2 Air Conditioning (ATA 21)

2.1 Definition

Those units and components which furnish a means of pressurizing, heating, cooling, moisture controlling, filtering and treating the air used to ventilate the areas of the fuselage within the pressure seals. Includes cabin supercharger, equipment cooling, heater, heater fuel system, expansion turbine, valves, scoops, ducts, etc. (**ATA 100**)

2.2 Fundamentals

Impact of atmospheric parameters. In the troposphere, the air temperature decreases with increasing altitude. In the stratosphere above 11000 m (36089 ft), the air temperature is at constant -56.5 °C. The air pressure also decreases with altitude. Although the oxygen amounts to approximately 21% independent of altitude, the partial pressure[1] of oxygen drops with increasing altitude. Our body is used to a partial oxygen pressure of about 0.21 times sea level pressure. If we want to survive at high altitudes

a) the oxygen fraction has to be increased (using an oxygen system) or
b) the total pressure has to be maintained close to sea level pressure (using a pressurization system).

For civil aircraft generally option b) is applied; flights in nonpressurized cabins[2] without supplemental oxygen are limited to an altitude of 10000 ft. Military aircraft use a combination of a) and b); cabin altitude[3] does not exceed about 20000 ft.

The **purpose of the air conditioning system** is to make the interior environment of the aircraft comfortable for human beings. Depending on the type of aircraft and altitude of operation, this may involve only *ventilation* of the cabin by supplying a flow of fresh air using air vents. If the temperature must be adjusted, some method of *heating* or *cooling* is required. At high altitudes the aircraft can fly above most of the weather conditions that contain turbulence and make flight uncomfortable. Additionally, the fuel efficiency of the aircraft is increased. *Pressurization* is necessary if the aircraft is operated at these high altitudes. In some parts of the world the relative humidity[4] is quite high. Water extractors are therefore used for *dehumidification* of the cabin air. This is necessary to prevent damage to electrical

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1 **Partial pressure**: The pressure exerted by one gas in a mixture of gases; equal to the fraction ... of one gas times the total pressure (**AIR 171**).

2 **Nonpressurized cabin**: An airplane cabin that is not designed ... for pressurizing and which will, therefore, have a cabin pressure equal to that of the surrounding atmosphere (**SAE 1998**).

3 **Cabin altitude**: The standard altitude at which atmospheric pressure is equal to the cabin pressure (**SAE 1998**).

4 **Relative humidity**: The ratio, expressed as percentage, of the amount of water vapor ... actually present in the air, to the amount of water vapor that would be present if the air were saturated with respect to water at the same temperature and pressure (**SAE 1998**).

and electronic equipment, aircraft insulation and structure. Reduced humidity also limits window and windscreen misting. At an altitude of 40000 ft the relative humidity is quite low (1% ... 2%) compared to the comfort level for crew and passengers (30%). Nevertheless, *humidification* of the cabin air would be impractical for the other reasons named and for the costs involved in carrying that water (**AIR 1609**).

The air conditioning system is a safety-critical system because passengers and crew depend on its proper function. Transport category aircraft will have two independent subsystems to meet these safety requirements. The certification **requirements** include minimum standards. The aircraft manufacturer may choose higher standards in order to increase passenger comfort.

Ventilation:

- Under normal conditions 4.7 l/s (10 ft³/min ≈ 0.6 lb/min) are required for each crew member (**JAR-25** § 831(a)).
- Manufacturers will typically provide a minimum of about 7.8 l/s (1.0 lb/min) for each person in the aircraft.
- In case of a failure (with a probability of not more than 10^{-5} 1/FH) the supply of fresh air should not be less than 3.1 l/s (0.4 lb/min) per person excluding supply from the recirculation system (**JAR-25** § 831(c)).
- In order to avoid draughts, the air velocity in the cabin should be limited to 0.2 m/s (40 ft/min) in the vicinity of the passengers (**AIR 1168/3**). Individual air outlets however show air velocities of about 1.0 m/s. Conditioned air may enter the cabin through cabin outlets at not more than 2.0 m/s.

