DESIGN AND ANALYSIS OF THE AIR INLET SYSTEM FOR FUEL CELL-POWERED ELECTRIC PROPULSION SYSTEMS IN REGIONAL AIRCRAFT

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Abstract

Electrified propulsion systems powered by hydrogen fuel cells are a promising technology for future, sustainable aircraft. However, operating a fuel cell in an aircraft poses challenges to other components, such as the air inlet system. Not only does the fuel cell have to be supplied with a constant stream of clean air for the cold combustion, but also high amounts of waste heat have to be discarded into the atmosphere by utilizing air liquid heat exchangers. This paper introduces and evaluates different air inlet system options using analytical methods. Inlet concepts are identified by analysing the state of the art. Promising concepts are selected using a qualitative evaluation. The most promising concept is sized for a reference propulsion system. The results of this study highlight the importance of careful air inlet design to ensure reliable operation and acceptable performance of fuel cell-powered aero engines. Performance and sizing data gained from the analytical calculations can serve as a baseline for the preliminary design of air supply systems for fuel cell-powered aircraft. Additionally, the process used in this work can be implemented for inlet systems designed for other engine types. Thereby, this work assists in the development of carbon-neutral air travel.

Keywords

Air Inlet, Fuel Cell, Electric Flight, Aerodynamics

1. INTRODUCTION

Fuel cells have the potential to use hydrogen more efficiently than conventional gas turbines [1]. However, fuel cell-powered aircraft are still in an early stage of development. While different fuel cell types exist, this work assumes an engine based on a low-temperature polymer electrolyte membrane fuel cell (LT-PEM-FC) and presents the design of an inlet system for this engine type. LT-PEM-FCs typically operate at about 80°C [2 p. 13] with an efficiency of 50% to 60% [2 p. 299]. This results in a low temperature difference to the ambient air during hot day take off conditions, posing a major challenge for LT-PEM-FC-based propulsion systems, as the excess heat generated by the fuel cell must be dissipated. Early studies [3] reveal a required air mass flow at take-off, which is about eight times higher than for cruise flight. Hence, a trade-off for the inlet design is required, which offers good performance in both flight conditions. Therefore, the investigation of different inlet types and options for geometry adjustment is necessary.

The goal of this study is to identify suitable solutions for delivering air to the fuel cell and thermal management system in a reliable, efficient and safe way, while resulting in minimal aerodynamic drag and additional mass.

2. STATE OF THE ART

2.1. Engine Topology

This work investigates the air inlet system of a potential fuel cell-powered all electric aircraft with a passenger capacity and size comparable to the ATR-72, a regional aircraft. The propulsion system is distributed over ten independent nacelle-integrated engines, which provide a maximum propulsive power of 300 kW each. The initial reference engine topology relies solely on PEM-fuel cells for electric power generation and does not include any additional means of energy storage, such as batteries. Hence, the fuel cells have to be capable of delivering sufficient power for take-off. Within the nacelles, the generated electric energy is conditioned by power electronics and transferred to electric motors, which drive a propeller. Furthermore, a thermal management system is integrated.

The air inlet system has to deliver air for multiple uses within the engine, see FIG 1. Oxygen from the ambient air is needed for the fuel cell. This air is provided by the inlet, filtered by the engine air protection system and compressed to achieve a suitable operating pressure. Before entering the fuel cells, the air is also humidified and passes through a small heat exchanger, which adjusts the air temperature for the fuel cells. The largest fraction of the air mass flow is required for the thermal management system. Here, air passes through heat exchangers (HEX) to transfer heat away from the coolant loops of all heat generating components.

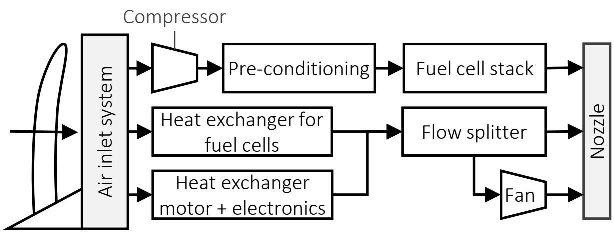

FIG 1. Air system of the reference engine topology

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Additionally, a small air mass flow has to be guided into the nacelle to prevent dangerous concentrations of hydrogen by ventilating the nacelle.

