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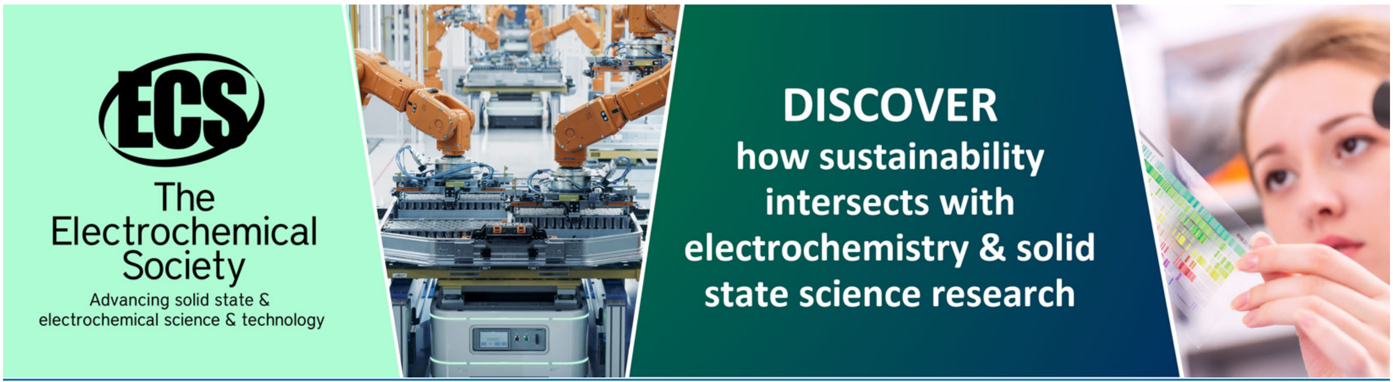

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Conceptual Design and Evaluation of Air Inlets of Fuel Cell-Powered Electric Aero Engines for Regional Aircraft

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Abstract. Hydrogen fuel cell-powered electrified propulsion systems hold great promise for the development of sustainable aircraft. However, the integration of fuel cells into aircraft presents unique challenges, particularly in the context of air inlet systems. Key development priorities are to ensure a constant supply of air to the fuel cells and to efficiently manage the transfer of waste heat from the fuel cells. This paper investigates different air inlet systems using analytical methods. Firstly, concepts are identified by analysing the state of the art in air inlet design. Secondly, promising concepts are selected through a qualitative evaluation. Finally, the most promising concept is sized for the given topology. The results of this research highlight the importance of careful air inlet design in order to achieve operability and acceptable performance with fuel cell powered aero engines. The performance and sizing data obtained from the performed analytical calculations can serve as a general basis for the preliminary design of scoop inlets and annular inlets for fuel cell-powered aircraft.

1. Introduction

The aviation sector Aviation must play its part in mitigating climate change impacts. This has led to the European Commission publishing Flightpath 2050 [1] and the commercial aviation industry developing ATAG Waypoint 2050 [2] to reduce aircraft carbon dioxide CO_2 emissions. Consequently, aviation is exploring sustainable and renewable energy sources such as green hydrogen. This, in turn, requires a shift in aircraft powertrain topology. Several concepts for electrified powertrain topologies have been identified to suit various passenger capacities and flight ranges [3]. Some of these topologies involve the use of hydrogen-fuelled low-temperature polymer electrolyte membrane fuel cells (LT-PEM-FCs) to provide electric power to electrically-driven propulsors. The typical operational temperature range for LT-PEM-FCs is around 80 °C with an efficiency of 50% to 60% [4]. This produces a significant amount of waste heat at a small temperature difference to the ambient air during hot day take-off conditions, presenting a challenge for the thermal management of the propulsion system to ensure reliable operation. Mostly due to these cooling requirements, the engine can demand up to eight times more mass flow during take-off than during cruise requirements [5]. Thus, a trade-off can be required for the inlet design in order to achieve good aerodynamic performance in both flight conditions. It is therefore necessary to examine different types of inlets and options for geometry adjustment.