Temperature control:

- The temperature control from the cockpit may typically be possible in a range between 18 °C and 30 °C.
- Heating and cooling requirements have to be met as specified for various steady state and transient scenarios. Here are some lessons learned:
  - During cruise almost always cooling is required (an exception is are flights without passengers).
  - Cooling loads on the ground on a hot day with passengers on board are higher then in flight.
  - Transient scenarios will probably determine the heating and cooling performance of the air conditioning system in civil subsonic aircraft:
    - Heating the cabin of a cold soaked airplane from -32 °C to 21 °C in 30 minutes (no passengers, no other internal heat loads, doors closed).
    - Cooling the aircraft from 46 °C to 27 °C in 30 minutes (no passengers, no other internal heat loads, doors closed) (**ARP 85**).
  - Cooling requirements for high-speed aircraft are driven by kinetic heating. Kinetic heating occurs when the aircraft skin heats up due to friction with air molecules.

In the flight range below Mach 2, the skin temperature is equal to the recovery temperature[5]: $T_{skin} \approx T_{ambient}\,(1+0.18\,M^2)$, where M is the Mach number.

Pressure control (for aircraft with a pressurized cabin[6]):

- Under normal conditions the cabin altitude in pressurized cabins must not be more than 2440 m (8000 ft) (**JAR-25** § 841(a)).
- In case of a failure (with a probability of not more than 10^{-5} 1/FH), cabin altitude must not be more than 4570 m (15000 ft) (**JAR-25** § 841(a)).
- For passenger comfort, the cabin rate of climb should not be more than 2.5 m/s (500 ft/min) and the cabin rate of descent should not be more than 1.5 m/s (300 ft/min) (**ARP 1270**).
- The flow rate of air for cabin pressurization shall be enough to account for cabin leakage (allowing for an in-service increase of 10% ... 15%) and cabin repressurization with 1.5 m/s (300 ft/min) (**ARP 85**).

2.3 Heating Systems

The simplest type of heating system, often employed on light aircraft, consist of a **heater muff** around the engine exhaust, an air scoop to draw ram air into the heater muff, ducting to carry the heated air into the cabin, and a valve to control the flow of heated air. Alternatively to the heater muff, a portion of the exhaust gases could also be fed to a **heat exchanger** to heat the ram air or the recirculated air from the cabin.

In larger aircraft **combustion heaters** are often employed. The heater burns fuel in a combustion chamber, and airflow around the chamber is heated and carried through ducts into the cabin.

Turbine engine-powered aircraft with a nonpressurized cabin normally make use of hot pressurized air tapped from the turbine engine compressor. This air is call **bleed air**. Temperature control is achieved by mixing the bleed air with ambient or recirculated air before it enters the cabin.

A **pressurized aircraft cabin** is usually heated by regulating the temperature of the air used to *pressurize* the cabin. This again is combined with an effort to *cool* the cabin. The combined process will be addressed in the following subsections.

[5] **Recovery temperature**: The equilibrium temperature of an object placed in a flow ... always less than the total temperature (**AGARD 1980**).

2.4 Cooling Systems

There are several **heat sources** that cause a need for cooling. *External heat sources* include heat transfer through cabin walls and heat received through solar radiation. *Internal heat sources* include passengers and crew, heat generated by electronic, electric, and mechanical equipment.

Cooling systems require **energy** for their operation. This energy may come form ram air, engine bleed air, an engine-driven compressor, or the auxiliary power unit.

Cooling may apply different **heat sinks** to get rid of the heat: ram air, engine fan air, cabin exhaust air, fuel, or expendable cooling media (water or liquid hydrogen). Note that any ambient air taken aboard is at total temperature[7].

The **cooling air** (ram air) may be **moved by** a fan driven by an electric or hydraulic motor, the air cycle machine, or an ejector pump.

