Aircraft Cabin Air Quality and Filtration

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This paper focuses on air filtration technologies utilized in modern commercial and military aircraft to maintain cabin air quality for passengers and crew. This filtration is critical because the industry's shift toward high-altitude, fuel-saving operations requires the Environmental Control System (ECS) to recirculate a portion of the cabin air, exposing occupants to potential hazards from both engine bleed air and the confined cabin environment. To purify recirculated air, modern aircraft primarily utilize High-Efficiency Particulate Air (HEPA) filters. This study compared three common HEPA filter geometries—the Pleat-Plate, V-Shape, and Cylindrical filter structures—finding that while all provided similarly high filtration efficiencies, the Cylinder filter demonstrated superior overall performance. The Cylinder filter exhibited the lowest initial resistance and the best energy consumption rating, in addition to providing a 17% longer service life. This superiority stems from its design features, which encourage inertial deviation for larger particles and a unique cylindrical pleat structure that promotes deeper dust deposition, thereby mitigating the increase in airflow resistance over time.

Nomenclature

ECS = Environment Control Systems

FAA = Federal Aviation Administration

HEPA = High-Efficiency Particulate Filters

PACK = Pressurized Air Conditioning Kit

SVOC = Semi-Volatile Organic Compound

VOC = Volatile Organic Compound

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I.Introduction

This paper focuses on air filtration technologies used in modern commercial and military aircraft to maintain cabin air quality during flight for passengers and crew.

In the 20th century, the search to minimize aircraft operational costs led to the exploration of flights at higher altitudes, where reduced drag allows the aircraft to consume less fuel. Modern airplanes fly at altitudes that come close to the troposphere, where fuel costs can be decreased up to 38% [1, 13].

At these high altitudes, the atmospheric conditions are not adequate for human presence and the low pressure, temperature and oxygen concentrations can cause discomfort and physiological issues to the aircraft occupants. The aircraft Environmental Control System (ECS) is responsible for keeping the cabin air conditions habitable to passengers and crewmembers during flight. To regulate cabin pressure, temperature and humidity at adequate levels for human beings, the ECS takes 75% of the required bleed air from the engines, making it one of the primary non-propulsive power consuming systems on board the entire aircraft environment [2, 12].

The use of bleed air makes the engines less efficient and increases the operational costs of flight. To further decrease the airplane's fuel consumption, the modern ECS is designed to consume less bleed air by recirculating a portion of the cabin air. Both bleed and recirculated air can contain chemical and biological contaminants harmful to human health. As a result of cabin air recirculation, the passengers can be exposed to such contaminants for prolonged periods. To mitigate the risks to occupant health and to maintain air quality in the cabin, modern aircraft use air filters to purify the recirculated air [1].

To explore the themes of cabin air quality and filtration, this paper is structured as follows: Section II details the Environmental Control System (ECS), its components and functioning. Section III identifies the main chemical and biological contaminants found in cabin air. Section IV presents and analyzes the main air filtration technologies used to mitigate these contaminants, and finally, Section V provides the concluding remarks.

II.Environmental Control System

The ECS is an essential onboard system that guarantees habitable conditions for aircraft occupants. It is a vital system to ensure passenger safety and comfort at high altitude flight. As altitude increases, pressure and temperature decrease and the consequences of human exposure increase in severity. Exposure to the atmosphere at 40,000 ft, around where most commercial modern aircraft fly, can cause death in a matter of seconds [2, 12].

To avoid these severe consequences for aircraft passengers, regulatory agencies, such as the FAA, limit the cabin pressure conditions at normal operations to those equivalent to an 8,000 ft atmosphere at maximum [3], which is the limit for the capacity of oxygen assimilation for a healthy person [2]. The purpose of the ECS is to maintain these safe and comfortable conditions required by regulations and passenger necessities.

A. ECS Structure and Functioning

The ECS covers several critical areas and in general encompasses several subsystems that cooperate to keep the cabin environment habitable. Figure 2 displays a simplified scheme of the air supply and conditioning system in an airplane.