This paper presents the design of an inlet that supplies air to the fuel cell and thermal management system of an LT-PEM-FC-powered aero engine. Firstly, the state of the art for air inlet is analysed to identify concepts. Secondly, promising concepts are selected via a weighted point rating. Finally, the most promising option is detailed to achieve a lightweight, reliable, efficient and safe concept.

2. State of the Art

2.1. Fuel Cell-powered Aero Engines

Electrifying the aero engine can lead to the introduction of several new components, such as

- electric motors and gearboxes,
- high power level power electronics and electrical wiring,
- electric generators, batteries and fuel cells, as well as
- hydrogen storages.

Electrified aero engines can be classified into three types of topologies: turbo-electric, all-electric and hybrid-electric architectures [3]. All-electric designs completely depend on galvanic cells, namely batteries and fuel cell systems (FCSs), to provide energy to the electrically driven propulsors. These designs can be entirely battery-based or fuel cell-based, where the FCS is supplemented by a battery, see Figure 1. Fuel cell-based systems have been tested in small aircraft, like the HY4, and are being extensively developed for deployment in regional aircraft by 2035. Kazula et al. [4] provide a detailed review of fuel cell types for electrified aviation. Furthermore, fuel cell systems and their associated mechanical, thermal and electrical components and subsystems (Balance of Plant, BoP), which are required for efficient, automated operation, are described in Kazula et al. [6], [7].

This study examines the air inlet system of an envisioned fuel cell- powered all-electric aircraft with passenger capacity and dimensions akin to those of the regional aircraft ATR-72 with a cruise flight Mach number of 0.55 [5], [8]. The reference propulsion system is divided into ten separate nacelle-mounted engines. Each engine provides up to 300 kW of propulsion power. The propulsion system relies solely on PEM fuel cells to generate electrical power and does not include any additional energy storage devices such as batteries. The fuel cells must therefore be able to provide sufficient power for take-off. The electrical energy generated in each nacelle is processed by power electronics and transferred to respective electric motors that drive a propeller. A thermal management system is also part of each nacelle.

The air inlet system must supply air for multiple purposes within the engine, as depicted in Figure 2. Oxygen from the ambient air is necessary for fuel cell operation, while the thermal management requires an even higher air mass flow. Hence, air is drawn in through the inlet, and large foreign objects are filtered by an engine air protection system. The air for the fuel cell undergoes an additional filtering process then and is compressed to ensure the right operation pressure. Prior to entry into the fuel cells, the air is also humidified and flows through a compact heat exchanger, which regulates its temperature for the fuel cell. For thermal management, the air is drawn through heat exchangers (HEX) by fans to extract heat from the cooling loops of all heat generating elements. In addition, a much smaller amount of air flow is channelled into the nacelle to avert hazardous levels of hydrogen via ventilation.