The above means may be combined in systems applying **two basic cooling principles**. These systems are known as:

- The *vapor cycle system*, in which the heat of vaporization is lost by evaporating a liquid refrigerant.
- The *air cycle system*, which is based on the reduction of heat by the transformation of heat energy into work.

Combination of both principles is possible.

The **vapor cycle system** (Figure 2.1) is what is used in refrigerators. The cooling process is best explained starting at the *compressor,* where the refrigerant (a special fluid) is in gaseous form. The compressor increases pressure and temperature of the refrigerant and pushes it through the entire system. A heat exchanger called a *condenser* extracts heat from the compressed refrigerant and carries the heat overboard. The refrigerant cools down a little and changes into liquid form. Still under pressure, the refrigerant goes past the *expansion valve* where it is sprayed into little droplets. Behind the expansion valve, pressure is low. With reduced pressure the temperature is also considerably reduced. The *evaporator* is the second heat exchanger in the system. The refrigerant, in the form of cold droplets, cools the air destined for the cabin that goes past the evaporator. By taking up the energy from the passing air in the evaporator, the refrigerant changes to gaseous form again. It now enters the compressor, where the cycle starts anew. Example: Dassault Falcon 10.

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6 **Pressurized cabin**: An airplane cabin that is constructed, sealed, and equipped with an auxiliary system to maintain a pressure within the cabin greater than that of the surrounding atmosphere (**SAE 1998**).

7 **Total temperature = stagnation temperature**: The temperature, which would arise if the fluid were brought to rest adiabatically (**AGARD 1980**).

The vapor cycle is a closed cycle that works with a phase change from gas to liquid and vice versa. The latent heat[8] involved in the phase change makes the vapor cycle very efficient.

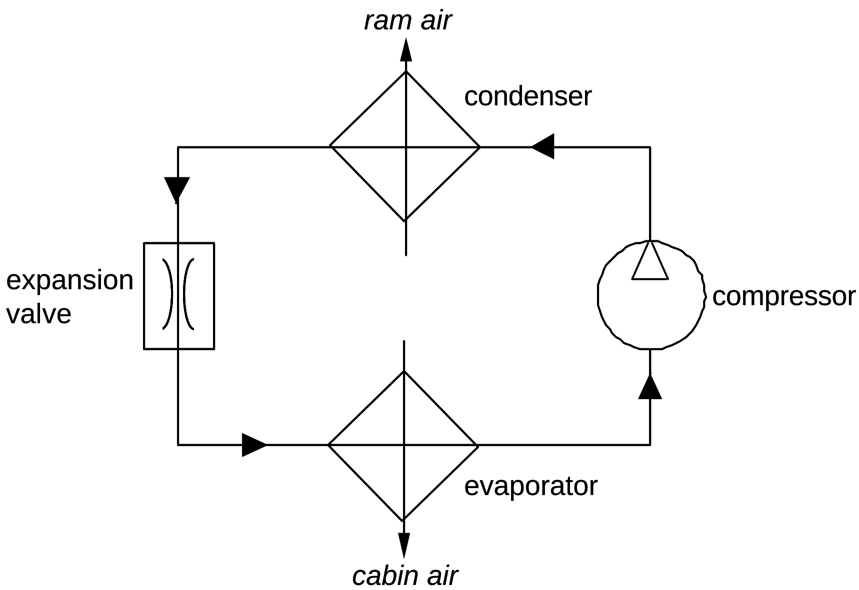

Figure 2.1 Vapor cycle system

If we substitute air for the refrigerant and a turbine for the expansion valve, we basically get a *closed air cycle system*. In aircraft air conditioning, however, the cold air leaving the turbine is used directly as cabin, air forming an *open air cycle system*. Various air cycle systems have been conceived. The discussion here is limited to three open air cycle systems: the *basic air cycle systems*, the *bootstrap system*, and the *three-wheel system*.

