

Aircraft Cabin Air Supply and the Internal Air System

Peter RN Childs¹

1. Imperial College, London, U.K.

Corresponding author:

Peter RN Childs

p.childs@imperial.ac.uk

Key words

cabin, bleed, air, internal, turbine, compressor, system, electric, driven, contamination, oil

Abbreviations

(none)

Abstract

This paper describes systems commonly employed to deliver aircraft cabin air, and the internal air system which is responsible for the supply of balancing, sealing and cooling air used with the engine to control the operation of bearings, discs and other critical components, as well as bleed air. A series of mechanisms that could be responsible for contamination of bleed and cabin air are considered including: ingestion into the compressor intake of poor quality air; leakage from a seal of oil; ingestion from the gases associated with a stall or surge event; off-gassing of cabin fittings and emissions from occupants.

Introduction

Operation at high altitudes enables the efficient operation of a jet engine which improves with temperature ratio, pressure ratio and, in the case of a turbofan, by-pass ratio as well. A typical jet engine will comprise a compressor, combustor, turbine and jet nozzle. Air is drawn in through an intake and passes through a series of stages of stationary and rotating blades that guide and add rotational energy to

the flow, thereby compressing it, prior to the air entering a combustor where fuel is added increasing the temperature of the compressed flow. Following the compressor, the gas flow passes through a turbine comprising a series of stationary and rotating blades which are designed to guide the flow and expand it allowing the energy within the flow to be converted to rotational power, which is used to drive the compressor. If sufficient energy is added in the combustor, then the gas flow exiting the turbine will still have significant energy associated with it and this can be used to expand within a jet nozzle to produce thrust.

Different configurations of jet engine provide advantages for particular applications, with turbofans and turboprops common in modern passenger aircraft. In a conventional turbojet where all the gases that enter the intake pass through the combustor the exiting air from the jet nozzle will still contain substantial levels of energy associated with heating the gas flow. An alternative more efficient configuration is the turbofan where only a fraction of the intake air is heated in the combustor. This form of engine is used for the vast majority of modern jet engines. For short city hops or heavy lift configurations a turbo-prop can provide an efficient solution with a gas turbine engine driving a propeller which provides the thrust for the aircraft.

While the principles of operation of a jet engine can be understood in terms of the momentum change between the gases flowing into the engine and those exiting it, the detailed machinery involves a considerable number of subsystems and advanced engineering. Examples include the fuel system, oil system, cooling air system, balancing air system, compressor stages, combustors, turbine stages, engine nacelle, sensors and control systems. Texts such as Rolls-Royce and Saravanamuttoo et al. provide introduction and in-depth consideration of the fundamental operation of the jet engine.^{1,2} In this paper consideration of the subsystems relevant to the operation of cabin bleed off-takes and sealing of bearings for compressors is given. Section 2 provides an introduction to the internal air system of a typical gas turbine engine. Section 3 provides an introduction to options for the supply of aircraft cabin air. Section 4 explores potential scenarios for the contamination of cabin air.

The Internal Air System

The internal air system of a gas turbine engine whether for aviation or other purposes,³⁻⁵ serves a variety of purposes including balancing of the thrust loads on discs, sealing of systems and providing cooling air and in the case of some aircraft cabin air. In order to provide the air necessary for these purposes bleeds from the compressor are made at various locations along the compressor, depending on the pressure required. The air is then supplied through a series of ducts and vents throughout the cabin.⁶⁻⁸ Compression of air requires energy and, in general, efforts are made to minimise such flows in order to minimise fuel consumption.

A key characteristic of the internal air system is the transfer of flow from one location to another. This will include oil, cooling and sealing air. For some components it is necessary to transfer air from a stationary component to a rotating component. Use is made of a variety of types of seal in order to exclude contaminants from a region of machinery or to aid the transfer of flow. Seals commonly used in gas turbine engine applications, where sealing is required between components rotating relative to each other, include labyrinth, brush and mechanical face seals.^{9,10} Each type of seal has its merits and under specified conditions can provide high levels of sealing performance. In general, a seal used between components with relative motion will permit some leakage. The level of leakage can be reduced by minimisation of the running clearance between components and, if an additional source of high pressure supply is available, use of additional sealing air can, for example, be used to help ensure exclusion of a contaminant.

A typical bearing system in a gas turbine engine will comprise a rolling element bearing fed with a supply of oil in order to improve the wear characteristics of the bearing and remove heat. This oil will normally be provided in the form of a fine spray or continuously pumped into fine feed holes within the bearing. Excess oil will spill off the raceways of the bearing and be collected within a sump and a pumping system used to enable recirculation of this oil via a de-aerator and heat exchanger and filters so it can be used again. Seals are used either side of the bearing to minimise or prevent loss of the oil. Different types of seals are used in different regions of the engines with the choice depending on parameters such as the nature of the fluid or particles to be contained or excluded, pressure levels, the level of

sealing required, life, servicing, temperature of operation, running clearances, relative growth of components, space available and cost.