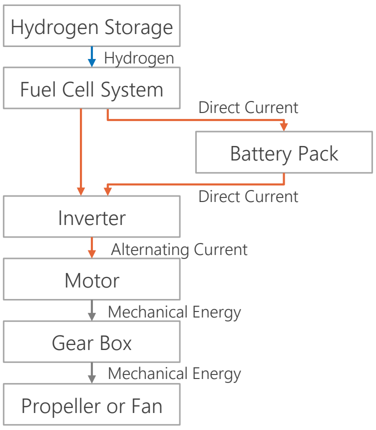

Figure 1. Propulsion system

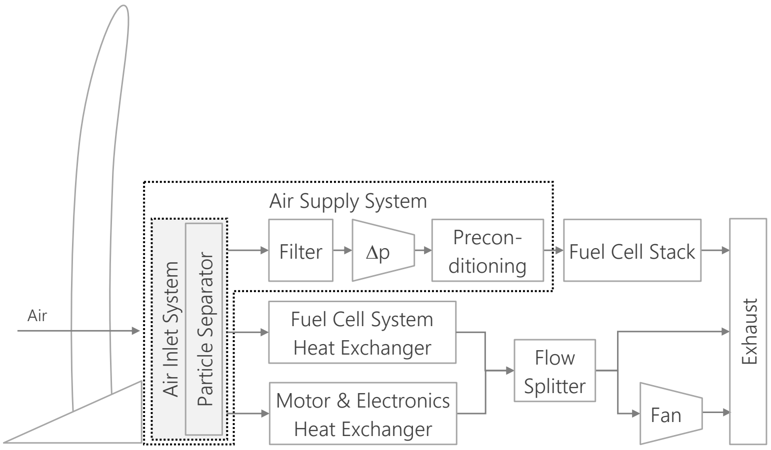

Figure 2. Air system of the reference aero engine

2.2. Air Inlets

2.2.1. Air Inlet Type. There are different types of air inlets available for different types of aircraft and for different purposes, as shown in Figure 3. For turbofan engines, pitot inlets are the preferred option [9]. However, they must be located at the front of a nacelle. As the propeller-driven engines analysed in this study are a puller configuration, the air inlets of turboprop engines are primarily considered.

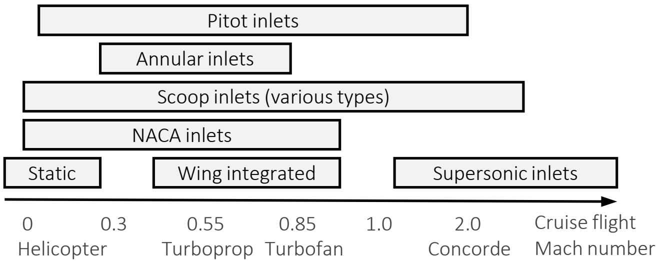

Figure 3. Air inlet types by typical aircraft cruise velocity

Turboprops often use annular inlets, which are located around the spinner, or scoop inlets located under the propeller cone. To reduce aerodynamic drag, some aircraft also previously integrated the air inlet and engines into the wing. NACA inlets are flush with the fuselage and typically used as auxiliary air inlets. However, NACA inlets have also been tested with positive results as primary inlets in experimental aircraft [10]. Static air inlets can be located at the side of the aerial vehicle. However, their poor total pressure ratio at higher speeds limits their use to helicopters only [11]. For supersonic aircraft, inlets with variable geometries are mostly utilised to attain optimal shock configurations [12]. Variants of pitot and scoop inlets can also be applied at low supersonic regimes. The relevant inlets types are depicted in Figure 4 and the advantages and limitations of each type are listed in Table 1 [13].

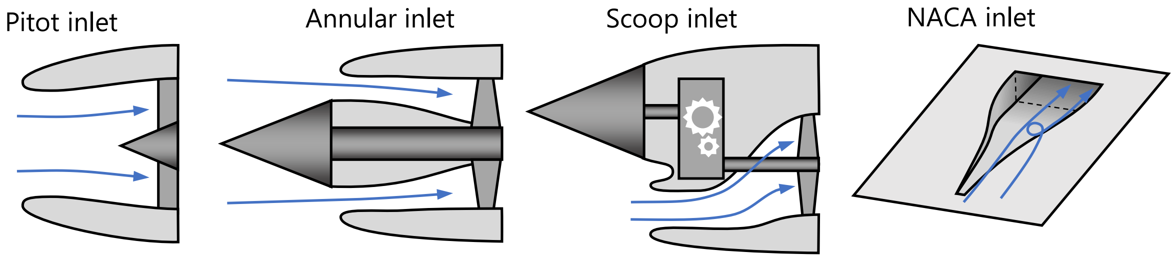

Figure 4. Different air inlet types

Table 1. Overview of different air inlet types

Type	**Advantages**	**Challenges**
Pitot inlet	+ Very high total pressure ratio + Low distortion + Commonly used, proven technology	- Incompatible with puller configuration - High spillage drag
Annular inlet	+ Compact + Low drag + Proven technology for turboprops	- Low total pressure ratio - Distortions due to propeller
Scoop inlet	+ High pressure recovery + Low distortion + Proven technology for turboprops + Easy integration of particle separator	- High drag, dependant on design - Curved ducts behind inlet can cause distortions
NACA inlet	+ Very low drag + Proven as auxiliary inlets	- Very low total pressure recovery ratio - Large design space requirements - Only experimental use as primary inlet