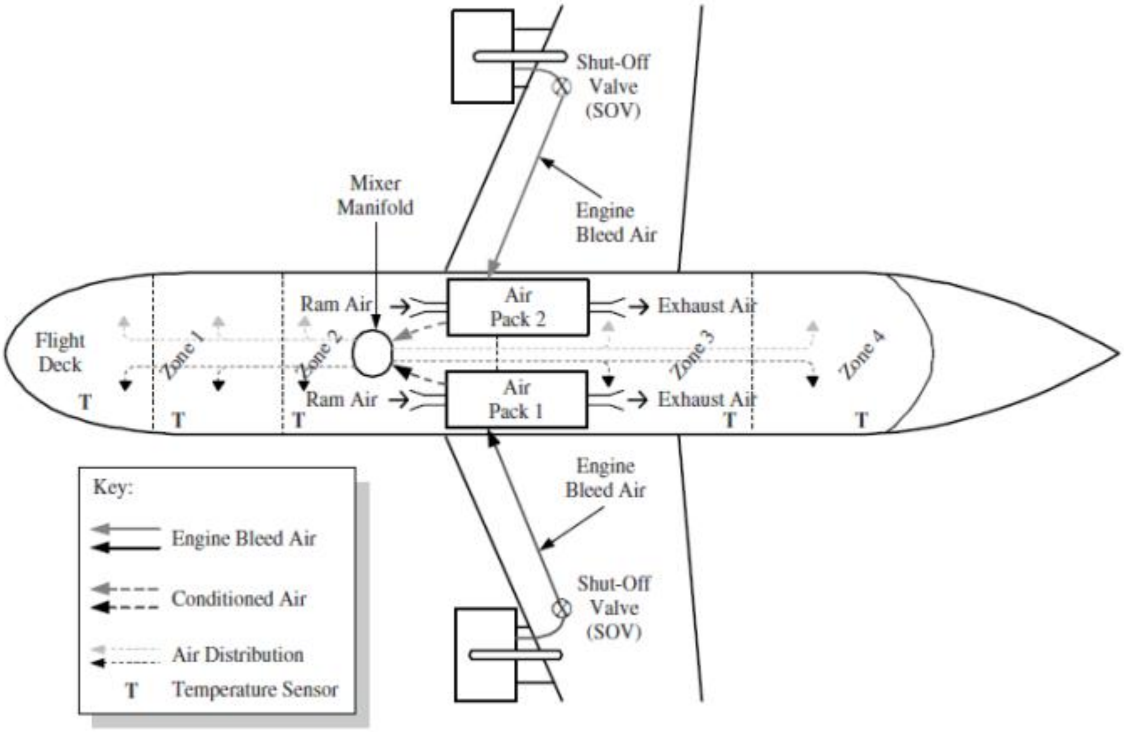

Figure 1 - ECS System [21]

The ECS begins to work at the boarding of the airplane passengers and finishes with their disembarkation at the destination. The air supply and temperature are selected by the crew and the autopilot works to maintain the air properties and quality as selected. Cabin pressure is controlled by valves located at bottom of the aircraft that exchange air with the atmosphere. Air temperature is maintained by mixing hot bleed air from the engines with cold ram air [2, 13].

The Air Supply System takes high-temperature and high-pressure bleed air from the engine high-pressure or intermediate-pressure compressor stages. This bleed air consumption by the ECS interferes with the engine compressor operating point and consequently reduces the engine performance, making the ECS one of the primary non-propulsive power consuming systems [2, 14].

The hot bleed air then goes into a pre-cooler to bring the air to a temperature and pressure compatible with the air conditioning PACK operation. The air temperature is further decreased on the PACK using Ram air, that is not mixed with the air that goes into the cabin, inside its primary and secondary heat exchangers, bringing the air conditions closer to the ones required by the cabin inhabitants. The water condensed during the turbine expansion is then removed by a water separator [2, 14].

Finally the conditioned air that exits the PACKs is mixed with filtered recirculated cabin air in the Mixer Manifold, where the air finally all meets the humidity, temperature and pressure conditions to be delivered [21].

