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Design Considerations for HVAC Systems in Wide-Body Commercial Aircraft

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MEMS 500

Design Considerations for HVAC Systems in Wide-Body Commercial Aircraft

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ABSTRACT

MEMS 500 (MEMS 5420) was an independent study course using the text "*Heating, Ventilating, and Air-Conditioning"* authored by McQusiton, Parker and Spitler (6th Edition). The course included the material up to and including the space heating load. The cooling load material was covered during the use of the TRACE 700 software developed by the Trane Company. The report presented herein was an additional requirement of the course.

This report provides an introductory overview to the technical considerations required when establishing the design conditions for heating, ventilation, and air-conditioning system selection in a wide-body commercial aircraft. Rather than focusing on specific computations applicable to a sole aircraft model, a generalized approach to understanding the environmental parameters affecting design conditions across any passenger airplane has been adopted.

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1.0 INTRODUCTION

As opposed to being viewed as a luxury, heating, ventilation and cooling (HVAC) systems which provide a safe and healthy environment have become accepted as a requirement for the majority of indoor spaces that humans occupy in the developed world. Rather than being confined to ground-based structures such as personal dwellings, schools, offices and retail facilities, considerable time, effort and money has also been invested in developing HVAC systems suitable for use in mass transportation. In particular, a pertinent application of HVAC technology can be seen in commercial aircraft to ensure that human health and comfort is maintained from ground-level all the way into the troposphere.

One of the primary differences in HVAC systems developed for commercial aircraft applications is the need to make extreme and unusual external environmental habitable for (temporary) human occupation. Whilst the most common conditions that are factored into the design of ground-based HVAC systems generally include hot and humid air contaminated with pollutants such as industrial exhaust gases, fumes and biological particulate matter, during any given flight the ambient air outside of the aircraft is typically cold, dry, and laced with potentially dangerous levels of trioxygen (ozone) **[3]**. Depending on the geographical location and elevation of the flight, these conditions may change substantially. Additional challenges to the design of HVAC systems in aircraft involve the need to ensure that the final working unit is lightweight, accessible for maintenance and repair, unaffected by vibrations induced by the aircraft's motion, and highly reliable in a manner that does not impact the integrity or efficiency of surrounding flight equipment. Indeed, this combination of factors makes the selection of a HVAC system in a modern-day jet airliner complicated, to say the least.

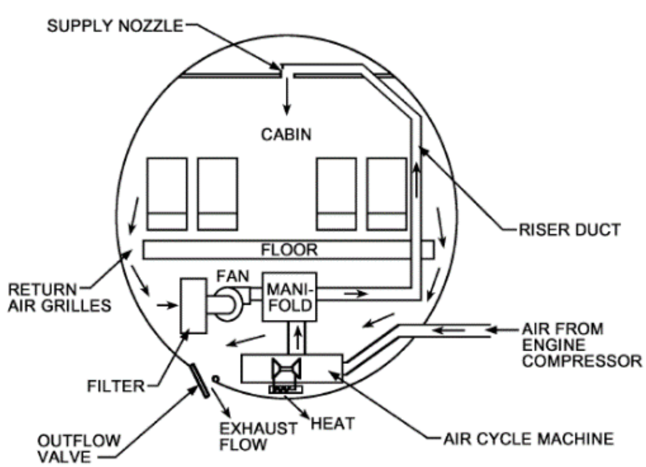

Figure 1 *– typical arrangement of an airflow path in an aircraft* ***[3]***

As with any occupied space, before the design of an aircraft HVAC system can be undertaken a robust estimate must be made regarding the maximum probable heat loss/gain occurring within the cabin section of the aircraft's fuselage, as well understanding other quantifiable parameters such as cabin air velocity and the effects of condition through the cabin walls **[3]**. Within the cabin of any given commercial airliner the primary mode of heat loss is that transmitted through the walls of the fuselage, whilst the primary gain is that of the occupants (passengers) and electrical equipment located within the space **[6]**. Of course, the actual concept of heat loss/gain is completely transient because of the constant variation in the large number of parameters that impact the thermodynamic state and contaminant quality of the air within the cabin at any given time. Such parameters, such as external (ambient temperature), air velocity, passenger density and in-flight human activity/metabolic rate **[5]**.

This report seeks to model the ideal case of the heat transfer occurring during the time-averaged flight of an Airbus A380 passenger airliner. Specifically, the ideal heat loss occurring through the skin of the aircraft, as well as other internal cabin parameters will be determined to demonstrate the means in which the values of heat transfer affect the design and selection of a HVAC system.

Figure 2 *– an A380-800 aircraft model operated by Emirates* ***[1]***

2.0 AIRCRAFT HVAC SYSTEM FUNCTIONALITY

Although not paramount to the primary aim of this report, a breakdown of the working principles of the air conditioning system of a commercial airliners is key to understanding the foundational principles of the design conditions upon which a HVAC system is based. Such background information will subsequently be presented herein.

The conventional design of an aircraft HVAC system relies on the supply of 'bleed air' which passes through the plane engine's low-pressure compressor stage. The manner of this design allows for an unbroken supply of air from the external atmosphere without imposing an additional weight penalty on the aircraft. The low-pressure compressor stage is the preferred choice for the bleed air source as its distance from the combustion chamber prevents the influx of high temperature, fuel-rich vapour into the cabin **[6]**.