2.2.2. Variable Air Inlets. A variable geometry inlet can adapt to changing air mass flow requirements and flight conditions, potentially enhancing total pressure ratios during take-off and reducing spillage drag compared to fixed-geometry inlets. Various mechanisms serve this purpose [9]:

- Blow-in-doors: inward opening doors within the inlet, which enable higher air mass flows.
- Vent- or bleed-doors: opening doors to allow excess air to exit the inlet.
- Movable lips: adjustable lips that can adjust the inlet area and the angles of attack, see Figure 5.
- Boundary layer treatment: suction or blowing slots to manipulate the inlet boundary layer.

2.2.3. Engine Air Protection Systems (EAPS). These systems safeguard helicopter and turboprop aircraft engines from dust, ice, bird strikes, and foreign object damage (FOD). EAPSs performance indicators include their total pressure ratio, their separation efficiency, and their scavenge air mass flow ratio [14]. Common EAPS types include:

- Inertial Particle Separators (IPS): curved ducts, which use centrifugal forces, see Figure 6.
- Vortex Tube Separators (VTS): multiple small tubes with swirl vanes for centrifugal forces.
- Inlet Barrier Filters (IBF): air filters, which can absorb particles, e.g. even carbon monoxide.
- Wire Mesh (Inlet Screen): potentially retractable screens that stop larger objects.
- Vortex Dissipators: downward-blowing pressurized air to divert foreign objects. [15]

For further details, refer to Table 2, which outlines characteristics of different EAPS [15]. Furthermore, means of ice protection are part of the inlet, compare Kazula et al. [16].

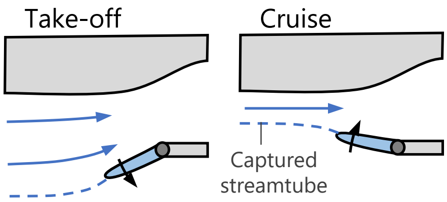

Figure 5. Inlet with movable lip

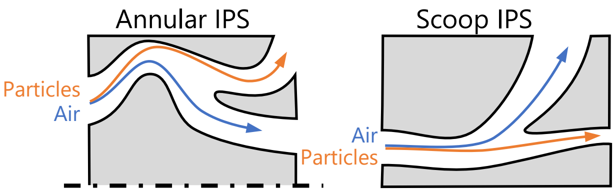

Figure 6. Inertial particle separators (IPS)

Table 2. Overview of different engine air protection systems

Type	**Advantages**	**Challenges**
Inertial Particle Separator (IPS)	+ Compact + Low distortion + Resistant to FOD	- Low separation efficiency - High scavenge mass flow (15-20%)
Vortex Tube Separator (VTS)	+ Low pressure loss + High separation efficiency	- Large frontal area - Scavenge mass flow (5-10%) - Susceptible to FOD - Icing issues
Inlet Barrier Filter (IBF)	+ Very high separation efficiency + No scavenge mass flow	- Pressure loss increases over time - Large frontal area - Increased maintenance efforts for filter replacement
Wire mesh / inlet screen	+ Lightweight + No scavenge mass flow + Low pressure loss possible	- Only protects from larger objects - Icing issues
Vortex Dissipator	+ No device inside the inlet required	- Only protects from ground debris - Bleed air required

2.2.4. Inlet Evaluation Metrics. In general, air inlets direct ambient air into the aircraft or the nacelle, supplying air to air breathing systems. When evaluating inlets, the aerodynamic performance is primarily determined by total pressure ratio, drag and airflow uniformity [17].

The total pressure ratio, $\Pi_{0,2}$, refers to the ratio between the total pressure, p_{t2}, retained as the air flows through the inlet and the total pressure, p_{t0}, in the free stream.

$$\Pi_{0,2} = p_{t2}/p_{t0} \tag{1}$$

Different descriptions for this value exist, such as inlet pressure recovery or pressure loss.