A key issue with operation of safety critical machinery is consideration of reliability and failure. Significant changes in the location of components in a gas turbine engine occur between start-up when the engine is cold and stationary and its running conditions at cruise or full power, due to temperature differences and centrifugal effects due to the high-speed rotation of the discs. These relative growths need to be considered in the detailed design of components and subsystems in combination with a desire to minimise the mass of the engines.³ As a result of such consideration significant use is made of interstitial seals such as labyrinth seals.⁹ These allow for relative motion between components but do involve some leakage which is a function of parameters including clearance between the fin tips and the casing, the pitch, angle, height and number of the fins, the sealing surface, eccentricity and pressure ratio. In the case of stepped labyrinth seals additional parameters include step height, configuration, distance from seal fin to step face and flow.¹⁰ Labyrinth seals can provide high levels of sealing functionality across a wide range of operating conditions and provide significant resilience in harsh environments. Use of stepped and blown configurations can further improve performance. Brush seals, which comprise a large number of small wire elements, can also be used in some locations, but can be susceptible to damage and blow through. Mechanical face seals, in theory provide a higher level of sealing. These seals comprise a sealing element such as a sprung carbon face running on a hydrodynamic film of lubricant. Such seals require relatively smooth levels of operation, in comparison to a labyrinth seal and are less resilient to vibration, run-out, eccentricity, and relative movement between components.

Cabin Air Supply Options

A series of technologies have been developed to provide pressurised cabin air including use of:

- Oxygen tanks
- Turbo-compressors
- Auxiliary power unit (APU) driven compressors

- Bleed air from the compressor of a jet engine.
- Electrically driven compressors

Early high altitude flights made use of pressurised oxygen tanks. Subsequently military and civil airliners used a radial turbine driven by exhaust gases to drive a centrifugal compressor or blowers to pressurise sufficient air for cabin use. The quantity of air required needs to be sufficient to provide replenishment of depleted oxygen levels but also sufficient for provision of fresh air and management of heat levels. Typically, the cabin air system will comprise a network with some air recirculated augmented by fresh air supplied from a compressor. A proportion of the air entering the recirculation system is exhausted ensuring a continuous supply of sufficiently oxygenated air. FAR 25 mandates the supply of 0.55 lb/minute per passenger (see also Timby (1970)), which represents a considerable flow-rate for a typical passenger aircraft requiring a drive of a few hundreds of kilowatts. The auxiliary power unit, a small gas turbine engine used to drive a generator to provide electric power, can also be used to drive a compressor to supply cabin air or to augment a cabin air supply. An expedient solution for the supply of compressed air is to bleed this from the axial compressor of a turbojet or turbofan. This approach has been used in the majority of passenger aircraft over recent decades. Recently the Boeing 787 has implemented a system using electric motors to drive a compressor.

Concerns have been consistently raised with cabin air quality and studies offering diverse views on the subject.¹¹⁻¹⁶

Cabin Air Bleed Contamination

A variety of mechanisms are plausible for contamination of cabin air depending on the system concerned. These include

- 1) Ingestion into the compressor intake of poor quality air (re-ingestion of exhaust on the runway; ingestion of exhaust air from another aircraft on the runway; intake vortex ingestion; flight-path gas ingestion)
- 2) Leakage from a seal of oil (in operation or pooling of oil in a nacelle)
- 3) Leakage from a seal of oil from a worn or malfunctioning seal
- 4) Ingestion from the gases associated with a stall or surge event

- 5) Off-gassing of cabin fittings
- 6) Emissions associated with occupants.

When an aircraft is on a runway it is conceivable due to the direction of winds, that a proportion of exhaust gas is driven back towards an intake nacelle and re-ingested. Similarly if an aircraft is following another aircraft closely on a runway ingestion of a small proportion of exhaust gases from the preceding aircraft is plausible. A jet engine or APU will emit a variety of substances formed by the high-temperature combustion of jet fuel during flight/taxiing in its exhaust including:

- water vapour,
- carbon dioxide (CO₂),
- small amounts of nitrogen oxides (NO_x),
- hydrocarbons,
- carbon monoxide,
- sulphur gases,
- soot and metal particles

As such if ingestion of a jet engine exhaust occurs, any or all of the above substances could enter the compressor and therefore enter the cabin, regardless of whether a bleed system is being used or an electrically driven compressor.

The large mass flows associated with a jet engine, can under certain conditions, lead to the formation of an intake vortex,⁵ with a highly swirling source flow located on the runway surface leading to ingestion of dust, debris and surface fluids into the engine nacelle. While a relatively rare occurrence, if such conditions were to occur for a cabin air system where the supply is derived from bleed air then there is a risk that any contaminants could enter the cabin air supply.

