin during specific ground operations is possible. In this case gaseous contaminants from the exhaust of surrounding aircraft and ground servicing vehicles may cause odour in the cabin. These odours are caused by VOCs, present as combustion products. Techniques have been recently developed to remove these unpleasant odours from the bleed air in the form of catalytic converters which use oxygen to breakdown VOCs into non-odorous compounds such as water vapour and small amounts of carbon dioxide [14].

8.2.1
Carbon Dioxide

Carbon dioxide (CO_2) is present in the external atmosphere at levels around 0.035%, equivalent to about 350 ppm. It is also produced in the cabin through human metabolic processes the major emission source of CO_2 on aircraft. Another source, related to specific airline cabin operations, is sublimation of dry ice used for cooling of galley storage areas. Many major airlines have installed dedicated galley cooling devices (air chillers) to cool the galleys storage areas, especially for the long range aircraft fleets, however some airlines do still use dry ice for local cooling within the galley.

Measurements have shown CO_2 levels in the cabin are generally between 400 and 3000 ppm, depending on passenger density and flight/ground phase, with mean values around 1000 ppm [7, 16]. The certification requirements of 5000 ppm (0.5%) set by the FAA and JAA [1, 2] are not approached within the breathing zones of passengers and crew during normal operations.

CO_2 is frequently used, in general indoor air quality applications, as a surrogate for actual air quality [9, 17]. This is especially true for "visitors" entering a room with a certain occupancy level. Many people have experienced this when coming into a room that has already been occupied for a certain time without any air exchange occurring; the air is obviously odorous to the new entrant. However, occupants who have been able to slowly adapt to the air CO_2 concentration will not detect CO_2 related odours. This is precisely the scenario in the aircraft cabin. There are no visitors to the cabin during flight and thus elevated concentrations of CO_2 cannot lead to a perception of "bad" air quality.

8.2.2
Carbon Monoxide

Carbon monoxide (CO) is a toxic, non-coloured, non-odorous gas which prevents inhaled oxygen being taken up by haemoglobin when present in high concentrations. It is a product of incomplete combustion. Since there are no combustion sources within the ECS, CO is not usually present in the cabin under normal operating conditions during flight. During ground operations CO contained in the exhaust gases of surrounding ground servicing vehicles or taxiing aircraft may enter the cabin under certain conditions. This cannot be controlled and is limited to the ground phases.

Various indoor air quality standards bodies, depending on the environment and application, have set threshold values for CO between 25 and 50 ppm [18, 19]. The FAA and JAA certification requirement is 50 ppm [1, 2].

Values measured in aircraft cabins are usually below one or two ppm, with peak values under 10 ppm [7, 8], these occurring usually during ground phases. At these low contamination levels the air quality within the cabin is not degraded.

8.2.3
Volatile Organic Compounds and Semi-volatile Organic Compounds

VOCs and SVOCs are generic terms for thousands of compounds containing carbon and hydrogen, often oxygen and nitrogen, and sometimes elements such as phosphorus and sulphur. SVOCs have a higher boiling point (above 250 °C) compared to VOCs (50–260 °C). Emission sources range from vehicle exhaust gases on the ground, cabin occupants through human metabolism (so-called bio-effluents), out-gassing of cabin furnishings and cabin operation (meals, beverages, servicing). As there are many compounds and several possible emission sources, an assessment of repercussions on occupant health or general cabin comfort is difficult.

Several measurement campaigns have been carried out to measure VOCs during flight, [7, 13, 20]. The use of various adsorbent tubes, e.g. Tenax, and different analysis methods allow as many compounds as possible to be detected with the maximum possible accuracy.

8.2.3.1
Volatile Organic Compounds

The largest fraction of the total VOCs present in the cabin air, between 70% and 90% of the detected organic compounds [13], consists of ethanol. Its origin is simply the alcoholic beverage served during the flight. In fact, most of the substances found in the cabin air during these measurement campaigns are also present in the “normal” indoor air of homes and thus present no unusual exposure situation. Additionally, wherever the measured values could be compared to existing or proposed indoor guide values, these values were not exceeded in a single case. This was also the case for health and safety at work exposure guidelines, such as the German MAK, in most cases even with the application of an appropriate safety factor of 100.

The notable exception to the above in this study [13] was nicotine, which was identified in the air of the smoking section. Concentrations approaching MAK-limit concentrations were determined in these areas, but did not approach this in non-smoking sections of the cabin.

The general results described above correspond to the results of other measurement campaigns and reviews, most performed in the USA [7, 15, 20]. The measurement campaigns cover most aircraft types from the main aircraft manufacturers. With such results it can be assumed that VOC concentrations are not heavily dependant on aircraft type but rather are connected to passenger loads and other sources of contaminants.

