

Cathode Air Filtration for H₂ PEM Fuel Cells

Donaldson Filtration Solutions

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Abstract

Hydrogen proton exchange membrane (PEM) fuel cells are emerging as a cornerstone technology for a clean transportation sector. These remarkable devices offer a clean and highly efficient method for electricity generation, with water vapor as their sole byproduct. However, beneath the surface of this seemingly simple technology lies a hidden challenge: the influence of ambient air quality on the fuel cell. While fuel cells utilize oxygen from ambient air to react with hydrogen, even trace amounts of contaminants present in that air can wreak havoc on the delicate inner workings of the cell.

This paper explores the critical role of filtration technology in safeguarding the smooth operation and extended lifespan of hydrogen fuel cells. It explores how filtration is used to capture and remove contaminants from the air stream before it enters the fuel cell. The paper will unveil the mechanisms by which contaminants can harm fuel cells and how filtration technology acts as a guardian, protecting these vital components from degradation and ensuring optimal performance. We will also explore the different types of filtration employed in hydrogen fuel cell systems and their impact on the overall efficiency and durability of the technology. By understanding the critical role of filtration, we can pave the way for a future powered by clean and sustainable hydrogen energy.

Introduction

In the context of mobile applications, including medium-duty and heavy-duty transportation as well as non-road mobile machinery, there are several types of powertrains available. The most common powertrain is the internal combustion engine, which is usually powered by a liquid fuel such as diesel. There are also alternative powertrains being developed or already in use, an often-cited alternative is a battery electric powertrain. However, for heavy duty applications, there are other interesting alternatives. Examples are internal combustion engines powered by gaseous fuels like natural gas or hydrogen, and hydrogen fuel cells.

Hydrogen fuel cells stand at the forefront of clean energy solutions in the segment of commercial vehicles. This alternative to the diesel engine promises efficient and eco-friendly power generation. However, their sensitivity to airborne contaminants poses a significant challenge. Exposure to typical pollutants like sulfur compounds, nitrogen oxides, volatile organic fractions, and ammonia can lead to performance degradation or even permanent damage of the fuel cell system.

For fuel cells specifically, Donaldson provides solutions to ensure that the intake air is free of rain droplets, dust,

and harmful chemicals that could damage the fuel cell stack and the balance of plant.

This paper explores the details of cathode air filtration for fuel cells. First the general problem of ambient air pollution and its effect on fuel cells is discussed. This is followed by section on filter media, its chemical adsorption behavior and the integrated of this media into a robust filter assembly.



Figure 1: FC3 cathode intake air cleaner

Air Quality

Contrary to popular belief, air quality has significantly improved in industrialized countries over recent decades, largely due to stricter emission regulations and enhanced air quality standards. In contrast, industrializing countries often face very high pollution levels, but once air quality becomes a priority, they too can achieve remarkable improvements. Despite these advancements, road transportation remains a major contributor to air pollution in both industrialized and industrializing nations.

Airborne chemical contaminants are pervasive in our environment, with composition and concentration varying widely across locations. Urban areas differ from rural ones, and variations occur on an hourly, daily, and seasonal basis, influenced by weather and wind patterns. Urban settings, particularly in 'street canyons' and tunnels, can trap local emissions, amplifying the pollution exposure for on-road fuel cell vehicles.

Sources of pollution are diverse, including transportation, industry, livestock, and household heating. Understanding contaminants concentration of nitrogen oxides, sulfur compounds, ammonia, and volatile organic fractions is crucial, typically these pollutants are measured in parts per million and parts per billion.

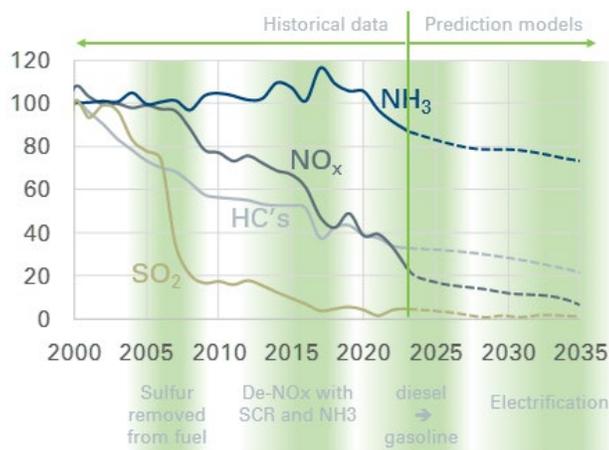


Figure 2: Evolution in roadside contaminants

Despite the complexity of air pollution, discerning the overarching trends is possible. The graph in Figure 2 illustrates the annual averaged roadside pollution level in an industrialized country, such as the UK. In the early 2000s, the introduction of fuel cell bus fleets required protection against sulfur dioxide exposure. Subsequently, investments in desulfurization installations by coal-fired power plants led to a reduction of background SO₂

Meanwhile the introduction of ultra-low-sulfur diesel fuel led to a remarkable reduction of roadside SO₂ levels.