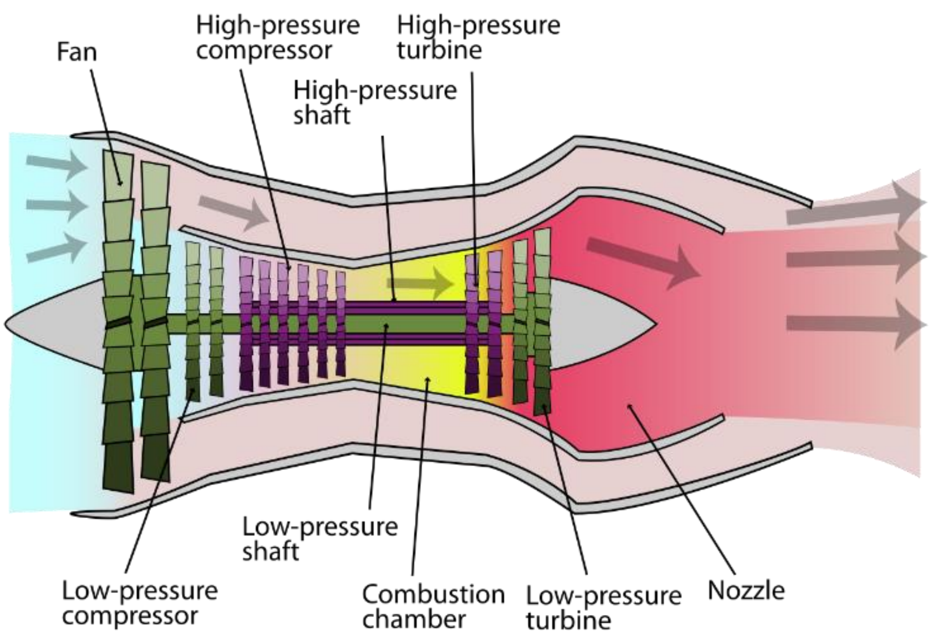

Figure 3** – diagram of a typical airliner turbofan **[6]

From here, the high temperature engine bleed air is cooled through heat transfer by the low temperature ram air (which is ambient air that flows in the opposite direction to the aircraft) through the ram air inlet duct which is located near the belly portion of the aircraft. This process takes place inside a heat exchanger, throughout which the two airstreams do not come into contact with each other. Following the heat transfer process, the converted hot ram air is discharged through the ram air exhaust duct which is located aft of the intake duct **[6]**.

Meanwhile, the colder engine bleed air passes through a compressor which in turn cools the air further by reducing the pressure. Afterwards, the now significantly colder air passes through the condenser to remove any excess water vapour in the air prior to being routed to the mixing chamber **[5]**. Delivery of the air into the cabin occurs via two different routes. The first, referred to as centralized air conditioning, is the often incorrectly perceived 'white smoke' that flows from the side wall panel directly above the cabin. This is the primary condition air that is supplied to the entire cabin. The second supply air category is the 'personal' air conditioning which is delivered through the individual vents located above every passenger seat **[3]**.

The carbon dioxide and airborne contaminates produced by the passengers is expelled from the cabin through exhaust ducts located on the bottom of the side wall panel adjacent to the cabin floor. A recirculation fan aids this process and discharges some of the 'used' air to the outside of the aircraft, while the remaining air is passed through a high-efficiency particulate absorbing (HEPA) filter **[3]**. After removing approximately 99% of airborne contaminates, the recirculation air moves to a mixing chamber where it is mixed with newly conditioned air arriving from the heat exchanger (mentioned previously).