Since most aircraft use around 50% recirculated air to supply the cabin in order to consume less bleed air and save fuel, the air must go through a series of filters (carbon dioxide filter, ozone filter and HEPA filter) before supplying it to the cabin, since different contaminants can be present both at the bleed and recirculated air [1].

III. Cabin Air Contaminants

The air supplied to the cabin environment consists of a mixture of bleed air from the engines and recirculated cabin air, both sources of air supply can be contaminated with chemical and biological hazards.

Bleed air is composed by fresh outside air from the atmosphere and in normal operation conditions is designed to be taken from the engine without any contaminant. This does not mean that the bleed air is completely safe, it can become contaminated with engine oil, hydraulic fluids and byproducts of the combustion if the system components designed to contain those substances are faulty, leaking into the ventilation system. As bleed air is high-temperature, leaking liquids exposed to it can evaporate and introduced into the passenger environment [4].

Recirculated air is taken from the cabin environment itself and thus is not fresh. The high number of commercial aircraft occupants corroborates to high concentrations of biological contaminants (such as viruses, bacteria, and mold).

The cabin may also present concentrations of byproducts of human respiration, such as carbon dioxide, that are hazardous to human if the air is not properly treated [4].

This section focuses on understanding the most common air contaminants that may be present on aircraft cabin. Then in the following sections, the methods to remove air contaminants and maintain air quality can be completely studied.

A. Carbon Monoxide

Carbon monoxide is a toxic gas that in high concentrations can cause anemic hypoxia to humans [5], due to its bonding with blood's hemoglobin which prevents the transportation of oxygen through the body [6]. Because of this severe effect that can lead to death if exposed for a sufficient amount of time, regulators, such as the FAA, established a limit of 50 ppm for CO concentrations to maintain cabin air quality and assure occupant safety [7].

CO is generated by incomplete combustion. Since no combustion takes place inside the ECS and it is designed to prevent that engine exhaust air containing this toxin is taken as bleed, under normal operation conditions and with proper system maintenance the CO concentrations do not exceed 2 ppm, which is below the limit enforced by aviation authorities and presents no harm to the aircraft occupants. Even during ground operations, when the airplane is close to ground servicing vehicles exhausting CO from engine combustion, the CO concentration does not exceed 10 ppm and does not present a hazard.

B. Carbon Dioxide

Carbon Dioxide (CO_2) is a gas naturally present in the atmosphere in around 350 ppm. It is a product of combustion, but this is not the main source of contamination since the ECS design and proper maintenance should prevent that CO_2 from the engines enters the ventilation system. In other hand, the cabin occupants produce this gas as a result of the respiration process and is the main source that can elevate the concentrations in the cabin environment. The dry-ice used in galleys to cool galley storage is a secondary relevant source of this gas [6].

Human exposure to high concentrations of this CO_2 can cause headaches, restlessness, and asphyxia for prolonged exposure [5]. Therefore, the FAA requires a limit of 5000 ppm for CO_2 in the cabin air to guarantee passenger safety and crew member work capabilities [7].

C. Volatile and Semi-Volatile Organic Compounds

Volatile and semi-volatile organic compounds (VOCs and SVOCs) are carbon and hydrogen chains that can or not contain other element as oxygen or nitrogen. The majority of these components found in the cabin are from human, food or beverage origin and pose no harm to passenger and crew. The ones that represent a concern for air quality are those that originate from engine lubricants and hydraulic fluids. Particular concern surrounds tricresyl phosphate (TCP) that can be associated with neurotoxic effects and to affect the behavior of the peripheral neural system [5].

In normal operations and in specific leakage conditions, the aircraft systems are designed to prevent oil and hydraulic fluid entering the ECS. One example of design is positioning the ventilation above the hydraulic lines. As a result, it is not common to VOCs and SVOCs to be significantly present in the cabin to significantly affect air quality [6].

D. Ozone

Ozone (O_3) is an instable gas that has greater natural concentration in higher altitudes of the atmosphere, peaking at 65000 ft. Nonetheless, pockets of ozone can be present at 30000 ft, where commercial airplanes fly, depending on the latitude and time of the year. To human beings, ozone is an extremely toxic substance that can cause irritations and serious damage to the respiratory system [6].