Further advancements, like diesel engines with NO_x reduction technology in the early 2010s, aimed to reduce nitrogen oxides but also introduced localized increases in NH₃. The diesel scandal around 2015 triggered a shift from diesel to gasoline cars, along with cleaner Euro6d diesel engines, resulting in a significant reduction in nitrogen oxides.

These past trends will continue to influence the future air quality as older generations of diesel and gasoline vehicles are replaced by newer and cleaner vehicles. Looking ahead, the gradual phasing out of combustion engines in favor of battery electric and fuel cell powertrains is expected to further improve roadside air quality. Donaldson collaborates with air quality experts to simulate future pollution levels in regions where fuel cell vehicles are anticipated to operate.

Fuel Cell Sensitivity to Air Contaminants

Figure 3 illustrates the impact of air contaminants on fuel cell performance, with the Y-axis representing fuel cell current density in Amps per cm² and the X-axis indicating time. Each graph demonstrates the effect of a common pollutant on the fuel cell performance.

Three separate phenomena can be observed:

Permanent degradation of the fuel cell occurs when it is exposed to sulfur dioxide. At common roadside concentration, the decline due to this poisoning is very slow, but it is permanent. More concerning are conditions where occasionally the vehicle is exposed to high concentrations, for example near roadworks, chemical factories or oil refineries.

Temporary degradation is a common phenomenon with many pollutants. The example depicted in Figure 3 shows the effect of NO₂. A fuel cell exposed to NO₂ will see a drop in performance. However, after the exposure, the fuel cell can recover from this temporary poisoning event. NO₂ typically originate in a high temperature combustion process, this is typically present in the tailpipe gasses of traditional combustion engines, and therefore present in on-road environments.

There is also the possibility of a mixed behavior. A typical example is ammonia. This pollutant causes a performance degradation. After the event, the fuel cell partly recovers automatically. However, for a full recovery, a harsh voltage reversal process is needed in the

fuel cell stack. Sources of ammonia can be urea-based SCR systems used in modern diesel vehicles, but also in farming environments near livestock.

by common pollutants such as road salts, ammonia, nitrogen oxides, sulfur compounds, and hydrocarbons. The fuel cell system is also sensitive to particles.