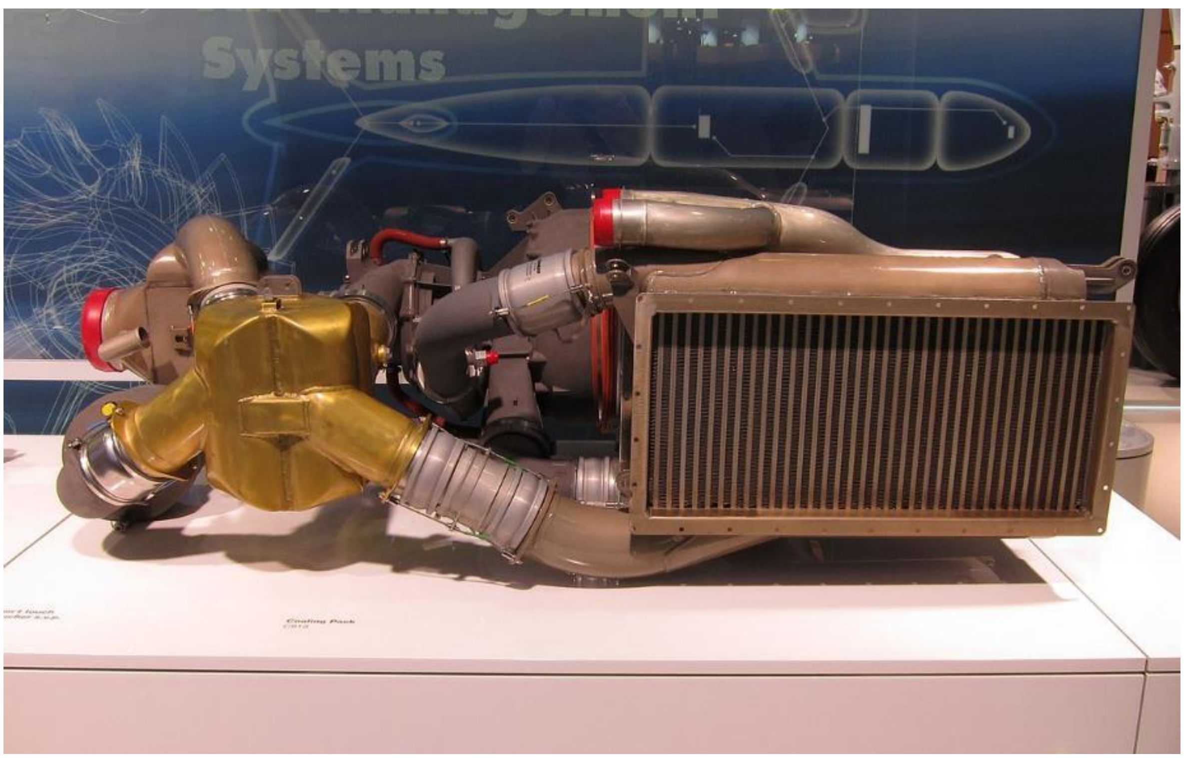

Figure 4** – air conditioning unit of a Comac C919 aircraft **[6]

As with most componentry on a large commercial aircraft, design redundancy is imperative. The HVAC system of an A380-800 (or any plane for that matter) is inherently important, and so in the case of an engine failure the opposite engine is capable of providing the required volume and flow rate of air needed to maintain the health and wellbeing of those onboard. A diagram of a typical system is shown below in **Figure 5**.

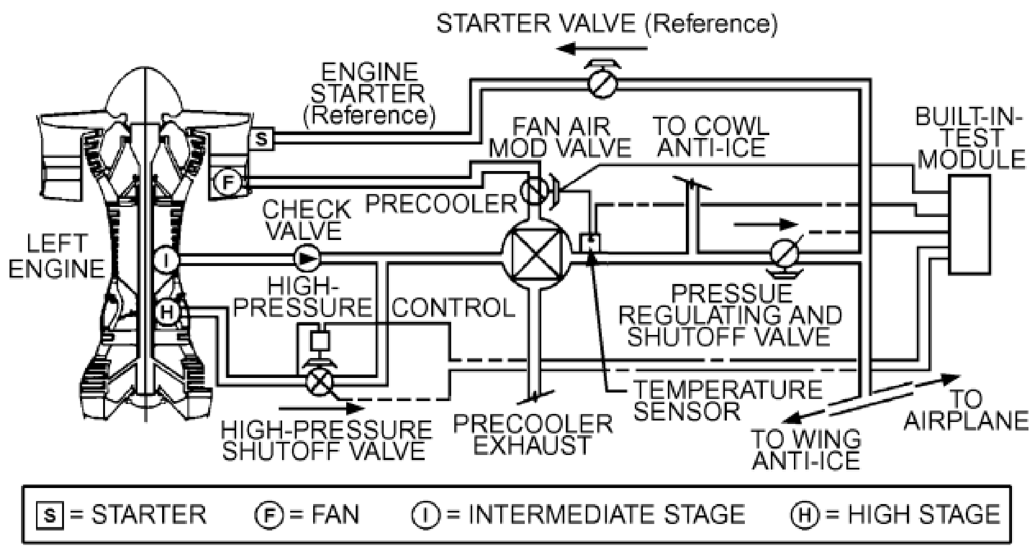

Figure 5** – schematic of a typical engine/auxiliary power unit bleed system **[3]

3.0 AIRCRAFT SPECIFICATIONS

To narrow down on the numerical values governing the design conditions of an aircraft HVAC system, the arbitrary choice of aircraft chosen to model throughout ***4.0*** – *Design Conditions* is that of an Airbus A380-800. The information listed in **Table 1** presents the dimensional and operational information that is ***typical*** of this particular plane and seeks to define boundary parameters that can be used to establish the design conditions needed for the sizing and selection of subsequent HVAC systems.

Many of the parameters described in this section have a direct impact on the magnitude of the heat flux between the internals space within the aircraft cabin and the external walls of the fuselage. As a result, it is imperative to note that the idealized nature of many of these parameters will have a direct impact on both the accuracy and validity of the ensuing computations and analyses in later sections.

Parameter	**Description**
General characteristics	
Capacity	575 passengers, 175.2 m^3 cargo
Length	72.72 m (238 ft 7 in)
Wingspan	79.75 m (261 ft 8 in)
Width	7.14 m (23 ft 5 in)
Height	24.09 m (79 ft 0 in)
Wing area	845 m^2 (9,100 ft^2)
Fuselage diameter	7.14 m (23 ft 5 in)
Empty weight	277,145 kg (611,000 lb)
Fuel capacity	253,983 kg (559,937 lb); 323,546 L (85,472 US gal)
Performance	
Cruise speed	903 km/h (561 mph, 488 kn)
Range	14,800 km (9,200 mi)
Service ceiling	13,000 m (43,000 ft)
Mach number	0.85
Landing speed	256 km/h (159 mph)
Take-off length	3,000 m (9,800 ft)

Table 1 *– general, dimensional and performance specifications for an A380-800* ***[9]***