The aerodynamic drag is the force that the external airflow applies to the inlet. To distinguish the impact of the air inlet type from the nacelle drag, the spillage drag is used. The spillage drag describes the additional drag that arises when the inlet operates below the designated air mass flow and hence has a too small inlet entry area. The spillage drag [18] is later used to quantify drag forces of the relevant inlet types for different inlet entry areas.

The distortion of the airflow refers to the uniformity of total pressure and velocity across a cross section, which is crucial for protecting compressor blades from high dynamic loads and ensuring optimal performance. The DC60 value is typically used to describe distortion upstream of compressors [17]. For potential heat exchangers downstream of the air inlet, this metric is less critical.

Apart from these aerodynamic requirements, inlets have also to comply with mass and integration, safety, as well as reliability and cost requirements, compare Kazula et al. [19], [20].

3. Methodology

In this study, a design process for safe and reliable concepts has been applied [19], [21], see Figure 7. This approach comprises traditional development phases, such as requirements, functional and conceptual analysis. Additionally, suitable safety and reliability methods are assigned to each phase of the development process to improve the product significantly. These methods are part of the safety assessment process in aviation based on Aerospace Recommended Practice ARP 4754A and described in ARP 4761. The conduction of selected of these methods in the context of fuel cell-powered aero engines have been presented by Kazula et al., e.g. the Functional Hazard Assessment (FHA) and the Fault Tree Analysis (FTA) [6], as well as the Common Cause Analysis (CCA), which comprises the Zonal Safety Analysis (ZSA), the Particular Risk Analysis (PRA) and the Common Mode Analysis (CMA) [22].

This paper focusses on the conceptual analysis phase, including concept generation, preselection and initial design. For the concept generation, the brainstorming 6-3-5 and the morphological box methods have been applied. The preselection has been performed by means of mandatory requirements derived from the requirements list. The evaluation has been achieved by a weighted point rating, compare [4]. The aerodynamic design and mass estimation of the concepts is based on handbook methods [17].

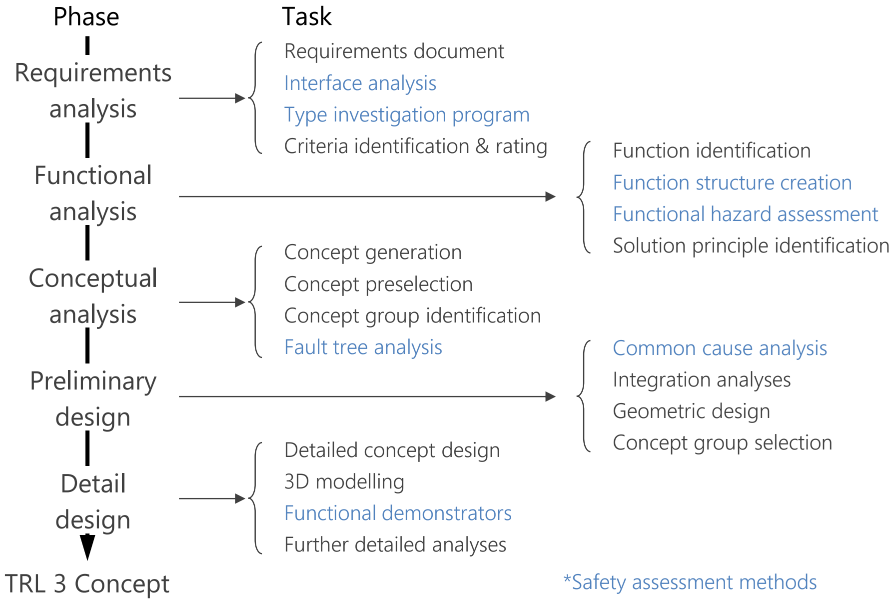

Figure 7. Design process

4. Selected Results

4.1. Concept Development

Prior to concept development, a structured list of requirements was established via requirement checklists, brainstorming, literature reviews, and analyses of interfaces and regulations from aviation authorities. Following this, a function structure tree for the inlet was developed and the appropriate inlet areas were initially sized. Subsequently, 16 concepts were generated using a morphological box and brainstorming techniques. The eight remaining concept options have been preselected for further investigation, with five of them displayed in Figures 8 to 12 [13].