In concern of this severe consequences of ozone intoxication, the aviation regulatory agencies have stablished that the concentrations of ozone in the cabin environment shall not exceed an average of 0.1 ppm in any 3 hour period above 27000 ft and the maximum concentration shall be 0.25 ppm anytime the aircraft is flying above 32000 ft [8].

At cruise altitude, the ozone concentration can reach 1 ppm for short periods of time, which significantly above the maximum permitted by regulators to assure cabin air quality and occupant safety. Therefore it is necessary that the aircraft has a strategy to filter ozone from the ventilated air [6].

E. Biological Contaminants

The most common biological contaminants found aircraft cabins are viruses, bacteria, fungi and molds. The main source of those are the humans inhabiting the aircraft, contaminated with a diverse microbiota. Among organisms, there can be some that are the cause of different diseases such as influenza, tuberculosis, and COVID-19, among others [6, 15, 17].

Since the aircraft cabin is a confined space, with limited external air exchange due to recirculation, and high occupant density, the environment has the potential to quickly become contaminated with viruses, bacteria, fungi and molds that can cause disease to human beings, then contributing to spread illnesses [1, 15, 17]. This has been a concern for authorities and aircraft manufacturers since the start of recirculation of cabin air in the 1940s [1], and became a special highlight of concern during the covid-19 pandemic. To minimize the risk of spreading diseases through the cabin, it becomes necessary to filtrate the air that is recirculated back using technologies used for maintaining air quality in hospitals, such as the HEPA filter [1]. This will be the focus of Section IV.

F. Particulates

The final air contaminant presented in this article is particulates, especially dust that can enter the aircraft environment. These particles can cause different effects on the occupants such as irritations and respiratory disorders. Even if its effects may not be as severe as the contaminants discussed in the previously in this section, it can affect general passenger comfort during the flight and should be filtered to maintain air quality [6].

IV.Cabin Air Filtration

In order to assure the cabin stays free from the before mentioned common contaminants and assure appropriate air quality for the airplane occupants several filter technologies were developed. Recirculated air is usually filtered right before it enters the mix manifold of the air conditioning system. Bleed air can be filtered either at source, where it has great pressure and temperature, or after leaving the air conditioning pack, in less extreme conditions. For the first case, the filtering technologies for bleed air would be very distinct from the ones used for recirculated air [4].

A. Recirculated Air Filtration

Recirculated air-filtration systems are designed to improve the health and comfort of passengers and crew by effectively controlling bacteria, viruses, dust and other contaminants from the cabin air. The air conditioning system ensures that the recirculated air goes through a filter before re-entering the main airflow. The main challenge of this filtration is wide range of contaminant sizes, from viruses with 0.01 μm in diameter to particles up to 10 μm. Table 1 illustrates the size variation of particles contained in the recirculated air [4].

Table 1 – Dimensional Comparison [4]

Item	Diameter (μm)
Human Hair	~ 30-50
Red Blood Cell	~ 8.0
Mycobacterium Bacteria (Tuberculosis)	0.2-1.0
Pneumococci Bacteria (Pneumonia)	0.5
Influenza Virus (Flu)	0.1

Rhinovirus (Common Cold)	0.03

In order to efficiently remove undesired particles from a large dimensional range, air filters mainly utilize the mechanisms listed below, and their combinations.

I. **Direct Interception:** this mechanism is present in filters that consist of a match of precisely sized pores. When a particle dimension exceeds the pore size it gets trapped through direct contact to the filter's surface. Similar to a sieve separating rocks from sand [4]. Figure 2 illustrates direct interception.

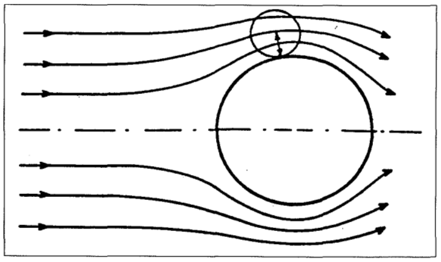

Figure 2 – Particle caught by interception [20].