Air traffic management has resulted in the use of air traffic 'corridors' with aircraft flying in the vicinity of air previously occupied by another aircraft. The nature of the free vortex produced by wings which sweep up jet exhaust and wingtip flows means that the air disturbed by one aircraft remains associated with the free vortex for some period until it is dissipated. The period concerned for a free vortex to be dissipated can be orders of magnitude more than the initial disturbance that caused it.⁵ A potential mechanism for contaminated air entering into a compressor is ingestion of

the dissipating exhaust gases from a previous aircraft that has flown through the airspace.

A bearing requires a continuous supply of oil in order to reduce friction and associated wear, and to remove heat. Oil is typically supplied continuously to a bearing and the used oil displaced or flung off the bearing is captured, cooled and filtered and recirculated in a bearing oil system.¹⁰ The nature of the seals whether mechanical, lip or interstitial means that some of this oil will leak out from the seal. In the case of mechanical face seals, the pads run on a hydrodynamic film of fluid. If there is, for example, vibration or a transient pressure difference it is plausible that some of the fluid associated with this hydrodynamic film could leak or be displaced from the seal. Indeed the need to replenish or top-up oil for the majority of engine types indicates such losses, albeit small quantities. The layout of an axial compressor, the typical form of compressor used in a turbofan, makes a plausible pathway for such leakage oil to find its way into a bleed system highly tortuous and convoluted. Possible routes that might be possible, under a series of aligning conditions include surge and stall, where transient reverse flows occur in the mainstream, breakage, malfunction or substantial wear of a seal leading to large scale leakage flows, pooling of oil following a shutdown. If a seal is worn, or subject to a pressure differential outside its design scope it is likely that the flows through it will be substantially higher than expected with the potential for spillage of oil into regions of the engine not designed for its containment. In the case of fan and compressor bearings, it is conceivable that pressure differentials and centrifugal forces could result in such spilled oil, if it was to occur, being spun around with the compressor drum assembly and if there are any abutment joints associated with this passing through these.

As indicated in the previous paragraph a bearing is supplied with a continuous flow of oil. If on shut down of an engine, the clearances are such that an egress of oil can occur, then it is plausible that this oil could pool in certain locations within an engine. The nature of a jet engine is that the exhaust has a smaller diameter than the intake. A further factor is that some modern engines have an asymmetric nacelle in order to accommodate the large diameter of the engine and provide adequate ground clearance. Either or both of these factors, combined with any leakage paths between

cylindrical joints in the compressor drum or turbine assembly could result in pooling due to gravity of leaked oil in the vicinity of the front fan on the lower diameter of the engine nacelle. Such liquid on start-up could plausibly be spun around the compressor, especially given the low axial velocity components on start-up, and potentially be supplied to bleed offtakes. Such a situation could potentially be mitigated by operational practice and use of a ports to allow venting prior to ducting bleed air into a cabin.

Off-gassing of plastics and fabrics has been associated with some alleged incidences of sick-building syndrome.^{17,18} Tris (2-chloro-1-methylethyl) phosphate (TCPP) and other chemicals are included in some foams and polymer materials as fire retardants. It is plausible that some emission of polymer associated chemicals relating to seats, carpets and cabin surfaces could occur, especially with newly built aircraft. A further consideration for air-quality in a cabin is any emission associated with a cohort of passengers and crew due for example to use of fabric chemicals, and personal hygiene products.

It should be noted that the plausible mechanisms for possible contamination of cabin air described in this section are subject to conjecture. Although plausible this does not mean that any or all of these mechanisms do actually occur. Nevertheless engineering practice involves detailed consideration of the possibility of a risk and its mitigation if there is likelihood of the risk occurring. As such each of these mechanisms warrants consideration. The majority of the scenarios described could be wholly or partially mitigated by the use of filtration within a cabin recirculation system.

Conclusions

In order to provide adequate levels of fresh air to passengers and crew for aircraft flying at altitude a range of technologies have been developed typically employing either a dedicated driven compressor or bleeding air from a jet engine compressor. This paper has examined a variety of mechanisms that seem plausible for the possible contamination of cabin air depending on the system concerned. These include

- Ingestion into the compressor intake of poor quality air (re-ingestion of exhaust on the runway; ingestion of exhaust air from another aircraft on the runway; intake vortex ingestion; flight-path gas ingestion)
- Leakage from a seal of oil (in operation or pooling of oil in a nacelle)
- Leakage from a seal of oil from a worn or malfunctioning seal
- Ingestion from the gases associated with a stall or surge event
- Off-gassing of cabin fittings
- Emissions associated with occupants.

Each of the plausible mechanisms for possible contamination of cabin air described is subject to conjecture. All of the mechanisms apply in principle to compressor bleed systems. Several of the mechanisms apply in principle to a dedicated driven compressor cabin air system. The majority of the scenarios described could be wholly or partially mitigated by the use of filtration within a cabin recirculation system.

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