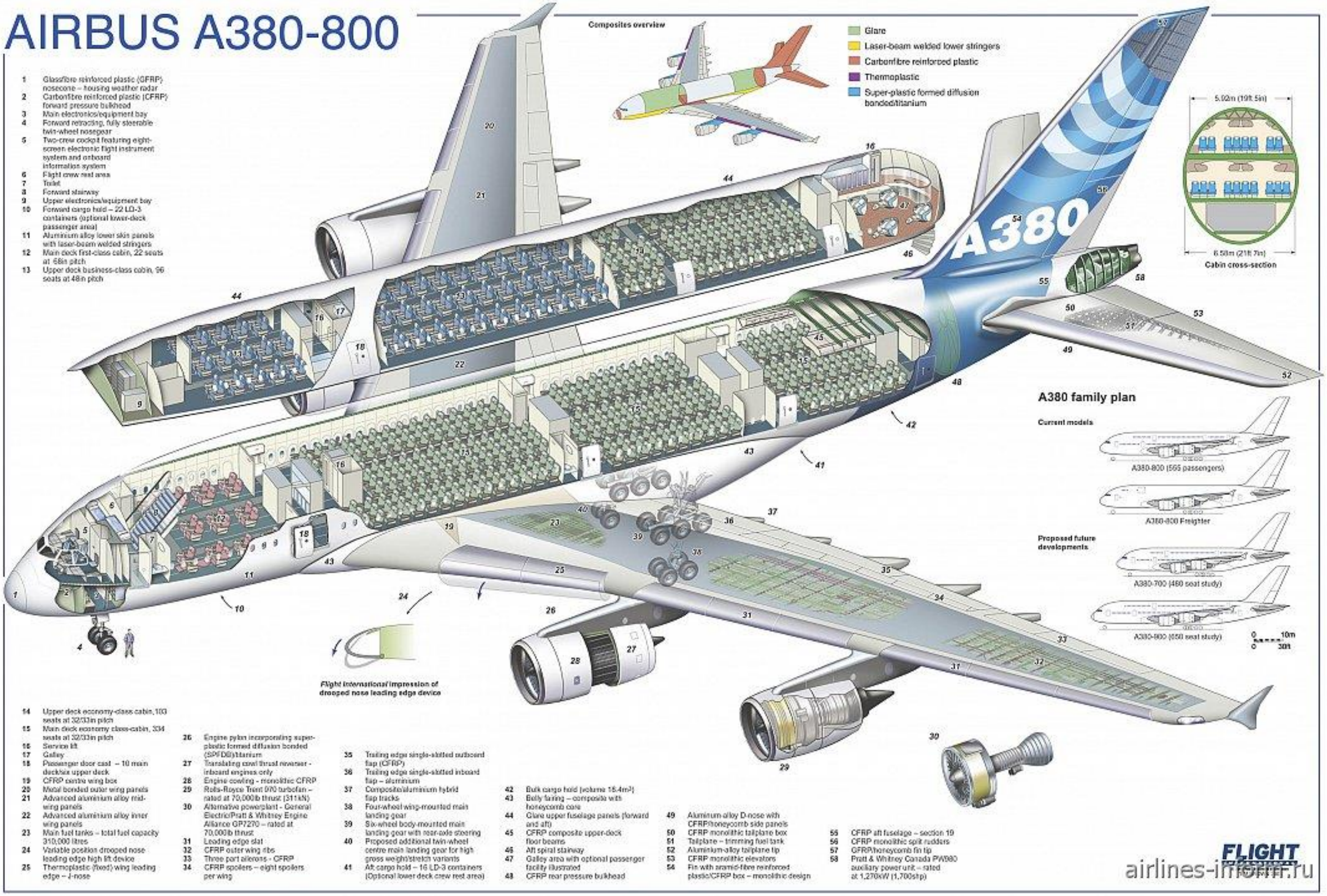

Figure 6** – typical internal arrangement of an A380-800 **[9]

4.0 DESIGN CONDITIONS

As discussed previously, design conditions for aircraft vary significantly when compared to what can be seen as more 'conventional' ground-based HVAC applications. Due to the fact that commercial air transportation is undertaken in a physical environment that is not inherently meant for human habitation, the differences in the quality and state of the air supplied to aircraft passengers and crew are accounted for by taking into account the design conditions described in this section. Using the information pertaining to an Airbus A380-800 as presented in **Table 1**, the ensuing calculations aim to provide a generalized approach to calculating various parameters associated with the heat transfer between the fuselage and the external atmosphere, and the heat generated from within the cabin itself.

4.1 Temperature, Humidity and Heat Transfer Modes

The plot shown in **Figure 7** depicts the average design ambient temperature profiles for days classed as either 'standard', 'hot' or 'cold' at increasing elevation above sea-level. Understandably, ambient temperature varies significantly with geographical location, and so the temperatures used for the design of a particular aircraft HVAC system may differ from the values shown in **Figure 1**.