II. **Diffusional Interception:** particles significantly smaller than the filter's pore size (such as viruses) can pass through mesh pores. These contaminants are affected by the Brownian motion of the air particles, making their paths oscillate randomly and increasing the probability of colliding with a fiber from the filter's mesh and getting captured from the cabin air. This mechanism primarily affects particles with diameter smaller than 0.1 μm [4]. Figure 3 illustrates diffusional interception.

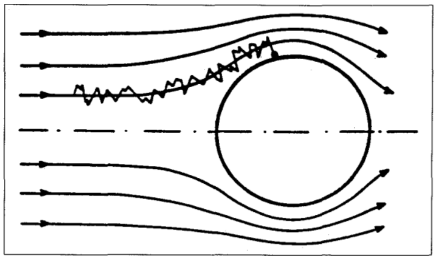

Figure 3 – Particle caught by diffusion [20].

III. **Inertial Impaction:** these mechanisms filters particles that are denser that the air as they eventually deviate from the airstream and collide with the filter's fibers. This works best for particles in the range from 0.3 μm to 10 μm [4]. Figure 4 illustrates the inertial impaction mechanism.

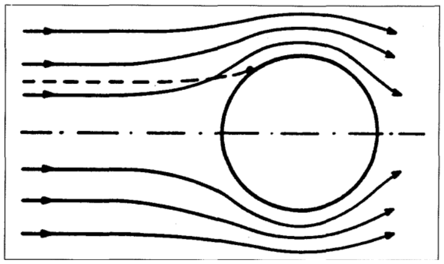

Figure 4 – Particle caught by inertial impaction [20].

B. High Efficiency Particulate Air (HEPA) Filter

To accomplish the task of keeping aircraft cabin air free from contaminants most cabin air filters follow the HEPA specification. This kind of filter is a highly effective air filtration device specifically designed to capture microscopic particles from the air. It works by forcing air through a fine mesh, most commonly fiber glass, that traps harmful pollutants [4]. To meet the HEPA standards, a filter must remove at least 99.97% of particles on the most penetrating size of 0.3 microns in diameter [9].

These filters are widely used in environments where it's critical to maintain a clean atmosphere to avoid contamination such as hospitals and aircraft cabins [4].

V. HEPA Filter Geometry Comparison

In modern aircraft, several different HEPA filter geometries are used. This article focuses in presenting and comparing three of the geometries commonly used by the two biggest commercial aircraft manufacturers, Boeing and Airbus.

Airbus A330, A340, and A380 series utilize the he **Pleat-Plate** filter structure. As the name suggests, this filter consists of a filtrating fiber linearly disposed in a plate [10, 19].

Boeing's airplanes utilize the **V-Shape** filter. It consists of several small Plate filter disposed in multiple V shapes, making the airflow hit the fiber surface at a different angle [10, 19].

Finally, in Airbus A320 series a **Cylindrical** filter is used. In this filter the fiber is disposed in cylindrical shape and the airflow enters the filter by the external surface of the cylinder, flowing through it´s center where the clean air leaves the filter and is recirculated through the ECS system [10, 19].

These different filter geometries are illustrated in Figure 5. Table 2 displays each filters specifications by the manufacturer.

Pleat-Plate

V-Shape

Cylinder

Figure 5 – Photograph of different filter structures [10].

Table 2 – Filter Specifications [10]

Filter Model	Structure type	Rated air volume [m³/h]	Filtration area [m²]	Filtration Velocity [cm/s]
CAF-B737	V-Shape	2040	13.666	4.15
CAF-A320	Cylinder	1360	13.855	2.73
CAF-A330	Pleat-Plate	850	8.982	2.63

For this article, the filter performance experimental results of the studies of Zhang et al. 2021 [10], Xu et al. [11] and Zhang et al. 2022 [19] for the filters specified in Table 2 were compiled in Table 3 and will be used to compare the HEPA filter structures.