2.2. Air Inlets

An air inlet guides ambient air into the aircraft or nacelle to supply an air breathing system such as an engine. The most important performance parameters for air inlets are the total pressure ratio, aerodynamic drag and the uniformity of the airflow [4 pp. 619–621].

The **total pressure ratio $\Pi_{0,2}$** describes the quotient of the total pressure p_{t2} that is preserved, while the air flows through the inlet to the total pressure p_{t0} in the far field.

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

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

The **aerodynamic drag** is the force that the external air stream acts upon the inlet. To separate the effect of the air inlet from the nacelle drag, the spillage drag is used to quantify drag forces of different inlet types and take the effect of the inlet area into account [5 pp. 941–943]. The spillage drag describes the additional drag that occurs when the inlet operates below the design air mass flow.

The **distortion of the airflow** describes uniformity of the total pressure and air flow velocity over a cross section. High uniformity is important for protecting compressor blades from high dynamic loads and for its performance. For compressor inlets, the DC60 value is used to describe the distortion [6 p. 257]. For a heat exchanger situated behind the air inlet, this metric is not as critical.

2.2.1. Air Inlet Types

For different aircraft types and purposes, several air inlet types exist, see FIG 2. Pitot-inlets are a common choice for turbofan engines. However, these inlets have to be positioned at the front of the nacelle. As the reference engines in this work will use a puller or tractor configuration, mainly air inlets from turboprop engines will be considered.

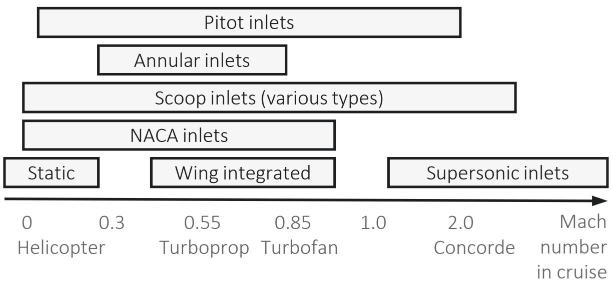

FIG 2. Air inlet types by typical aircraft cruise velocity

Turboprop engines often use annular inlets, which are positioned around the spinner, or scoop inlets, which are commonly mounted below the propeller cone [6 pp. 268–270]. In the past, some aircraft integrated the air inlet and the engines into the wing in order to reduce aerodynamic drag. NACA-inlets are flush with the fuselage and are mostly used as auxiliary air inlets. However, NACA inlets were also successfully tested as primary inlets in experimental aircraft [7]. These inlet types are illustrated in FIG 3 and their respective advantages and challenges are listed in TAB 1.

Static air inlets are facing towards the side of the aircraft and are exclusively used on helicopters due to their very poor total pressure ratio at higher speeds [8]. Supersonic aircraft use specialised inlets, which often feature variable geometries [9]. Variants of pitot and scoop inlets can also be used at supersonic speeds.

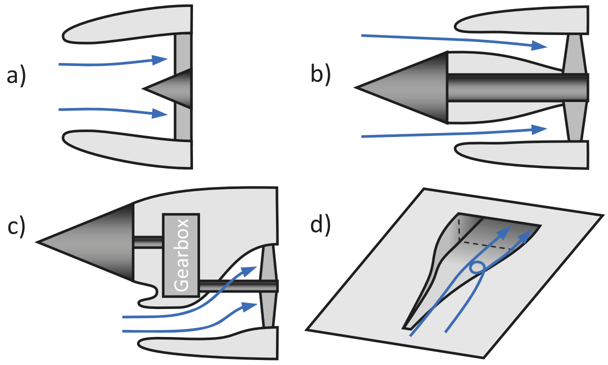

FIG 3. Schematics of different air inlet types: a) Pitot inlet, b) Annular inlet, c) Scoop inlet, d) NACA inlet