In the **open basic air cycle system** (Figure 2.2), bleed air is cooled in a *heat exchanger* with ram air. The bleed air drives a *turbine*, using the pressure differential between bleed and cabin pressure. The bleed air is cooled during the expansion in the turbine. The work extracted from the turbine drives a *fan* that augments the airflow through the heat exchanger. In the cold air behind the turbine, water is condensed in form of minute drops (fog). A *low-pressure water separator* extracts this water. A *bypass valve* is used for temperature regulation and to prevent ice builtup in the water separator. Example: Lockheed C-130.

[8] **Latent heat**: The unit quantity of heat required for isothermal change in a state of a unit mass of matter ... (**SAE 1998**).

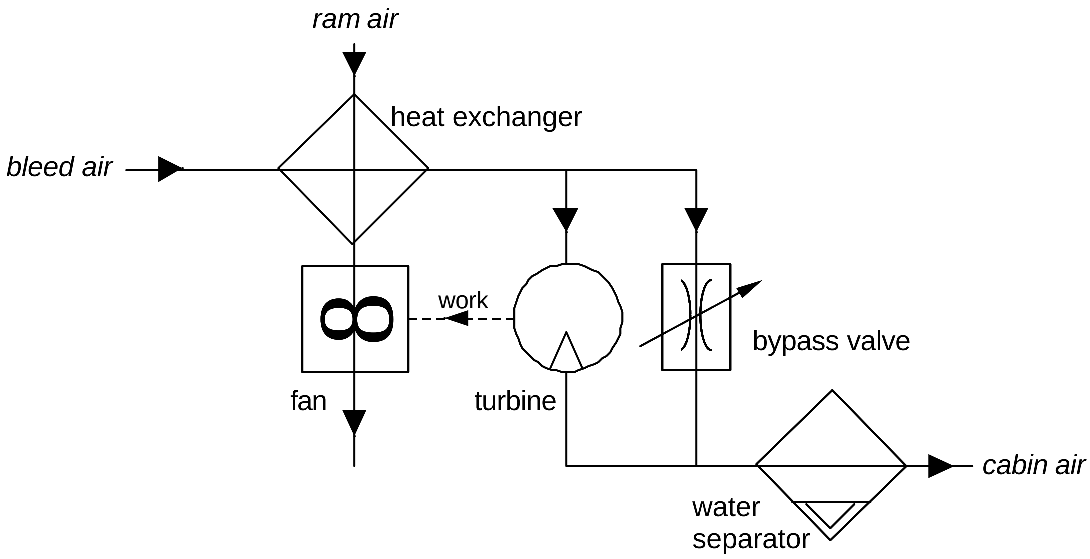

Figure 2.2 Open basic air cycle system

The turbine can also be used to drive a compressor that further increases the pressure of the air supplied to the cooling turbine. A higher pressure ratio leads to a higher temperature drop across the turbine and hence an improved performance. An air cycle system with a turbine coupled to a compressor is called bootstrap system.

The **open bootstrap air cycle system** (Figure 2.3) directs bleed air through a *primary heat exchanger*. The air is compressed and then passed through a *secondary heat exchanger* (or *main heat exchanger*). The air then enters the *turbine*, where it is expanded to cabin pressure. A *low-pressure water separator* reduces the water content. Heat energy is converted into shaft work and used to drive the bootstrap *compressor*. The primary and main heat exchangers are cooled by ram air. The *fan,* used to augment the airflow through the heat exchangers, may be driven by an electric motor. Bypass lines are integrated for temperature control. Example: Boeing 727.