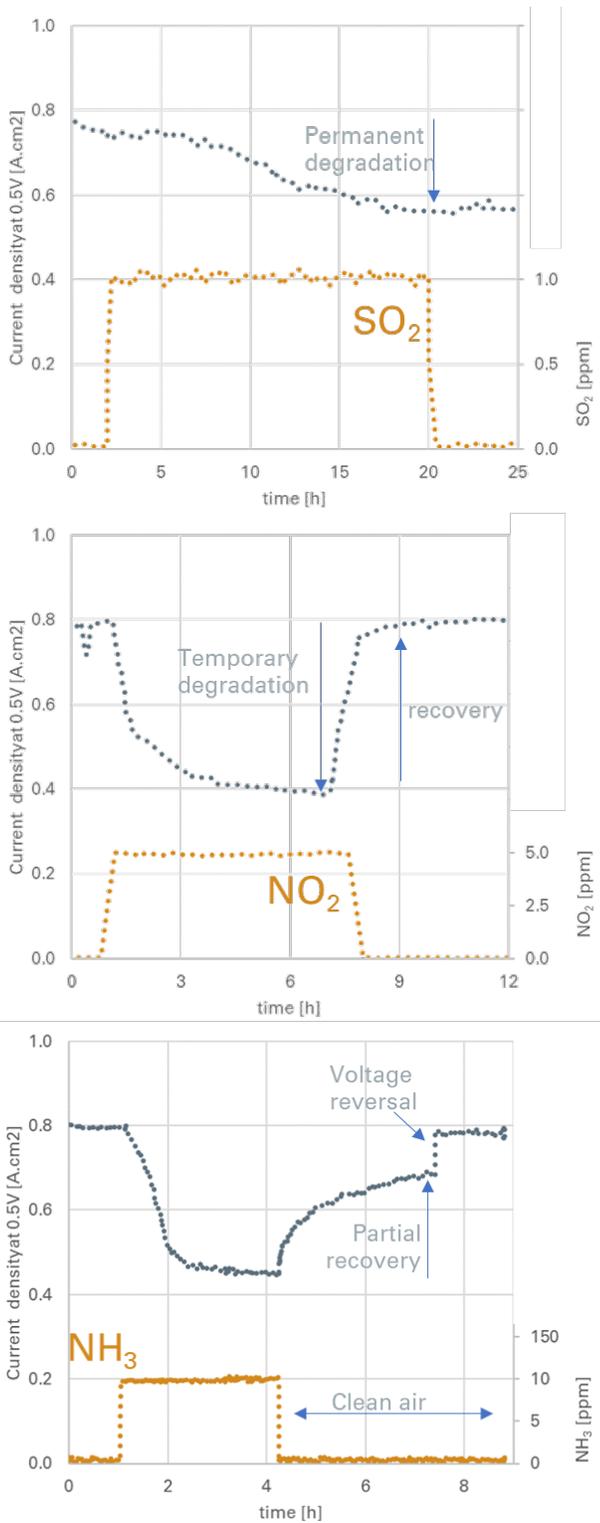


Figure 3: Fuel cell performance degradation

Besides the actual fuel cell stack, the humidifier membrane can be temporary or permanently deactivated

Ingress of particulate matter from the cathode air into the fuel cell system poses a significant risk of obstructing critical components such as the Humidifier membrane, the Gas Diffusion Layer (GDL), the Micro Porous Layer (MPL), and various flow channels. This obstruction diminishes media transport, resulting in a noticeable performance decrease. Furthermore, salt particles exacerbate the situation by impairing the ion conductivity of membranes. Furthermore, the typical hard dust particles can mechanically damage the compressor wheel, reducing its efficiency and ultimately leading to a destruction of this wheel and all downstream components.

Fuel cells represent a dynamic technology continuously undergoing optimization across various fronts. One area of enhancement is the reduction in usage of precious metals in the membrane coating, leading to significant cost reduction. Additionally, minimizing the ionomer membrane thickness is crucial to mitigate electric losses. However, these advancements may make fuel cells more susceptible to chemical poisoning by common air-borne contaminants. Therefore, effective chemical filtration of cathode air is essential for ensuring the durability and longevity of newer generations of optimized fuel cells.

Filtration Media for Cathode Air Intake

The cathode or air-facing side of a fuel cell necessitates dedicated filtration to safeguard against both temporary and permanent performance impairments. This filtration system comprises multiple protection layers, each engineered for specific functions. A particulate layer is imperative for capturing dust and soot, while additional layers serve chemical filtration purposes. Leveraging over a century of expertise in particle filtration, Donaldson integrates advanced fine fiber technology, such as Ultra-Web®, into customizable dust layers to ensure optimal protection in diverse environments.

Chemical filtration media combines functionalized chemistry with activated carbon and resins to effectively eliminate various air-borne chemical contaminants. To cater to diverse customer requirements and specific ambient air pollution profiles, the dust and chemical filtration layers can be incorporated in co-pleated configurations, separate media packs, or entirely distinct element setups.

Optimizing the balance between dust and chemical filtration performance vis-à-vis environmental conditions is crucial for maximizing system longevity and safeguarding vehicle integrity. Donaldson's media and element flexibility enables tailored solutions for every fuel cell cathode air intake filtration application. Donaldson offers a range of fuel cell filter media grades meticulously fine-tuned to address the rigors of demanding applications. Proprietary media formulations adeptly capture chemical pollutants, preventing their migration to the fuel cell in response to fluctuations in ambient temperature, pressure and humidity.

The chemical layer serves three primary functions: capturing base gases, acidic gases, and organic compounds through distinct layers. Figure 4 gives a visual overview of the media cross-section, revealing multiple layers, each fulfilling a specific role.

In environments characterized by high dust but low chemical contamination levels, segregating media layers entirely is an option. These can be consolidated into a single element or maintained as two separate elements, with the dust element typically replaced more frequently due to lower costs.