8.2.3.2
Semi-volatile Organic Compounds

SVOCs may be present as the breakdown products of aircraft fluids such as engine lubricants and hydraulic oils. These contaminants do not enter the cabin air under normal operating and through specific design measures ingress following failure conditions is also minimised. Precautions are taken to prevent hydraulic liquid and fuel entering the air system; for instance ensuring air conditioning ducts are placed above the hydraulic fluid lines in the aircraft. APU oil seal leakages are extremely rare and engine oil seal leakages even more rare. Oil and lubricant ingestion into the bleed system from spillages during servicing is also a rare event and recommendations for correct servicing practices are provided in aircraft maintenance manuals. As SVOCs are conjectured to be present only after a very unlikely incident, and highly infrequently, no reliable data has been collected on the possible types and concentrations that could be expected.

8.2.4
Ozone

Ozone (O_3) is produced in the upper layers of the atmosphere. It is usually present in relatively high concentrations above 65 000 ft (20 km) altitude. Depending on season and latitude, pockets of ozone may occur at lower altitudes, including altitudes at which commercial aircraft fly. The ozone concentration is generally higher at northern latitudes during the winter and spring months [21]. Ozone is highly toxic for humans and the regulatory authorities have set the maximum allowable concentrations within the cabin and cockpit as follows [1, 2]:

- 0.1 ppm for any three-hour period when the aircraft is above FL 270 (27 000 ft (8230 m))
- 0.25 ppm as maximum concentration at any time when the aircraft is above FL 320 (32 000 ft (9755 m))

Measurement of ozone during in-flight surveys have returned results showing ozone remains within the certified limits set down above [6], although lack of data has been highlighted as a concern [3].

The outside ozone concentration may reach 1 ppm for a short time at cruise altitudes. Ozone is unstable and its decomposition is accelerated by heat (for instance, in the bleed system) and contact with metallic surfaces and components within the cabin itself. However, this natural breakdown process is not sufficient for such elevated outside concentrations. Ozone converters are therefore required for aircraft flying routes that pass through latitudes where high levels of ozone are expected. These routes cover almost all city pairs being bounded through northern flight paths (north Atlantic, north Pacific) and therefore most long-range aircraft are equipped with ozone converters. Ozone converters are also offered as optional equipment by Airbus for their shorter range aircraft types.

8.2.5
Bacteria, Viruses, Fungi, Moulds

The presence of microbiological matter in the cabin has been the subject of debate for some years, with the SARS outbreak providing additional data for the understanding of the mechanisms at work. There is a general misconception that bacteria and viruses are propagated through the ECS. Several studies have now shown that the mechanism of transmission is proximity and person-to-person contact. Both the WHO tuberculosis study [22] and the CDC led study of possible airline transmission of SARS [23] indicate that proximity, specifically in the few rows in front of the index case, is a major factor in the transmission of these diseases. In the case of the tuberculosis study, exposure time was also found to have played a significant part, with no transmission occurring on flights with duration under eight hours. These studies confirm the position of the aircraft manufacturers that micro-organisms are not spread through the ECS.

Bacteria and fungi can be measured with handheld devices collecting onto agar plates. The analysis of these plates is carried out in a laboratory where two complementary analyses are performed; an overall identification of the amount of bacteria and fungal spores in the air in addition to an analysis regarding the species captured. Viruses however cannot be measured with handheld devices and virus concentrations are therefore not measured directly in the cabin during in-service flights. Some studies [24] have taken a sideways look at the question of infection rates although they do not address transmission methods and thus do not allow conclusions to be drawn with respect to the amount of viral material in an aircraft cabin at any given time. They also fail to take into account other mechanisms, such as the number of people from different backgrounds met by the cabin crew, environment differences between departure and arrival airports and physiological factors such as jet lag.

In [13] it was found that very low concentrations of mainly non-pathogenic bacteria and fungi were detected in the different cabin sections. It was also determined that there was a proportional increase in the germ concentration as the passenger density increased. Thus the highest concentrations were found in the economy class section of the aircraft measured. On the other hand, the germ concentrations in the in-coming ventilation air was so low that it would fulfil requirements for operating theatres (Airbus A340) or intensive care wards (Airbus A310). When peak concentrations of bacteria occurred, for instance following a sneeze or a cough in the vicinity of the measurement equipment, the concentrations reduced rapidly to the background level. This indicated the efficacy of the aircraft ventilation system. The Institute for Hygiene and Environmental Medicine of the Medical University of Lübeck provided expert evidence that bacteria of the type and concentration found are irrelevant for health considerations and confirmed that in their view the only actual health risk is in person-to-person contact. The infection is transmitted over short distances as droplets after a sneeze or cough.