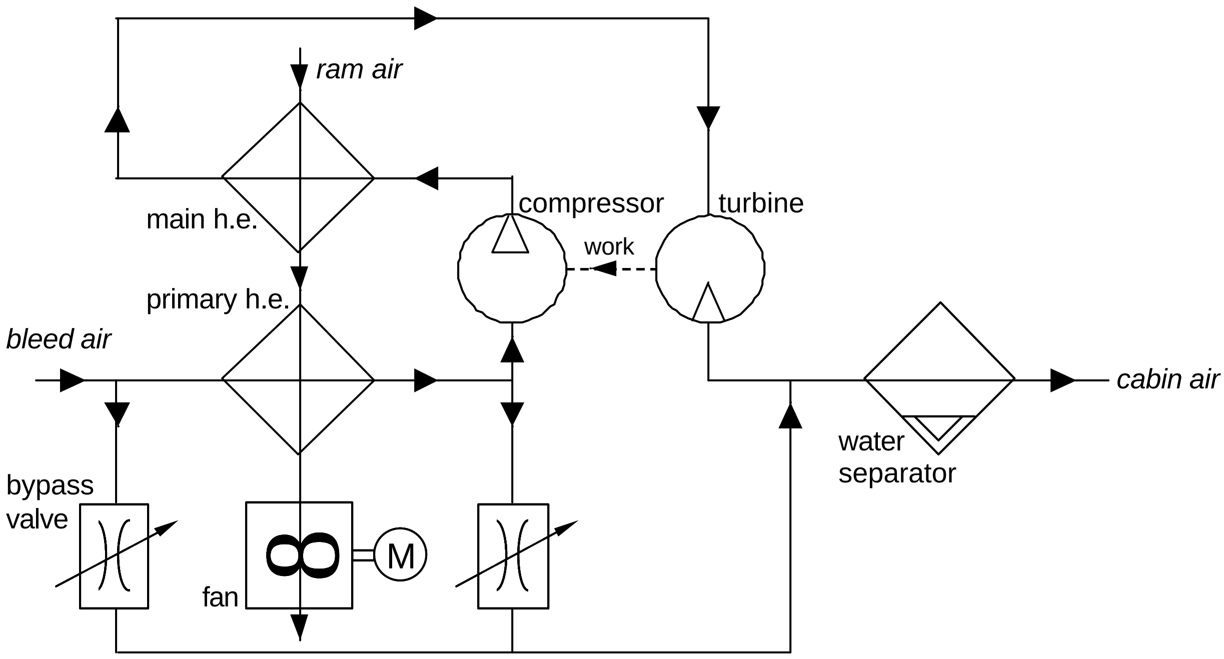

Figure 2.3 Open bootstrap air cycle system

Two types of **water separators** exist. So far we have seen the application of a *low-pressure water separator* that is installed behind the turbine and limits cabin air to temperature above 0 °C. In contrast, a *high-pressure water separator* is installed before the turbine. Separating the water before the turbine requires at least one more heat exchanger: a condenser or a condenser and a reheater. The advantage of the high-pressure water separator is that the air may be cooled down to temperatures of -50 °C. This results in higher temperature differences at the heat exchangers and a higher efficiency of the system.

More recent transport category aircraft use the **open three-wheel air cycle system** with a **high-pressure water separator** (examples: B757, B767, A320). The three-wheel system is a bootstrap system where the turbine drives not only the compressor but also the fan. Figure 2.4 shows this configuration.

2.5 Pressurization Systems

As we saw above, pressurization is necessary to fly at high altitudes (compare with Figure 2.6). The use of pressurization is found in aircraft ranging from light single-engine aircraft up to big turbine-powered transport aircraft. Although the basic controlling mechanisms for each of these types are the same, the **sources of pressure** and details of the system vary. Pressure generation and distribution are the responsibility of the pneumatic system and are discussed in Section 13 in more detail. Reciprocating engines can supply pressure form a *supercharger*, a *turbocharger*, or an *engine-driven compressor*. Turbine-powered aircraft usually use *bleed air* as a source for compressed air. Bleed air is air that is taped form the compressor section of the turbine engine.

Heating and cooling with an open air cycle system provides *conditioned air* to the cabin that is used at the same time for pressurization. Heating, cooling, and pressurization all have to be integrated in such a way that an optimum overall system solution results.

The flow of air into the cabin is approximately constant. **Pressure control** is hence achieved by varying the amount of flow out of the cabin. This is done with a regulated *outflow valve*. The outflow valve may be operated directly, by pneumatic pressure, or by electric motors.