The layer responsible for removing the chemical contaminants from the air contains a proprietary mix of activated carbon and resins. Activated carbon and resins are two well understood materials known for their exceptional adsorption capabilities, each employing

distinct mechanisms: chemisorption and physisorption for activated carbon, and ion exchange for resin.

Chemisorption involves a chemical reaction between the adsorbate molecules and the surface functional groups of the activated carbon, forming strong chemical bonds. Physisorption, on the other hand, relies on weak van der Waals forces between the adsorbate molecules and the carbon surface, without any chemical bonding. This dual mechanism, combined with activated carbon's porous structure, enhances its adsorption efficiency for a wide range of substances.

Activated carbon's porous structure, consisting of micropores, mesopores, and macropores, provides ample surface area and accessibility for adsorption processes. Micropores predominantly facilitate physisorption due to their small size, while mesopores and macropores contribute to both chemisorption and physisorption processes, enhancing the overall adsorption capacity of activated carbon.

Resins, on the other hand, operate primarily through ion exchange, a process where ions in the resin matrix are exchanged with ions in the surrounding air. This exchange occurs between functional groups present in the resin and ions in the air, leading to the removal of unwanted ions from the air and their retention within the resin matrix.

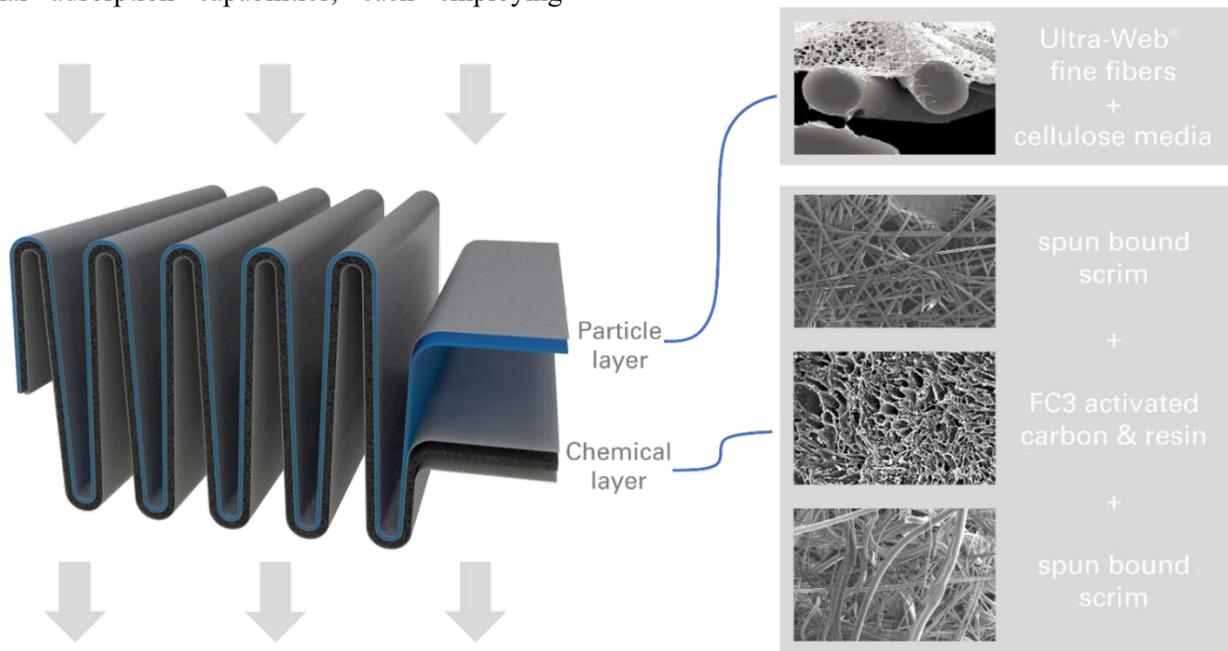


Figure 4: Cathode air FC3 filter media construction

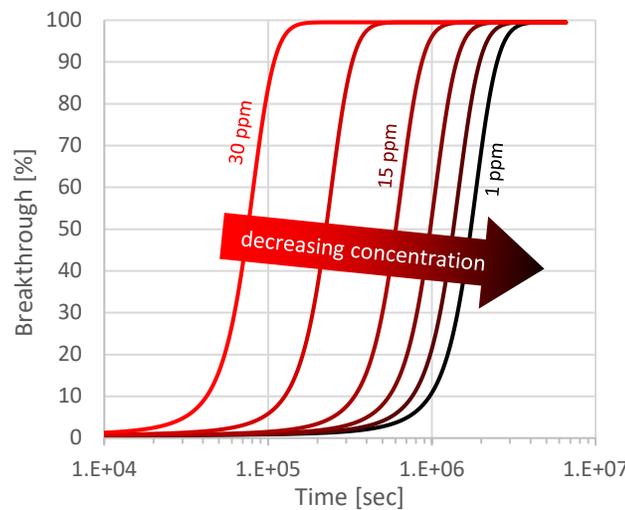
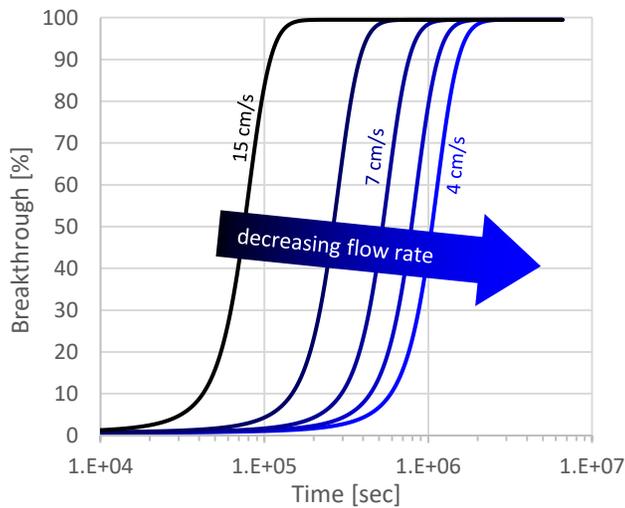


Figure 5: Chemical breakthrough in function of flow rate and flow rate

Chemical performance

Characterizing chemical media performance is done through adsorption testing at accelerated conditions. Unlike particle filtration, the chemical media is the most efficient at the start of a test with increasing breakthrough, and decreasing efficiency over time. The media’s performance can be characterized by an efficiency curve, or more commonly with the inverse, a breakthrough curve. Through the duration of the test, chemical breakthrough will increase with a termination condition of full saturation and 100% breakthrough.

Figure 5 demonstrates a typical breakthrough behaviour. At higher flow velocities and higher contaminant concentrations, breakthrough tends to occur earlier.