Other studies have come to the same general conclusions. Another study, [15], confirmed a low bacteria concentration in aircraft cabins when compared with other modes of transportation. Considering these results one can summarise that concentrations of bacteria and fungal spores are generally low in aircraft cabins and are not spread throughout the cabin by the air recirculation system, with the biological contaminant survival rate generally decreasing at low RH.

8.2.6
Particulates

Measurements of the dust load (weight per volume air) have shown relatively low concentrations of particulates within aircraft cabins [6, 7, 16]. This is particularly so in aircraft cabins when smoking is prohibited. However, most studies have not measured the particle load in the outside air or the recirculation air. Particle count and size distribution have also generally not been measured.

In order to better clarify total particulate contaminant loads, cabin interior particulate loads, the dust loads within the recirculation air and a control measurement outside the aircraft at departure and arrival airports have been studied [13]. The study involved fixed installed particle counters in the cabins of two aircraft, an Airbus A310 and an Airbus A340. The particle counters were installed in the first or business class, the economy class and in the smoking section (if available on the aircraft). Particle counters were also installed in the recirculation system with handheld measurements being conducted for the outside measurements.

The two aircraft represent two different cabin distribution and recirculation philosophies, with the A310 having local mixing in the dedicated cabin zones and the A340 having a central mixing unit with distribution to the cabin zones. Additionally, the A310 recirculation air is filtered with EU9 class filters (90% efficiency at 0.5 micron) while the A340 has HEPA-filters installed (filters as defined by EN 1822-1 [25]) approximately equivalent to the EU13 classification.

The study results confirmed the hypothesis regarding the effect of filter efficiency. As was expected, the mean particle concentration within the recirculation air was found to be lower than, or equal to, the outside air concentrations for all ground and flight cases for both aircraft types. Additionally, on those aircraft with HEPA filters installed, the outside air is up to 2800 times more highly contaminated with particles compared to the recirculation air. Even during cruise, when the outside air has a very low particle concentration, the outside air is still up to 250 times more contaminated with particles compared to the recirculation air.

Additionally, the occupants, cabin furnishings such as carpets and cabin operations such as meal services could be confirmed as the main emission sources for particles, since substantially higher concentrations were measured in the cabin than in the supply air. As might be anticipated, the study also found that particle concentrations were much higher in the smoking section when compared to the non-smoking section, especially during flight.

9
Interdependency of Factors

When considering aircraft design parameters many factors from single contaminants to individual aspects of the cabin environment are taken into account. Some of these factors are shown in Fig. 7. However, the human perception of comfort is not just a sum of several variables. Most of the factors already discussed influence others and are themselves influenced by others. To make matters even more complicated, the perception of the cabin environment is not only influenced by these main factors but also by a lot of other variables that are not influenced or controlled by aircraft systems. There are person-related aspects such as demographics and personal constitution, cabin operations and work schedule related items for the cabin crew, and the specific physiological aspects such as the long sedentary position for the pas-

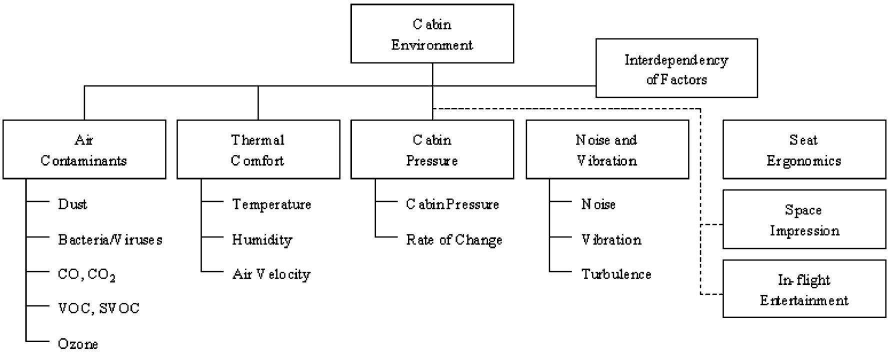

Fig. 7 Interdependency of factors – Airbus Library

sengers and flight crew. Other factors such as the perception of space, fear of flying, the colour and light perception also have a significant influence on the overall comfort perception, however, communication of these feelings and perceptions may be difficult for the occupants themselves. For instance, there is some evidence that low cabin pressure combined with some alcohol consumption increases the complaint rate substantially.

However there is a considerable knowledge gap within both the engineering and medical communities regarding these interdependencies. Work has been carried out within the EU-funded research programmes ASICA, FACE, CabinAir and HEACE to further identify and understand interdependencies, however, it is certain that such a complex subject will continue to draw research efforts. In order to fulfil recommendations from the NRC report, [3], a centre of excellence is being put in place in the USA. An ASHRAE sponsored research project into multiple factors combined with an FAA sponsored monitoring package installation has also started, and these results will hopefully fill in some currently existing knowledge gaps. Knowledge of how the interdependencies function is ultimately seen as the key to decreasing complaint rates from passengers and crew, since none are individually critical for human health and most do not substantially reduce the comfort perception by themselves.