TAB 1. Overview of different air inlet types

Type	Advantages	Challenges
Pitot inlet	+ Very good total pressure ratio + Low distortion + Commonly used, proven technology	- Incompatible with tractor configuration - High spillage drag
Annular inlet	+ Compact + Low drag + Proven technology for turboprops	- Low total pressure ratio - Distortions due to propeller
Scoop inlet	+ Good pressure recovery + Low distortion at inlet + Proven technology for turboprops + 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 ratio (in relation to other inlets) - Space requirements for inlet ramp - Only experimental use as primary inlet
Wing integrated inlet	+ Low drag + Low distortion + Good total pressure ratio	- Integration of engine components into the wing - Worse performance if combined with swept wings

2.2.2. Variable Air Inlets

A variable geometry inlet can react to varying air mass flow requirements and other changing flight conditions. Such an inlet has the potential to improve the total pressure ratio during take-off and reduce the spillage drag in cruise flight compared to a fixed-geometry inlet. Different mechanisms exist to fulfil this purpose.

Blow-in-doors are small doors, usually positioned around an inlet, that open inwards when a high air mass flow is needed [7]. Vent- or bleed-doors are similar to blow-in-doors but serve the purpose to let excess air exit through an opening in the walls of an internal duct. These two functions can be combined in one door, which can both let additional air flow into the inlet or let excess air exit [10 pp. 332–333]. For rectangular inlets, movable lips can be implemented to adjust the inlet area and improve aerodynamics at high angles of attack [11 pp. 446–447], see FIG 4.

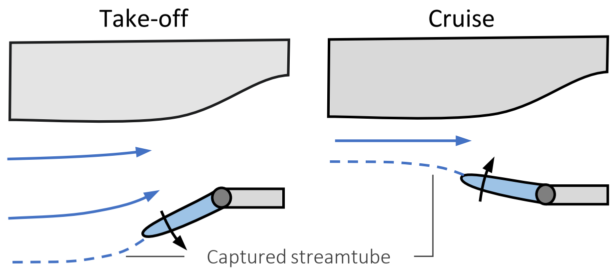

FIG 4. Inlet with movable lip in different operating conditions

In some cases, segments of the inlet can be closed completely to stop airflow from entering an inlet. For example, in supersonic ramp inlets this can be achieved by radially moving a ramp, until the inlet is completely closed [7], [12]. Variable geometry inlets are commonly found on supersonic aircraft to enable ideal shock configurations. As this is not required for regional aircraft, specialised supersonic inlet designs will not be investigated in this work.

2.2.3. Engine Air Protection Systems

Engine air protection systems (EAPS) are commonly used in helicopters and turboprop-powered aircraft to protect engines from dust, ice, bird strikes or generally foreign object damage (FOD) [13]. Some turbofan and turbojet aircraft that are designed to take off from unpaved runways also use protection systems [14]. Key performance indicators for engine air protection systems include the total pressure ratio, the separation efficiency and the scavenge flow ratio [15].

The **total pressure ratio or pressure loss** describes the same losses as for the air inlet in general, compare section 2.2. Pressure losses occur as the air flows through particle separators, filters or other protection systems.

The **separation efficiency** describes the share of particles that is removed from the core airflow. This number can differ with the type of sand that is used in the test [15]. Smaller particles are usually harder to separate from the airflow.

Some types of EAPS use a part of the airflow to move particles out of the engine through a bypass duct, the so called **scavenge flow** [16]. The scavenge air mass flow should be minimised, as it cannot be used by the engine.

Potential EAPS types are the Inertial Particle Separator (IPS), the Vortex Tube Separator (VTS), the Inlet Barrier Filter (IBF), the wire mesh or inlet screen and the Vortex Dissipator [16].

Inertial Particle Separators (IPS) work by changing the direction of an air flow within a duct. Due to the inertia of heavier particles, these are unable to follow the turn and flow into a bypass duct, see FIG 5.