Time-to-breakthrough is a function of media properties, face velocity, chemical contaminant, concentration, and flow uniformity. Shown here are impacts of face velocity and chemical concentration. With an increase in face velocity or reduced residence time, a decrease in time-to-breakthrough is observed (Figure 5 top). Similarly, changes in concentration are shown to impact the time to breakthrough (Figure 5 bottom).

Figure 5 demonstrates the typical behaviour for a single contaminant. This is the usual way of quantifying the performance. However actual ambient air is characterized by a multitude of contaminants. And as described earlier, this specific mix of contaminants is highly variable. Hence it is important to understand the ambient air composition of where the fuel cell is operated.

In the absence of a dedicated testing standard for fuel cell cathode air filtration, established cabin air filtration test procedures like ISO 11155-2, ISO/TS-2, DIN 71460-2, and SAE J1533_201907 are commonly utilized. Due to practical limitations, laboratory tests necessitate acceleration. This involves exposing the filter to contaminant levels 2 to 5 orders of magnitude higher than what is present in ambient air. Consequently, such accelerated testing may distort results, given the different pollutant capture mechanisms at very low concentrations. Moreover, conventional tests typically examine single contaminant species, whereas real-world air is a complex mixture of substances, posing additional evaluation challenges. Furthermore, the common test procedure occurs at a fixed humidity level and temperature, while real-life fluctuations in humidity and temperature can influence the performance of the media. Donaldson extends beyond conventional test procedures, conducting evaluations in its own laboratory to assess real-life contamination profiles.

Air Cleaner element

The flat-sheet filter media is pleated into a corrugated structure. This allows for a compact media pack, while still having a large surface area for capturing dust, and a large quantity of chemically adsorbing materials. This corrugated media pack is then integrated into a filter element. Several element styles are common, including a rectangular media pack, a round media pack, and an oblong media pack, as illustrated in Figure 7.

Previous generations of fuel cell air cleaners sometimes employed wrapping or stacking of the chemical media. In this configuration, multiple layers are placed on top of each other to reach sufficient chemical adsorbing

material. However, this method leads to a high pressure loss, and low dust loading capacity. Hence, modern fuel cell rarely use the stacking method and are more commonly using a pleated media pack (Figure 6).