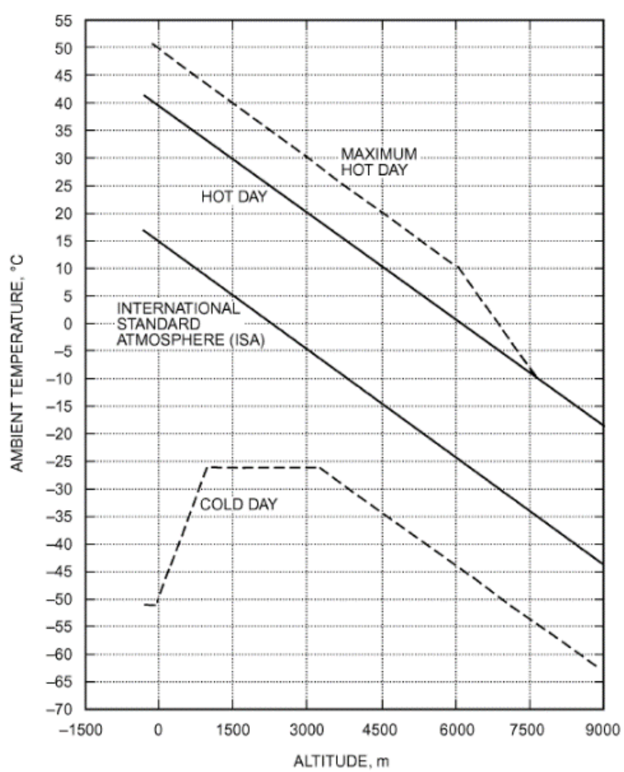

Figure 7** – averaged ambient temperature profiles **[3]

Similarly, the design ambient moisture content at various elevations is plotted in **Figure 8**. As one would expect, greater heights above sea level are synonymous with lower humidity ratios due to the almost parabolic decay of water vapour at high altitudes. It is obvious then that both temperature and moisture content parameters are integral when defining the design conditions of an aircraft HVAC system, as the optimum operating point for the equipment such as compressors and humidifiers need to be capable of efficient operation under a wide range of ambient conditions.

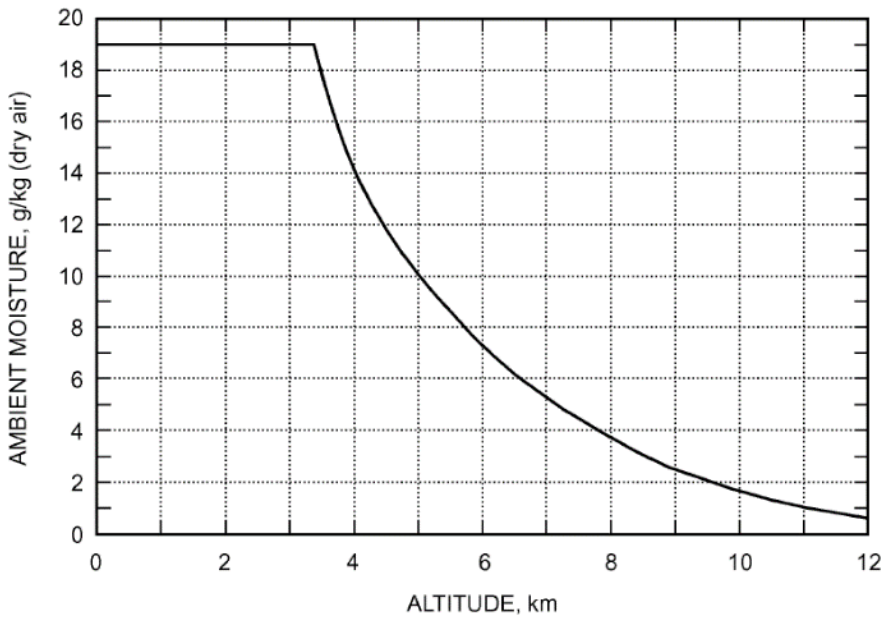

Figure 8** – ambient moisture content as a result of altitude variation **[3]

Heating and/or cooling loads for *any* commercial aircraft model are determined by an analysis of the several elements that contribute to said loads at either a fixed or transient rate. In no particular order of frequency or intensity, during a standard flight the following modes of heat transfer are typically encountered **[3]**:

- Convection between the outer aircraft skin and the boundary layer formed by the air flow over the outer surface of the aircraft
- Convection between the interior surfaces of the cabin and the surrounding cabin air
- Convection and radiation between the aircraft cabin and passengers

- Radiation between the outer aircraft skin and the external environment
- Solar radiation directly on the fuselage, through windows, and reflected up from the ground below
- Convection and radiation from internal sources of heat such as lights, television screens and kitchen appliances
- Conduction through cabin walls and the aircraft structure

Note that although the design of aircraft HVAC systems must be done so in a manner that incorporates the time during which an aircraft is grounded (i.e., not in flight, such as when boarding, taxiing, and disembarking), for the sake of this report only computations associated with in-flight design conditions will be accounted for.

4.2 Calculation of Ambient Air Temperature

The temperature of the ambient air immediately adjacent to the outer skin of the fuselage (i.e., within the boundary layer), also known as the adiabatic wall temperature, can be calculated by utilising the following equation [3]:

$$T_{\mathrm{AW}} = T_{\infty} + r(T_{\mathrm{T}} - T_{\infty})$$

In this equation:

- T_{AW} … is the adiabatic wall temperature; expressed in units of K
- T_{∞} … is the static ambient air temperature; expressed in units of K
- T_{T} … is the total ambient temperature; expresssed in units of K
- r … is the recovery factor for a turbulent boundary layer, and is related to the Prandtl $r = \mathrm{Pr}^{1/3}$

In turn, the total temperature of ambient air T_{T} can be found by [3]:

$$T_{\mathrm{T}} = T_{\infty}\left(1 + \frac{\gamma - 1}{2} M^2\right)$$

Where:

- γ ... is the heat capacity ratio, which is the ratio of the heat capaity of air at a constant pressure to the heat capacity at a constant volume, or $\gamma = c_{\mathrm{p}}/c_{\mathrm{v}}$,
- M ...is the Mach number of the aircraft, which is dependent on crusing speed