The experimental methodology of those studies centered on assessing the filtration performance and dust-holding capacity of cabin air filters using a standard positive pressure test system comprised of a wind tunnel, aerosol/load dust generation, sampling, and control systems. Filtration efficiency was determined primarily using the particle counting method, focusing on 0.3-μm particles, with the test method referencing European standard EN 1822–2009 and international standard ISO 29463-2017 [16]. The load dust used was **A2 Fine Test Dust**, selected as the most suitable experimental dust for PM10, which is the primary pollutant causing resistance increase in cabin filters [10].

Figure 6 illustrates the test system utilized for the studies of Zhang et al. [10] and Xu et al. [11].

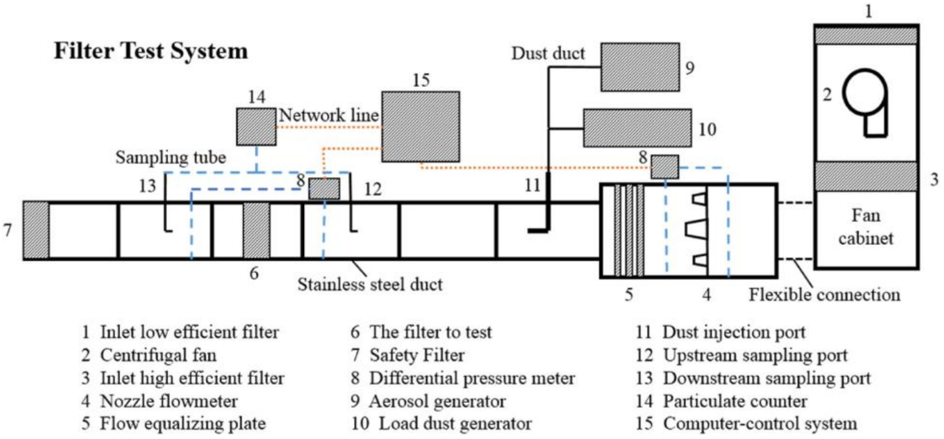

Figure 6 – Test System for performance of cabin air filters [10].

Table 3 – Filter Geometry Performance Parameters [10, 11, 19]

	Cylinder	V-Shape	Pleat-Plate	Desired
Initial Resistance [Pa]	136	336	308	Lower
Efficiency (0.3 μm)	99.981%	99.977%	99.8%	Higher than 99.97%
Quality factor	0.063	0.025	0.020	Higher
Energy Consumption [kWh/(m^3/s)]	2071	4627	5235	Lower
Resistance Increase rate [Pa m^2/(g(cm/s))]	1.32	1.40	3.15	Lower
Service Life [h]	16,900	14,400	-	Higher

* As each filter model has a different flow rate, the direct comparison of the energy consumption would be misleading, since each filter uses that energy to clean different amounts of air. Because of this, the energy consumption has been normalized by the filter's rated flow rate from Table 2 to provide a fairer comparison between the different structures.

The filtration velocity from Table 2 was derived from the ratio of each filter's rated air flow by the filter area. As can be seen from the values from Table 2, this velocity is rather slow for all 3 filter types, which is key to the filters to have the high efficiency required by the HEPA. A lower filtration velocity favors the diffusional interception mechanism by providing more opportunities for the undesired particulate contaminants to collide and interact with the fiber material, getting captured by the filter [10].

The last column of Table 3 explicates what is generally desired of each studied characteristic for a filter. If low or high values of each property are necessary for a good filter and if there is any threshold that needs to be met.

As can be seen in table 3, all 3 filter structures have similar high efficiencies for the most penetrating particle size of 0.3 μm. Thus, all filters studied can provide a safe environment for the aircraft occupants free from dangerous contaminant concentrations and the main differences between filters remain in their energy consumption parameters.

The resistance of a filter can be defined as the pressure drop between the filter’s entry and it’s exit. This is an important parameter because a higher resistance requires a higher effort from the ECS system to make the air flow through the filter, impacting the overall energy consumption [10]. This explains why the cylinder filter, which has the lowest resistance to airflow, also is the one which has the better energy consumption rating.