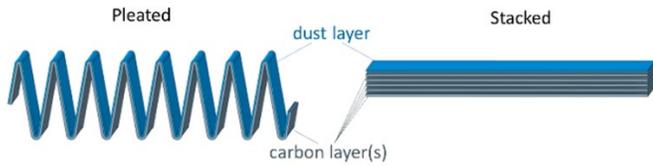


Figure 6: Media pleating vs. stacking

The relationship between the pressure restriction of the fuel cell air intake and system efficiency is intricately linked to the energy consumption of the compressor. A restriction necessitates greater compressor output to maintain optimal airflow, resulting in increased energy consumption by the compressor. This, in turn, diminishes the overall efficiency of the fuel cell system. Moreover, excessive pressure drop can impair the performance of the fuel cell stack by limiting the supply of air, leading to oxygen starvation, reduced power output, higher cell temperatures and diminished system reliability. Thus, addressing pressure drop is crucial for optimizing system efficiency and performance.



Figure 7: Panel, oblong and round FC3 filter elements

Service interval

In the world of diesel engine air filters, it is customary to employ a low-cost pressure restriction indicator, to signal when the filter requires replacement. This practice is not indicative of the filter's performance; in fact, filters often exhibit enhanced efficiency when loaded with dust. Rather, it serves to mitigate potential engine issues related to high intake pressure restriction. Dust filters typically maintain their effectiveness even when heavily loaded with dust.

In contrast, the behavior of chemical filters within fuel cell intake systems differs significantly. Initially, these filters demonstrate nearly 100% chemical removal efficiency. However, as they age, their effectiveness diminishes progressively until they cease to function entirely. Remarkably, even when a chemical filter has exhausted its chemical capacity, it may exhibit similar pressure restrictions as when new. Consequently, an alternative approach is required to ascertain the end-of-life status of a chemical filter.

Flow uniformity

In the context of dust filtration, the uniformity of flow over the filter element is typically not a high concern, as the presence of areas with high flow rates leads to a faster accumulation of dust, increasing locally the restriction and thus re-directing the flow towards areas with lower dust loading. This redistribution mechanism eventually results in an even distribution of dust throughout the filtration element, promoting uniform filter element loading, and efficient utilization of the filter media.

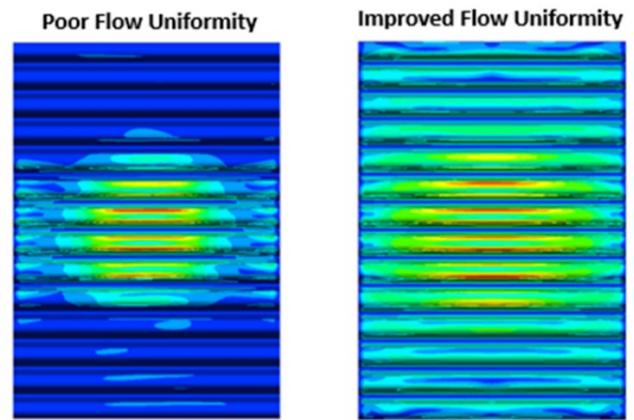


Figure 8: Flow uniformity on a panel element

However, the situation is different in chemical 'filtration', where areas with higher flow rates become saturated more rapidly, without any impact on the flow restriction. This leads to earlier local breakthrough and reduces the overall

performance of the element. The effectiveness of the filtration element in this case is highly dependent on the uniformity of flow. A perfectly uniform flow results in the same breakthrough as that of a flat media sample, while any deviation from perfect flow uniformity leads to a less pronounced breakthrough curve.

Flow uniformity refers to the even distribution of the air flow over the filter media, it is quantified according to following formula:

$$\gamma = 1 - \sum_{i=1}^N \frac{|v_i - \bar{v}|}{2 \bar{v} S} S_i$$

With: S: the total surface area of the filter media, v_i : the local flow velocity, \bar{v} : the average flow velocity, and S_i : the surface area for the local flow velocity

Figure 8 demonstrates an example of the effect of flow uniformity on a pleated panel element. In the system on the left, the ‘imprint’ of the inlet duct is clearly visible, indicating that most of the air, coming from the inlet goes straight to the center section of the filter element. Meanwhile, the system on the right has certain flow features (not shown) that improve the flow uniformity and give a better distribution of the air and its contaminants on the filter element.