An aircraft must have enough **structural strength** to withstand the stresses caused by a pressurized cabin. The limiting factor as to how high an aircraft can operate is the maximum allowed cabin differential pressure, i.e., the difference between the cabin pressure and the pressure at maximum altitude for which certification is sought: $\Delta p = p_{cabin} - p_{max,alt}$. Aircraft are not intended to fly with a cabin pressure below ambient pressure.

Safety valves are used to safeguard against unauthorized positive or negative differential pressure. A *pressure relief valve* opens automatically if the cabin differential pressure gets above permitted limits. An automatic *negative pressure relief valve* opens automatically if the negative cabin differential pressure gets above permitted limits. A *dump valve* is used to release remaining cabin differential pressure when the aircraft lands. Note that one pressurization control valve may serve more that one function in a specific aircraft design.

2.6 Example: Airbus A321

The Airbus A321 has two *air conditioning packs*, which are open three-wheel air cycle systems. Figure 2.4 shows an air conditioning pack with the air cycle machine, the heat exchangers, and a high-pressure water separator.

The cabin temperature can be adjusted by computer individually in three different cabin zones (Figure 2.5). The air conditioning packs (Figure 2.4) deliver air at a temperature to satisfy the zone with the lowest temperature demand. Air from the packs is delivered to the *mixing unit*. Also, recirculated air from the cabin enters the mixing unit through *filters* and *cabin fans*. The recirculated air amounts to 40% of the total air supplied to the cabin. Recirculated air restores some humidity into the cabin. *Trim air valves* mix hot bleed air with the air from the mixing unit to attain the individually requested zone temperatures.