Assuming an ambient air temperature of $-40°\mathrm{C}$ ($208.15\ \mathrm{K}$) (which corresponds to a cruising altitude of approximately $9000\ \mathrm{m}$ as per **Figure 7**) at a constant pressure, the properties of air are **[12]**:

- $\mu = 13.74 \times 10^{-6} \times 10^{-6}\ \mathrm{N \cdot s/m^2}$ ... dynamic viscosity
- $\nu = 8.11 \times 10^{-6}\ \mathrm{m^2/s}$ ... kinematic viscosity
- $\rho_{\mathrm{w}} = 0.4671\ \mathrm{kg/m^3}$ ... ambient density
- $c_{\mathrm{p}} = 1.007\ \mathrm{kJ/kg \cdot K}$ ... isobaric specific heat
- $c_{\mathrm{v}} = 0.7162\ \mathrm{kJ/kg \cdot K}$ ... isochoric specific heat
- $k = 19.18 \times 10^{-3}\ \mathrm{W/m \cdot K}$ ... thermal conductivity

Begin by calculating the Prandlt number Pr:

$$\mathrm{Pr} = \frac{c_{\mathrm{p}}\mu}{k}$$

$$\mathrm{Pr} = \frac{(1.007\times10^{3})(13.74\times10^{-6})}{(19.18\times10^{-3})}$$

$$\mathrm{Pr} \approx 0.721$$

Using this value of Pr to determine the recovery factor r:

$$r = \mathrm{Pr}^{\frac{1}{3}}$$

$$r = (0.721)^{\frac{1}{3}}$$

$$r \approx 0.90$$

From here, calculating the heat capacity ratio γ:

$$\gamma = \frac{c_{\mathrm{p}}}{c_{\mathrm{v}}}$$

$$\gamma = \frac{1.007\times10^3}{0.7162\times10^3}$$

$$\gamma \approx 1.41$$

It is now possible to determine the total ambient temperature T_{T}:

$$T_{\mathrm{T}} = T_\infty \left(1 + \frac{\gamma-1}{2} M^2\right)$$

$$T_{\mathrm{T}} = (208.15)\left(1 + \frac{1.41-1}{2}(0.85)^2\right)$$

$$T_{\mathrm{T}} \approx 238.98 \text{ K } (-34.17°\text{C})$$

Finally, the adiabatic wall temperature T_{T} is calculated:

$$T_{\mathrm{AW}} = T_\infty + r(T_{\mathrm{T}} - T_\infty)$$

$$T_{\mathrm{AW}} = 208.15 + (0.90)(238.98 - 208.15)$$

$$T_{\mathrm{AW}} \approx 235.90 \text{ K } (-37.25°\text{C})$$

4.3 Calculation of Air Speed

The Mach number of the aircraft is related to the local air speed by the following expression [3]:

$$u_\infty = M\sqrt{\gamma R T_\infty}$$

Here:

- u_∞ ... is the aircraft air speed; expressed in units of $\mathrm{m/s}$
- R ... is the universal gas contant; $287\ \mathrm{m^2/s^2 \cdot K}$

Substituting in the known values and solving for the air speed u_∞:

$$u_\infty = M\sqrt{\gamma R T_\infty}$$

$$u_\infty = (0.85)\sqrt{(1.405)(287)(208.15)}$$

$$u_\infty \approx 246.26\ \mathrm{m/s}$$

4.4 Calculation of External Heat Transfer Coefficient

The fact that the fuselage of the aircraft is essentially at free-stream static pressure permits the use of a flat-plate analogy to determine the external heat transfer coefficient h at any point x along the length of the fuselage. It therefore follows that [3]:

$$h = \rho_\mathrm{w} c_\mathrm{p} u_\infty 0.185 (\log \mathrm{Re}_x)^{-2.584} \mathrm{Pr}^{-\frac{2}{3}}$$

For the sake of calculation, an arbitrary length of $x = 40\ \mathrm{m}$ (corresponding to the assumed length of the economy-class cabin within an A380-800) will be used. Finding the Reynolds number Re_x:

$$\mathrm{Re}_x = \frac{\rho_\mathrm{w} u_\infty x}{\mu} \qquad \text{... Where } 10^7 < \mathrm{Re}_x < 10^9$$

$$\mathrm{Re}_x = \frac{(0.4671)(246.26)(40)}{(13.74 \times 10^{-6})}$$

$$\mathrm{Re}_x \approx 3.35 \times 10^8$$

This value of Re_x is within the acceptable range of $10^7 < \mathrm{Re}_x < 10^9$.