Figure 9: Range of FC3 cathode air filter offering (add bus to this)

Air Cleaner assembly

The pleated filter element is installed in an air cleaner housing. These assemblies come in various sizes, catering to fuel cells from around 10kW up to 300kW. Beyond standard offerings, Donaldson specializes in custom solutions, converting existing diesel engine filters for fuel cell applications. Whether it's panel-style elements, round elements, or those compatible PowerCore® technology, Donaldson’s broad range of heavy-duty air cleaners can be modified with dedicated fuel cell filtration technology.

Model	FC3A08	FC3A09	FC3A13
Gross Power Fuel cell	5-70 kW	60-140 kW	130-350 kW
Dimensions (D*L)	227*359 mm	267*433 mm	349*597 mm

Table 1: Donaldson FC3 fuel cell catalog air cleaners

The filter media must be incorporated into an element and installed in a housing with appropriate ducting to function effectively.

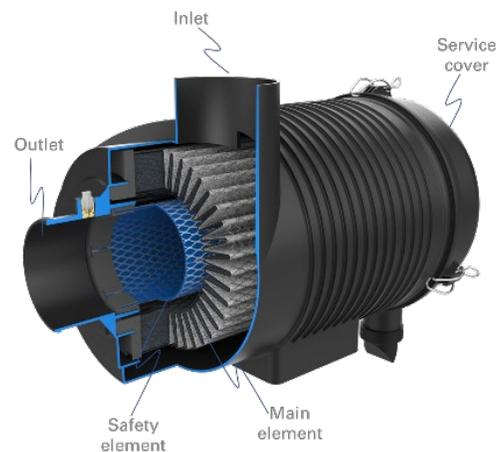


Figure 10: Catalog FC3 intake air cleaners

At Donaldson, there is extensive experience spanning over 100 years in designing and producing such systems for heavy-duty industries, often catering to harsh and dusty environments. This includes all the accessories,

such as clamps, inlet ducts, pre-separators, indicators and much more.

Donaldson offers a range of filter housings suitable for fuel cell applications, available in our catalog line. These housings are typically adapted from heavy-duty diesel engine systems, but with specialized fuel cell filter elements. An overview of this range of catalog filter is shown in Table 1. In Figure 10, the FC3A09 air cleaner is shown.

These catalog air cleaners are often the most economical solution for fuel cell customers. However, it is possible to convert almost any existing air cleaner for use in a fuel cell application. Figure 9 shows the typical range of fuel cell projects.

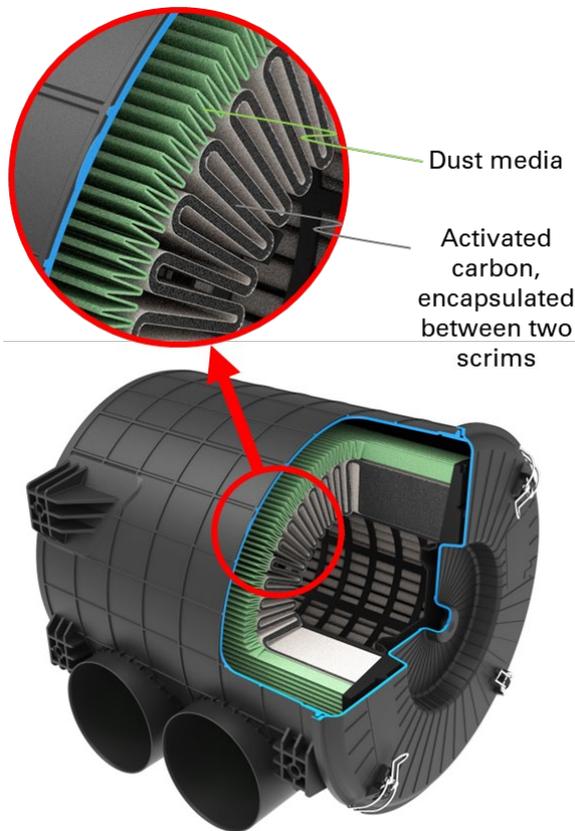


Figure 11: FC3 Air cleaner with separate dust and chemical layers

In certain situations, it is beneficial to physically separate the dust filtration function from the chemical filtration function. This decouples the two tasks (dust-chemical) and allows for more flexibility and sizing the system for high dust or high chemical capacity. Typically, high dust capacity is reached by have a large surface area.