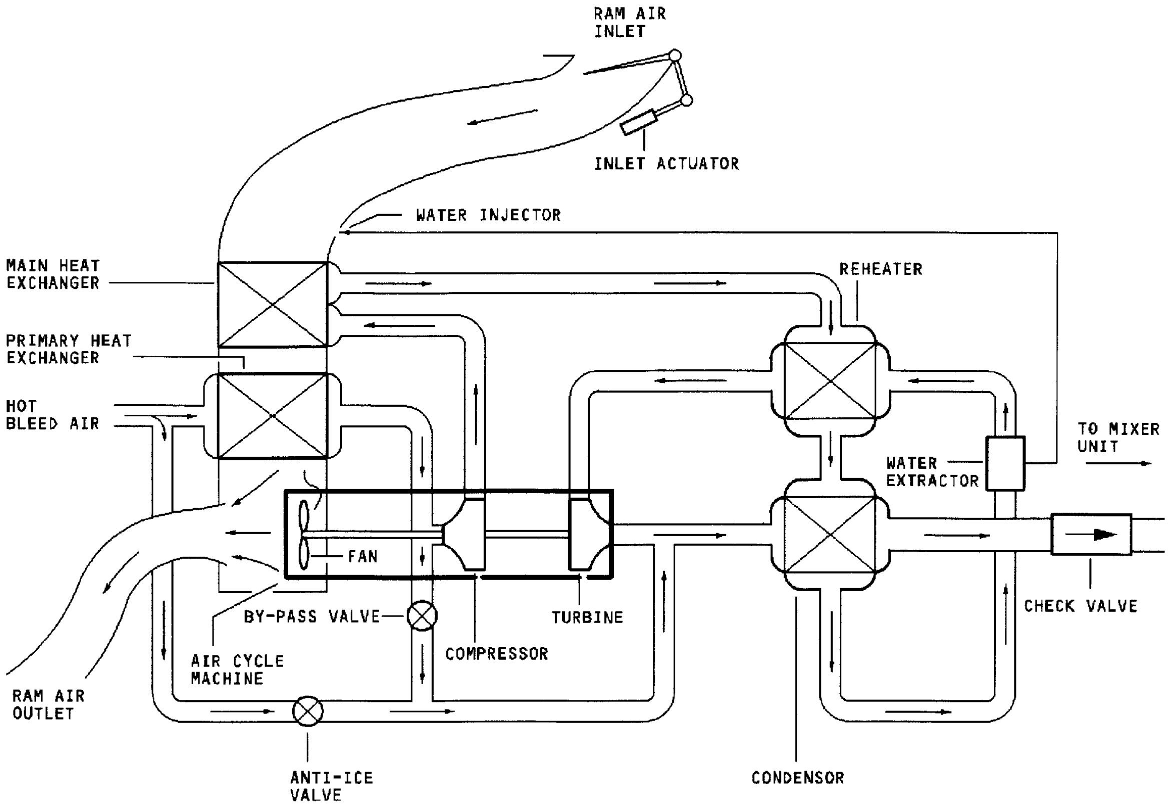

Figure 2.4 A321 air cooling in the "pack"

The pressurization control system includes two *cabin pressure controllers*. Operation may be fully automatic, semiautomatic, or manual. The *outflow valve* is equipped with three electrical motors. Two *safety valves* avoid excessive positive (593 hPa = 8.6 psi) or negative (-17 hPa = -0.25 psi) differential pressure (compare with Figure 2.6).

Figure 2.7 shows the *air distribution* in the cabin.