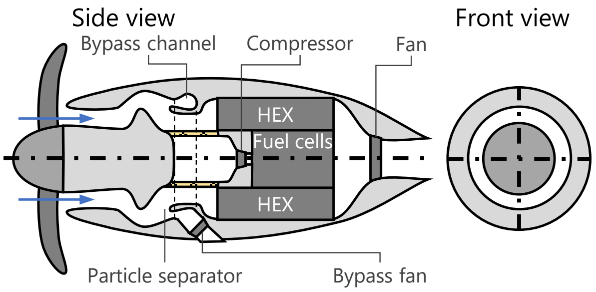

Figure 8. Annular inlet concept

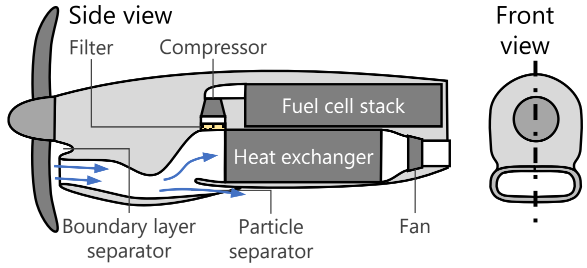

Figure 10 Scoop inlet concept

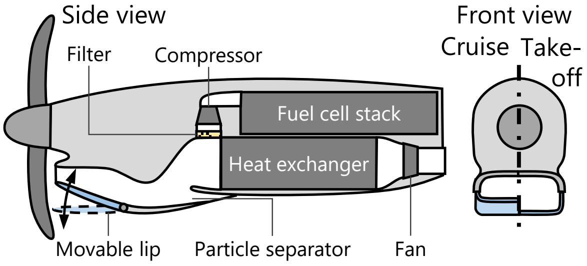

Figure 11. Movable lip scoop inlet concept

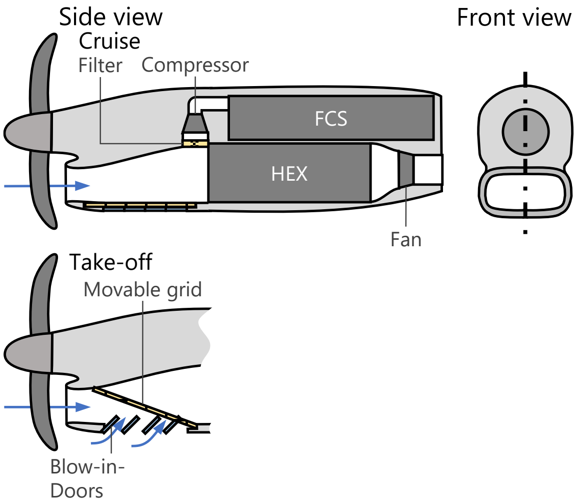

Figure 9. Blow-in door scoop inlet concept

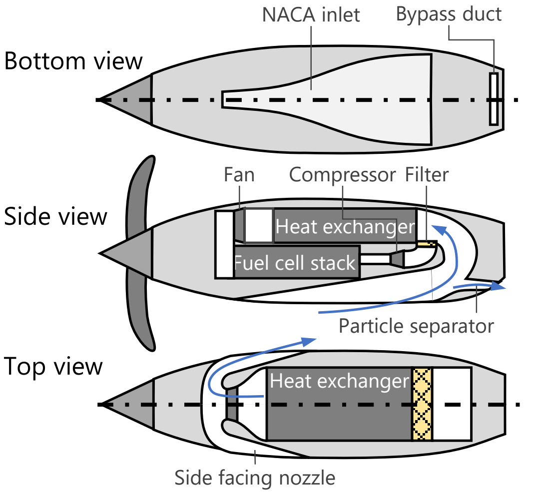

Figure 12. Reverse airflow NACA inlet concept

4.2. Concept Evaluation

The next phase involved the preliminary sizing and CAD modelling of the concepts. In addition, the study focused on the influence of inlet area, pressure recovery and aerodynamic drag. Pressure recovery, for instance, is critical to the required cooling fan power, as 1% pressure recovery corresponds to approximately 10% required compressor power. Using a weighted point rating, which is described in detail by Kazula et al [4], these analyses allow for an objective evaluation. Hereby, the six criteria *i* safety, reliability and cost, mass and installation space, total pressure recovery, flow uniformity and aerodynamic drag have been weighted via pairwise comparison to achieve weightings w_i. Next, the fulfilment of the criteria by the respective concepts was rated on a scale from very poor to very good and a relative rating r_j was calculated for each concept j. The results of the evaluation for the top three concepts are presented in Table 3. At the higher temperatures of fuel cell operation, the benefits of variable inlet concepts diminish as the amount of cooling air required decreases.

Table 3. Inlet concept evaluation

Evaluation Criteria	**Weighting w_i**	**Annular Inlet**	**Scoop Inlet**	**Movable Lip Scoop Inlet**
Total pressure ratio	0.267	-	+	++
Safety	0.267	++	++	+
Aerodynamic drag	0.200	+	-	+
Mass and installation space	0.133	++	+	o
Flow uniformity	0.067	+	++	++
Reliability and cost	0.067	++	++	+