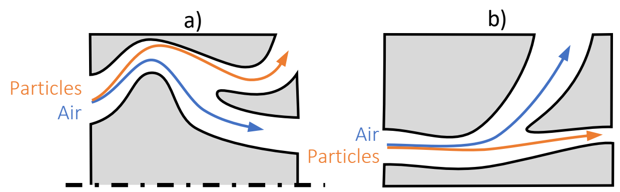

FIG 5. Different inertial particle separators: a) section of an annular IPS, b) integrated with scoop inlet

Vortex tube separators (VTS) consist of multiple smaller tubes, which use swirl vanes to produce a rotating airflow where particles are separated from the core airflow by centrifugal forces. Inlet Barrier Filters (IBF) pass the air through a filter, which stops particles from entering the engine [17]. For PEM-FC, special filters exist, which also absorb carbon monoxide that may otherwise damage the cathode [18]. Some aircraft use wire meshes, also known as inlet screens, to stop larger objects from damaging the engine [12]. These screens may be retractable. Vortex dissipators blow pressurised air downward to deflect foreign objects that may otherwise be sucked into the engine [14]. TAB 2 lists characteristics of different EAPS.

TAB 2. Overview of different engine air protection systems (expanded upon [16])

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

3. METHODOLOGY

In order to elaborate an optimal design, the air inlet system is split into three subsystems: the primary inlet, variable components and an engine air protection system. Different solutions for these three subsystems are identified from inlet systems that are already flying or have previously been studied [7], [10], [15], [19], [20], [21], [22]. Unsuitable subsystems are then eliminated. Next, concepts for the full system are outlined, using new options and the subsystem solutions that were selected in the first step. Following this, the subsystems are evaluated, using analytical calculations and empirical data. Using these results, each concept for the full system receives a total score and the most promising concept is selected. This selection process is visualised in FIG 6. The chosen concept is then further detailed and a preliminary geometry is designed. To visualise the concept, a CAD Model is created. This model can serve as a baseline for a subsequent CFD analysis to verify the analytical assumptions.

3.1. Preselection

In order to reduce the number of concepts that have to be analysed in the detailed evaluation, a selection list [23 pp. 180–181] is used to preselect the concepts. Only concepts, which can potentially fulfil all preselection criteria are evaluated using a more detailed weighted point rating.

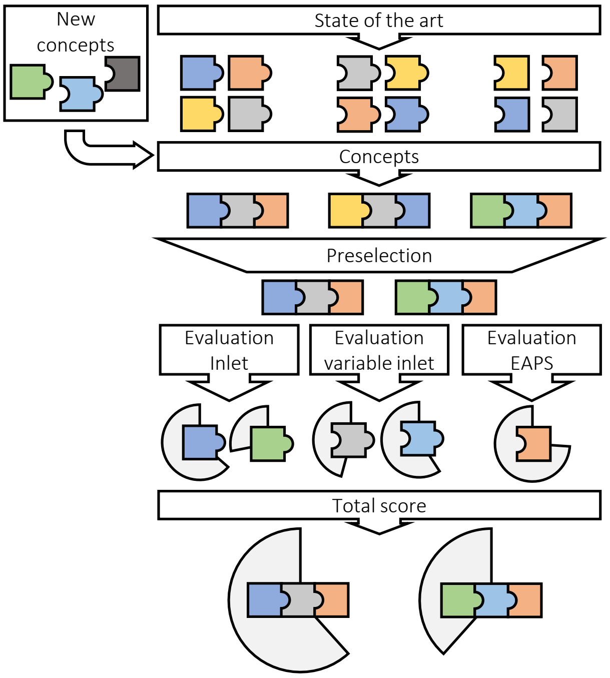

FIG 6. Conceptual design and evaluation process

3.2. Weighted Point Rating

To evaluate different concepts and subsystems, a weighted point rating is used [23 p. 193]. First, the criteria are weighted by a pairwise comparison. All criteria are compared in a matrix. The more important criterion receives a "+" (2 points) and the less significant criterion "-" (0 points). If both criteria are deemed to have the same importance, both will receive a "o" (1 point). To obtain a relative weight g_i, all points p_i from one row (for one criterion) are added up and divided by the total number of points. This number corresponds to the number of criteria n squared for the matrix used in this work.