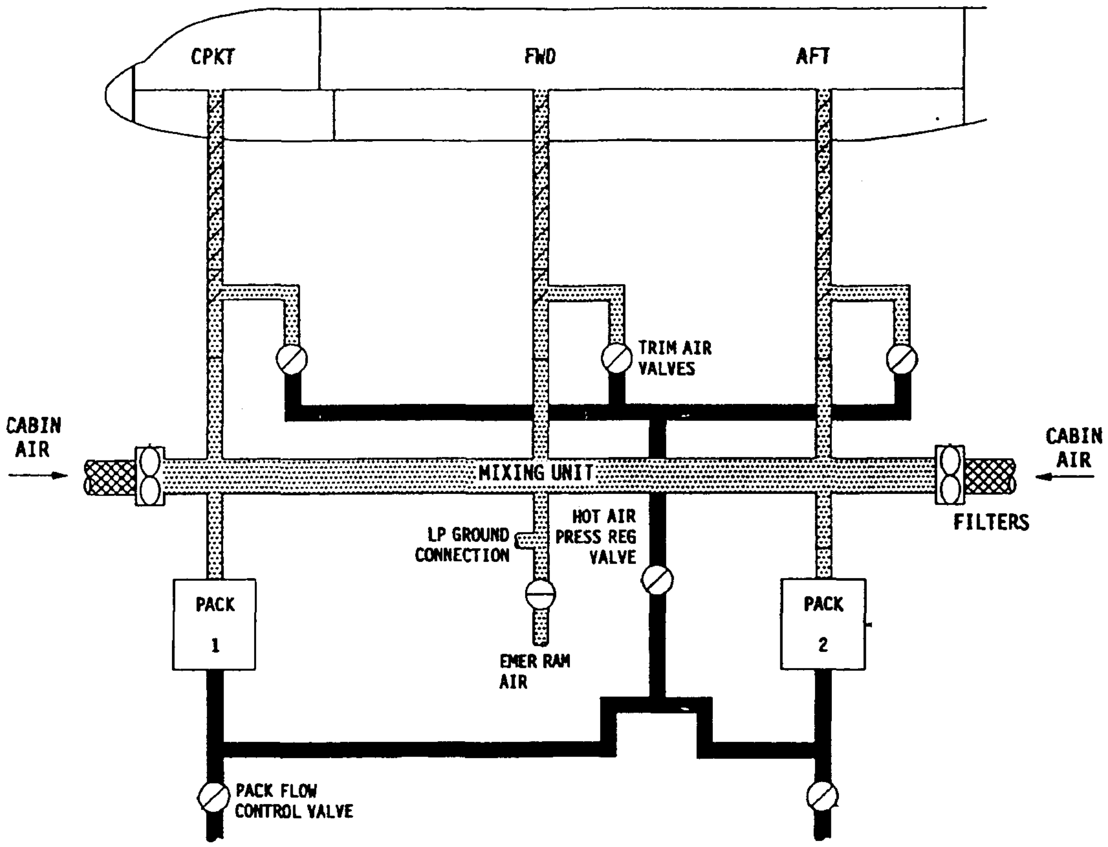

Figure 2.5 A321 air conditioning

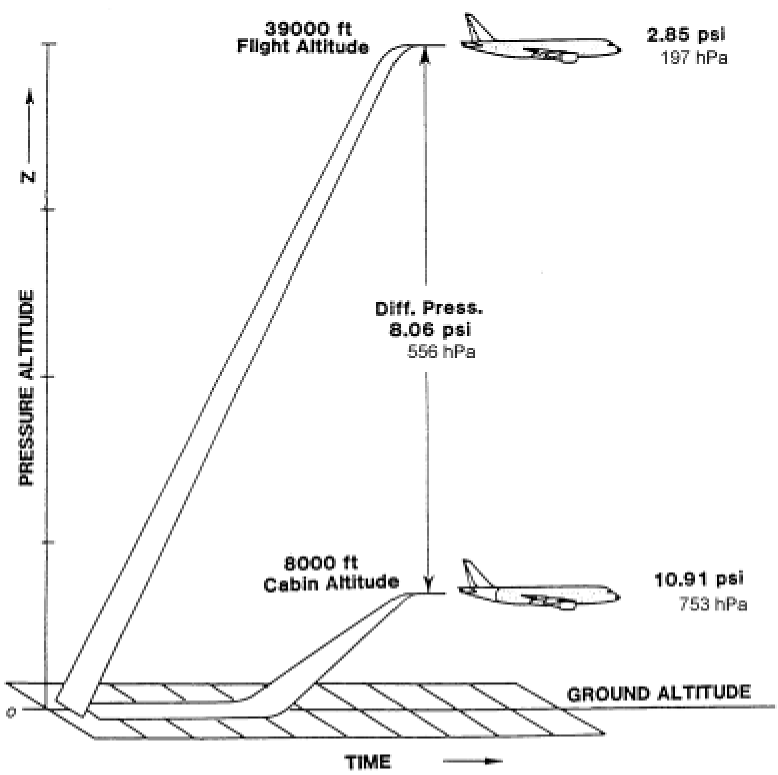

Figure 2.6 A321 pressure control

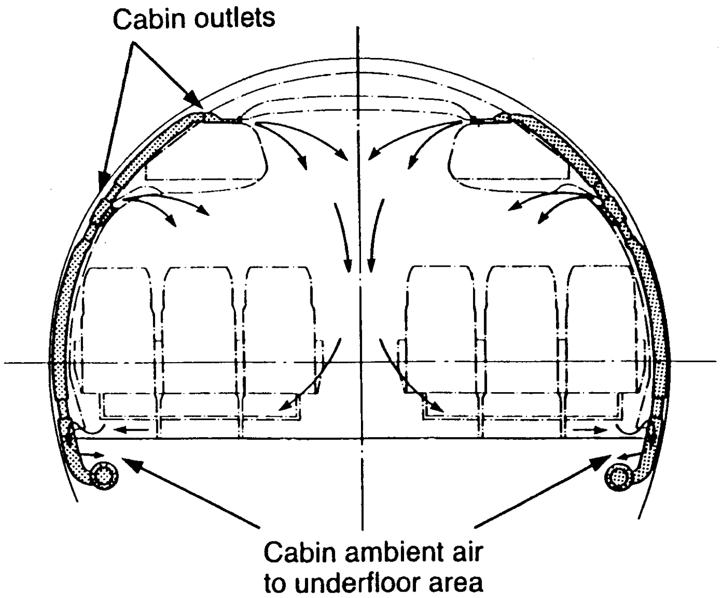

Figure 2.7 A321 cabin air distribution