Solving for the heat transfer coefficient h by substituting in the known values:

$$h = \rho_{\mathrm{w}} c_{\mathrm{p}} u_{\infty} 0.185(\log \mathrm{Re}_x)^{-2.584} \mathrm{Pr}^{-\frac{2}{3}}$$

$$h = (0.4671)(1.007 \times 10^3)(246.26)(0.185)(\log(3.35 \times 10^8))^{-2.584}(0.721)^{-\frac{2}{3}}$$

$$h \approx 104.91\ \mathrm{W/m^2 \cdot K}$$

Now that a suitable value of h has been arrived at, the convective heat loss from the outer skin q can be determined using the following expression **[3]**:

$$q = hA(T - T_{\mathrm{AW}})$$

In this equation:

- q … is the convective heat loss from the outer skin of the fuselage; expressed in units of W
- A … outside surface area of the passenger cabin; expressed in units of $\mathrm{m^2}$
- T … is the outer skin temperature (assumed equal to T_{T}); expressed in units of K

Idealising the shape of an economy-class section of the fuselage as a cylinder with a length of $40\ \mathrm{m}$ and a diameter of $7.14\ \mathrm{m}$, the surface area A can be determined:

$$A = 2\pi r L$$

$$A = (2)(\pi)\left(\frac{7.14}{2}\right)(40)$$

$$A \approx 897.24\ \mathrm{m^2}$$

From here, it is possible to solve for the convective heat loss q.

$$q = hA(T - T_{\mathrm{AW}})$$

$$q = (104.91)(897.24)(238.98\ - 235.90)$$

$$q \approx 2.9 \times 10^5\ \mathrm{W}$$

$$\boldsymbol{q \approx 0.29\ \mathrm{MW}}$$

This result indicates heat loss *from* the aircraft skin *to* the ambient air on the external side of the fuselage.

4.5 Calculation of External Radiation

Ignoring the influence of the aircraft's wings, nose, and aft portion of the fuselage, the section of the planes fuselage that surrounds the economy cabin radiates heat primarily to the sky **[3]**. Starting from ground level, as the plane increases in elevation there is a corresponding decrease in the amount of air to radiate to, meaning that the difference between air temperature and sky temperature increases. Recall that sky temperature is defined as the temperature one would meausre if pointing an infra-red 'thermometer' at the sky **[3]**. Conversely, air temperature describes the kinetic eneergy of motion of the gases that comprise the air itself. For the fuselage, the heat loss to the sky through means of radiation is quantifed by the below expression **[3]**:

$$q_{\mathrm{R}} = A\sigma\epsilon(T^4 - T_{\mathrm{sky}}^4)$$

In this equation:

- q_{R} … radiation heat loss from the outer skin; expressed in units of W
- σ … Stefan-Boltzmann constant; $5.67 \times 10^{-8}\ \mathrm{W/m^2 \cdot K^4}$
- ϵ … Emissivity of the fuselage skin surface/paint

Most commonly, the skin of an aircract is manufactured from aluminium and aluminium alloys comprised of other metals such as zinc, copper and magnesium. In the case of an A380-800, we ignore the effect of paint coatings on the skin of the plane and instead take the emissivity of highly polished aluminium as 0.1 **[10]**.

Solving for the radiation heat loss q_{R}:

$$q_{\mathrm{R}} = A\sigma\epsilon(T^4 - T_{\mathrm{sky}}^4)$$

$$q_{\mathrm{R}} = (897.24)(5.67 \times 10^{-8})(0.1)(235.90^4 - 208.15^4)$$

$$q_{\mathrm{R}} \approx 6204.6\ \mathrm{W}$$

$$\boldsymbol{q_{\mathrm{R}} \approx 6.2\ \mathrm{kW}}$$

Evidently, in-flight radiative losses are minimal compared to conductive effects through the skin of the aircraft, which will be discussed to a greater extent in the next section.

4.6 Conduction

The transient path of conduction from the internal cabin air to the external environment is a combination of multiple heat transfer elements in both series and parallel with each other **[3]**. Although the external skin of the aircraft (which is typically manufactured from aluminium and composite alloys) has a low emissivity, the material is quite conductive in nature and hence must be insulated to avoid an increased ability of heat to escape to the outside of the plane. As shown in **Figure 9**, the outer skin of the aircraft is supported by circumferential and longitudinal ribs **[3]**.

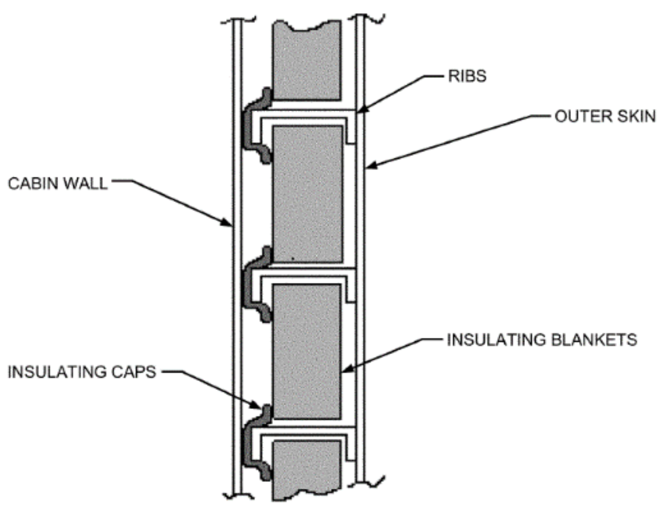

Figure 9** – sectional view of internal-to-external aircraft insulation layout **[3]

To maintain optimum passenger comfort, the internal cabin wall temperature should not be too different from the air temperature within the cabin due to the fact that passengers are frequently mobile throughout the cabin and in contact with various internal surfaces **[3]**. **Figure 10** shows an example of thermal insulation padded around the circumference of the internal cabin skin.