The studies mentioned also analyzed the service life of the Cylinder and V-Shape structure. As filter is used, the particles deposit into the fibers and pose a new obstacle for the airflow, which makes the filter’s resistance increase through time. It is defined that a filter should be substituted when its resistance doubles the initial value. For the cylinder filter this happened at 16,900 hours, which is a 17% longer service life when compared to the V-shape Structure.

VI. Discussion

Although all 3 filter geometries presented in section V presented a high filtration efficiency, being able to provide high air quality for the cabin occupants minimizing the risk of contamination, the Cylinder filter had the better performance in all other parameters, providing a combination of high filtering efficiency, low energy consumption and long service life.

First, the cylinder filter presented less than half the resistance (pressure drop) than the other filter models. This parameter is directly related to the amount of effort the ECS requires to make the air flow through the filter, influencing the energy consumption of the system. Considering the ECS system is one of the primary consumers of non-propulsive power, a filter with a lower pressure drop, such as the cylinder, can be used by airlines to reduce the operational costs.

It is important to note that the performance gap between the Cylindrical and V-Shape geometries cannot be attributed solely to the lower filtration velocity of the A320 system. While the V-Shape filter operates at a face velocity 52% higher than the Cylindrical one, its initial resistance is 147% higher. According to Darcy's Law principles, this non-linear increase in resistance suggests that the Cylindrical geometry possesses intrinsic aerodynamic superiority. This is likely due to the 'inertial deviation' effect acting as a pre-filter for larger particles and the wedge-shaped pleats allowing for deeper dust loading before clogging occurs.

The cylinder filter also presented the lowest resistance increase rate among the three analyzed models. During the operational life of an air filter, the intercepted air impurities are deposited in the fiber media, reducing the space available for the air to flow through the filter, increasing its resistance. Airplane filters are replaced based on this pressure drop increase, normally when it doubles its initial value [10], thus the cylinder filter having a low pressure increase rate is related to its longer service life, requiring to be replaced with lower frequency and allowing the airline to reduce maintenance costs.

Since the tested filters had the same filter media made of ultrafine glass fiber and had similar filtration efficiencies, the difference in their performance relies upon their geometries. The superiority of the performance of the cylinder filter has two possible explanations.

The first advantage stems from airflow steering, as the Cylinder filter subjects the incoming airflow to bends close to 90° before entering the pleats, while the V-shape filter only involves small-angle turns, as can be visualized in Figure 7. This substantial change in direction favors the inertial deviation mechanism, causing large particles to deviate from the streamline, getting separated from the air that returns to the cabin, but not directly captured by the filter's fibers, reducing the cloth of the filter [10].

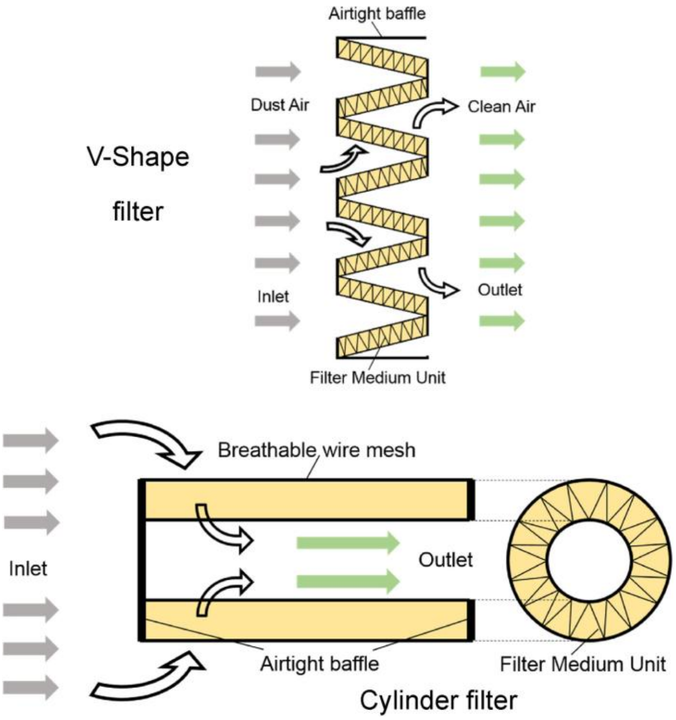

Figure 7 – Flow field characteristics of different filter structures [10].