Relative Rating r_j		**0.73**	**0.75**	**0.78**

Cell Values: Fulfilment of the criterion is very good ++, good +, average o, poor - or very poor --

4.3. Preliminary Design of the Movable Lip Scoop Inlet Concept

Figure 13 illustrates the variable scoop concept. In comparison to existing scoop inlets, initial results indicate a high total pressure ratio ranging from 0.975 to 0.99, based on the flight conditions.

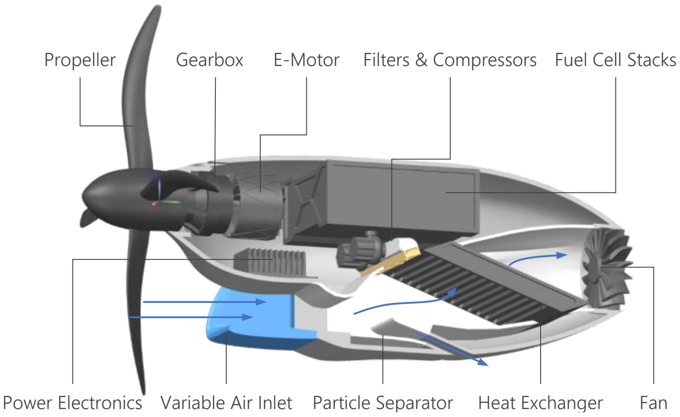

Figure 13. Sectional view of movable lip scoop inlet concept

5. Conclusions

The motivation for designing inlets in the context of future PEM fuel cell-powered aircraft propulsion has been described. An overview of existing technological solutions for engine inlets has been given. The advantages and limitations of the most relevant inlet types, as well as their relevance for application on fuel cell-powered aero engines have been identified. Following, 16 inlet system concepts have been elaborated, analytically sized, preselected, modelled and evaluated.

The most suitable options for inlet systems of PEM fuel cell-powered aero engines are represented by concepts that use scoop inlets, annular inlets, or scoop inlets with adjustable entry area. Here, a combination with inertial particle separator (IPS) and filter for fuel cell cathode air is required.

The conducted analyses highlight the high potential of scoop inlets and annular inlets. Furthermore, the influence of fuel cell operating temperature, ideal pressure recovery and entry area on the sizing of the fuel cell system and the cooling fan, on system mass and efficiency, aerodynamic drag, as well as reliability and safety is identified. These results may assist further investigations concerning PEM fuel cell-powered aircraft propulsion and support the way to more environmentally friendly transport.

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