Meanwhile, high chemical capacity is achieved by using a large volume of resin and carbon adsorbent. Maximizing both the volume and the surface is not always possible, and sometime mutually exclusive. Therefore, in certain configurations it is beneficial to split the media pack, and optimize the dust pack for surface area, while the chemical pack is optimized for volume.

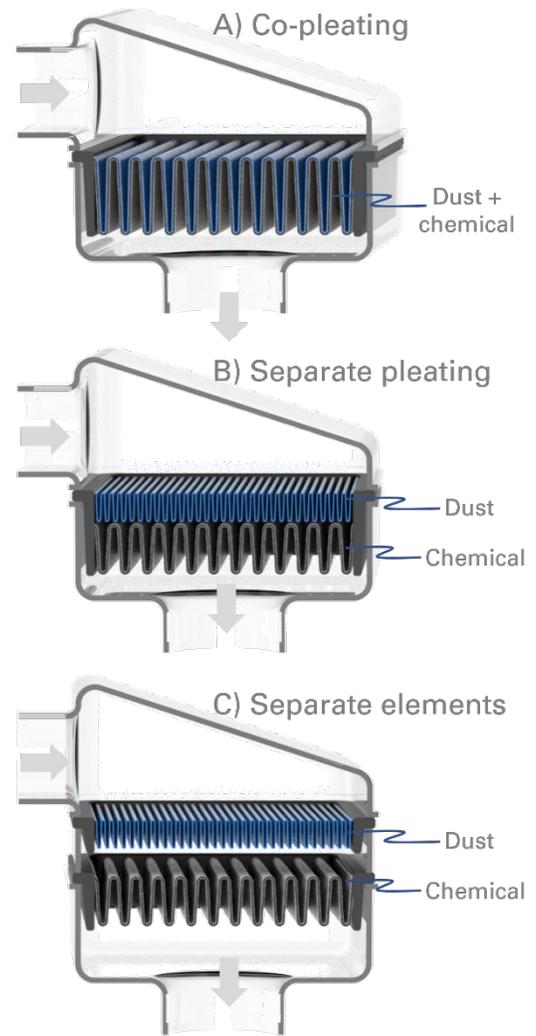


Figure 12: Media pleating combinations

Splitting the filter media pack can offer advantages during the design phase as well as in end-user servicing practices. By creating two separate elements—one for dust filtration and the other for chemical adsorption—manufacturers can provide users with greater flexibility in maintenance. For instance, in environments with high dust levels, the dust element can be serviced more frequently than the chemical element. Or in settings with low dust but high chemical pollution, servicing the chemical element more frequently than the dust element may be preferable.

Figure 12 demonstrated the different possible combinations. In A, the dust and chemical layers are co-pleated, as is also demonstrated in Figure 10. This is the most straightforward solution. In layout B, the dust and chemical pack can be sized independently, but still form part of one single service element, see also Figure 11. This allows for flexibility in the design phase. Layout C has two separate media packs, each one being a separate element, this gives flexibility in the design phase, but also toward the end user, allowing independent servicing of the dust or chemical element.



Figure 13: FC3 compact air cleaner

Figure 13 illustrates a multiple-stage intake air filtration system designed to remove both dust and chemical contaminants. This technology leverages the established Donaldson PowerCore® diesel intake air filter family. The unit features an integrated pre-separator at the inlet, capable of removing rain droplets and up to 80% of incoming dust. This pre-separation stage is followed by a replaceable PowerCore dust filter element for high efficiency particulate filtration. Chemical contaminants are subsequently removed by the downstream FC3 chemical filter pack. The pre-separator, the dust filter element and the chemical pack are housed within a single unit, allowing for ease of integration while enabling independent servicing of each component. The specific design depicted in Figure 13 incorporates a dual outlet configuration. This feature allows for the connection of two fuel cell systems to a single intake air cleaner. This configuration is a common practice in contemporary heavy-duty commercial vehicles, where power requirements often range from 150 kW to 300 kW. In such applications, achieving the desired power output frequently necessitates the combined operation of two smaller fuel cells.

Conclusion

Donaldson is providing air filtration solution to the heavy-duty diesel market since 1915 for diesel engines. This knowledge and product portfolio is now also extended to hydrogen fuel cells. For this new powertrain, a chemical adsorption function is added to this existing portfolio of rugged and robust air cleaners.

The chemical filtration function assures that the fuel cell operated efficiently, even in heavily polluted environments, without compromising its durability.