10

Summary

The main challenge for aircraft ventilation systems is to ensure that the predicted air requirement for a special zone is in fact achieved. This means that they realise the objectives of an equal distribution throughout the length of the cabin as well as an appropriate flow pattern within the cabin.

The analysis of the mentioned parameters shows that none of them are critical for the health of the cabin occupants and do not adversely affect comfort. This is especially true for healthy individuals. However, there is a lack of know-how surrounding single parameters, such as the cabin pressure for unhealthy, very young and elderly persons, as well as for the interdependencies of the different factors, which are not limited to the cabin environment but also include personal and operational aspects.

References

1. JAR 25.831/841, Amendment 16
2. FAR 25.831/841, Amendment 105
3. National Research Council (2002) The Airliner Cabin Environment and the Health of Passengers and Crew. National Academy Press, Washington DC

4. House of Lords (15/11/00) Air Travel and Health. Her Majesty's Stationery Office, UK
5. Parliament of the Commonwealth of Australia (2000) Air Safety and Cabin Air Quality in the BAe 146 Aircraft. Senate Printing Unit, Canberra, Australia
6. ASHRAE Research Project 957-RP (1999) Relate Air Quality and Other Factors to Symptoms Reported by Passengers and Crew on Commercial Transport Category Aircraft 7.
7. Dumyahn TS, Spengler JD, Burge HA, Muilenburg M (2000) Comparison of the Environments of Two Transportation Vehicles: Results of Two Surveys. In: Nagda NL (ed) ASTM 1393. American Society for Testing and Materials, West Conshocken, PA
8. DIN 1946, part 2 (1994) Ventilation and Air Conditioning. Beuth Verlag, Berlin
9. ANSI ASHRAE Standard 55 (1992) Thermal Environment Conditions for Human Occupancy
10. Thibeault C (1997) Special Committee Report: Cabin Air Quality. Aviat Space Envir Md 68:80–82
11. ANSI ASHRAE 62 (2001) Addendum n, Ventilation for Acceptable Indoor Air Quality
12. Cain WS, Leaderer BP, Isseroff R, Berglund LG, Huey RJ, Lipsitt ED, Perlman D (1982) Ventilation Requirements in Buildings – Control of Occupancy Odour and Tobacco Smoke Odour. Atmos Environ 17(6):1183–1197
13. Dechow M, Sohn H, Steinhanses J (1997) Chemosphere 35(1):21–33
14. Nurcombe C (2004) Treatment of Aircraft Ground Air Sources (VOC Removal). Presentation to ASHRAE Summer Meeting, Nashville
15. Spengler JD, Burge H, Dumyahn T, Muilenberg M, Forester D (1997) Environmental Survey on Aircraft and Ground-based Commercial Transportation Vehicles. Harvard School of Public Health, Harvard University, Cambridge, MA
16. Lindgren T, Norbäck D, Andersson K, Dammström BG (2000) Aviat Space Envir Md 71:774–782
17. ANSI/ASHRAE Standard 62-89 (1989) Ventilation for Acceptable Air Quality
18. American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Value (TLV): 25 ppm, 29 mg/m^3 TWA
19. World Health Organisation (WHO) Threshold Limit Value (TLV): 10 ppm, 11.6 mg/m^3 8h TWA
20. Space DR, Johnson RA, Rankin WL, Nagda NL (2000) The Airplane Cabin Environment: Past, Present and Future Research. In: Nagda NL (ed) ASTM 1393. American Society for Testing and Materials, West Conshocken, PA
21. FAA (1980) Transport Category Airplanes Cabin Ozone Concentrations AC 120-38. FAA, Washington, DC
22. Valway S, Watson J, Bisgard C, Scudeller L, Espinal M, Raviglione M (1998) Tuberculosis and Air Travel: Guidelines for Prevention and Control. WHO, Geneva
23. Olsen SJ, Chang HL, Cheung TY, Tang AF, Fisk TL, Ooi SP, Kuo HW, Jiang DD, Chen KT, Lando J, Hsu KH, Chen TJ, Dowell SF (2003) New Eng J Med 349:2416–2422
24. Whelan EA, Lawson CC, Grajewski B, Petersen MR, Pinkerton LE, Ward EM, Schnorr TM (2003) Occup Environ Med 62:929–934
25. European Standard (1998) EN 1822-1 High Efficiency Particulate Air Filters (HEPA and ULPA)