The second advantage lies in the unique cylindrical pleat structure, which is more conducive to the dust-holding process than flat pleated counterparts. Specifically, the Cylinder filter's structure, where the outer pleat spacing is greater than the inner pleat, encourages the particulate matter to deposit deeper into the pleat channel. This deeper deposition helps mitigate the overall increase in airflow resistance of the filter medium during operation [18].

Both the superior energy efficiency and the reduced maintenance required by the cylinder filter have a broader impact in the aerospace industry. As the ECS system is one of the main consumers of non-propulsive power in the aircraft, even the marginal reduction of it’s energy load caused by a better filter design, that requires less power to make the air flow through it, is an important step towards aircraft electrification and following the More Electrical Aircraft Market tendency.

The better energy efficiency of the ECS also requires less fuel consumption and reducing the aircraft pollutant emissions into the atmosphere. The use of a filter with requires less frequent replacement, minimizes the amount of waste generated in maintenance. Both these aspects are crucial to increase aircraft sustainability in a world interested in minimizing the consequences of climate change.

Therefore, the use of an optimized and efficient air filter design, such as the cylinder, is crucial to getting closer to important aerospace industry goals of More Electric aircrafts and sustainability.

VII.Conclusion

This article has examined the critical role of air filtration technologies in safeguarding cabin air quality for passengers and crew aboard modern commercial and military aircraft. Driven by the need to minimize operational costs, modern flight operations involve flying at high altitudes, which necessitates the use of the Environmental Control System (ECS) to maintain habitable conditions. Furthermore, to decrease fuel consumption, the ECS is designed to recirculate a portion of the cabin air, making it one of the primary non-propulsive power consuming systems. Since both the engine bleed air and the recirculated cabin air can introduce contaminants, filtration is essential to mitigate health risks associated with prolonged exposure in a confined space.

The analysis in this article compared the performance of three common HEPA filter geometries: the Pleat-Plate, V-Shape, and Cylinder structures. Experimental results showed that all three structures maintain similarly high efficiencies for 0.3 μm particles, confirming their ability to provide a safe cabin environment. However, key differences were observed in energy consumption and service life parameters.

The Cylinder filter demonstrated the superior overall performance, featuring the lowest initial resistance (136 Pa, compared to 336 Pa for V-Shape and 308 Pa for Pleat-Plate) and, consequently, the best energy consumption rating of 2071 kWh/(m^3/s). The Cylinder filter also provided a 17% longer service life, lasting 16,900 hours before its resistance doubled. This superior efficiency is attributed to its design, which favors inertial deviation by subjecting airflow to substantial bends, and its unique cylindrical pleat structure that promotes deeper dust deposition, thus mitigating the long-term increase in airflow resistance.

This article had the limitations of collecting data of a limited number of studies for the filter performance comparison. This is because the operational performance of the different kinds of aircraft air filters has not being studied with test procedures that properly simulate the aircraft environment, making the available data for a comparison extremely limited. For future research, it would be beneficial to develop a standardized test protocol that simulates cabin pressurization cycles and humidity variations to evaluate the filter's performance under more realistic operational conditions, allowing to test a broader range of filter designs under a standardized procedure, in conditions closer to real world operation.

Future research should investigate the quantitative impact of low-resistance filters, such as the cylindrical geometry, on the overall electrical load of More Electric Aircraft (MEA) architectures. Integrating these high-efficiency filters is crucial to maximizing the fuel-saving potential of 50/50 air recirculation strategies in next-generation environmental control systems.

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FOLHA DE APROVAÇÃO

Candidato(a): Jose Ignacio Herrera

Título do Trabalho: Aircraft Cabin Air Quality and Filtration

Data da defesa: 22/12/2025

Comissão julgadora

Avaliador	Resultado (nota)
Fabriciu Alarcão Veiga Benini (orientador)	10,0
Jorge Henrique Bidinoto	10,0

Resultado final: **Aprovado**

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