Figure 10** – prefabricated insulation blankets on a Boeing 777 **[6]

4.7 Analysis of Aircraft Cabin Air Velocity

When it comes to the passenger cabin of a commercial aircraft, particularly a wide-body plane such as an A380-800, the internal space can be modelled closely to that of high-density buildings such as lecture halls, cinemas and theatres. In such settings, the air-conditioning system is set to a cooling mode in which the supply diffuser temperature is cooler than that of the room temperature. However, unlike buildings situated at or just above sea level, in aircraft cabins the ducting networks generally have higher air velocities and smaller fractions of recirculated air (approximately 50%) **[3]**.

Because the velocity characteristics of an airplane are uniquely affected by transitional flow behaviour, turbulence induced by the air diffuser can affect the perceived 'draftiness' within a cabin and lead to passengers feeling uncomfortable or even cold **[3]**. **Figure 11** shows a computational fluid dynamics (CFD) model of cabin air velocities within a wide-body aircraft provided by ASHRAE. Due to the transient nature of the velocity field, variations in such a setting will always exist and give rise to different sensations of 'coldness' at various areas in a given row of occupied passenger seats.

Albeit this, an overall pattern begins to emerge that shows the consistent flow path in which ventilation air enters through the centre of the cabin and then exists the suction vents located adjacent to the floor on both sides of the plane.

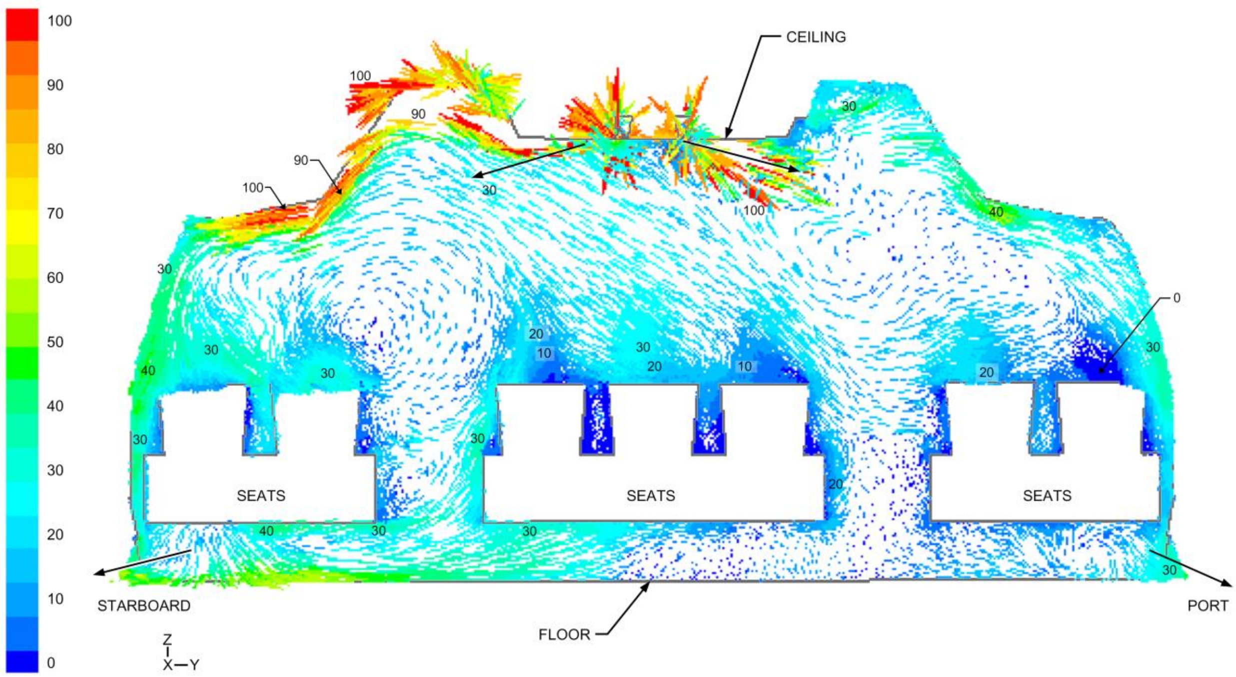

Figure 11 *– CFD model of aircraft cabin air velocities* ***[3]***

The time-averaged mean air flow velocities have a direct impact on passenger comfort, and so as with HVAC systems design for commercial and residential buildings, several comfort indices such as predicted percent dissatisfied (PPD) and predicted mean value (PMV) are used to evaluate the effect of various air velocities on passenger comfort in aircraft **[3]**.

5.0 CONCLUSION

Well before the outbreak of the COVID-19 pandemic in December of 2019, properly designed HVAC systems in commerical aircraft were critical in ensuring that passenger comfort and thermoregulation were maintained during both ground (hot) and in-flight (cold) operations. Often overlooked by the everyday frequent flyer, commercial airline HVAC systems are now presented with the challenge of reducing the transmission of COVID-19 through smart design which incorporates the underlying thermodynamic principles that have been utilised in space heating/cooling for decades.

For this to be possible, it is imperative that the HVAC teams behind the design, selection, installation and maintenace of HVAC systems in modern aircraft take into account the large array of design conditions which will ultimately impact the sizing and performance requirements of the final system. Although by no means an exahustive list of factors that need to be accounted for during system design, it has been insinuated throughout this report that the most important design condition which directly impacts these requirements is the thermal loads attributed to heat entering and leaving the plane through conductive and radiative effects. Although transient by definition, a decent numerical approximation of the heat flux and internal cabin velocity for a given aircraft designation is crucial in the selection of a HVAC system which is capable of maintaining high quality space conditions for aircraft passengers and crew alike.

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End of Report