(2) $g_i = p_i/n^2$

Second, the different subsystems or concepts that are evaluated are assigned points from "--" (poor, 0 points) to "++" (very good, 4 points) for each criterion. This is a qualitative evaluation, but if available the points are based on values that were obtained for total pressure ratios and drag forces. The separate points $m_{i,j}$ are multiplied with their respective weights and then added up [24]. To normalise the ratings for each concept, the scores are divided by 4. A concept which receives the best possible ratings would have a score of $w_j = 1$.

(3) $w_j = \frac{1}{4}\sum_{i=1}^{n} g_i\, m_{i,j}$

For visual representation of the weighted point ratings, utility value profiles are used. These profiles are bar charts, which display the point value for a criterion as the height of the bar and the weighting of this criterion as the width of the bar [23 p. 188]. The total score corresponds to the total area covered by all bars in the diagram.

3.3. Important Calculation Methods

For the analytical calculations in this work, air is described as a compressible ideal gas. Compressibility effects have to be considered, as the aircraft is flying at $Ma = 0.55$.

For the preliminary design, total pressure ratios and drag forces are obtained based on experiments and CFD analyses carried out in other studies [20], [21], [22], [25], [26] or based on empirical calculation methods proposed in literature [10], [19].

3.3.1. Adiabatic Flow

To investigate the airstream through the inlet system, a method is needed to calculate the state of the airflow based on known total pressure and temperature values as well as the desired mass flow and duct cross section. The state of the airflow is calculated using the iterative process illustrated in FIG 7, which starts with the total values and refines the results with each iteration.

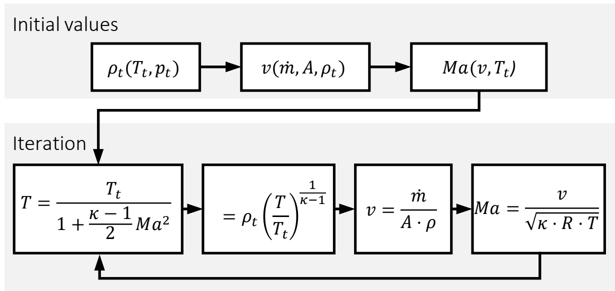

FIG 7. Iterative calculation process to predict compressible airflow properties in a duct with a known cross section

4. SELECTED RESULTS

Requirements and performance data for different air inlet types and engine air protection systems are elaborated and summarised in this work. The potential of the selected concept is analysed and challenges in the design of an air inlet system for new engine topologies are identified.

4.1. Requirements

To identify suitable concepts, requirements for the inlet system were elaborated and classified in the following four categories aerodynamic properties, mass and installation space, safety as well as reliability and cost.

The inlet system has to meet **aerodynamic requirements**. Most importantly, it must be able to deliver the required air mass flow to the engine. Further aerodynamic properties, which must be optimised are the total pressure ratio and aerodynamic drag. Also, the inlet should minimise flow distortions. These are not as critical as with a turbine engine, a no compressor is situated directly behind the intake. However, the flow into the main heat exchangers should be as uniform as possible to achieve an ideal heat dissipation within the heat exchanger. In current engines, the inlet is also dampening the noise from a fan or compressor. In the reference engine, the dominant noise component should be the propeller. Still, the inlet system should not produce excessive noise.

The **mass and installation space** of the inlet system should be minimised. This category also includes the resistance of the inlet to structural loads that are expected in normal operation [27 pp. 128–129].

Safety is a very important aspect in aircraft design. For this reason, the inlet has to contribute to avoiding malfunctions of the engine. One task of the inlet system is to protect the core components from foreign objects within the airstream. The inlet itself also has to be resistant to external influences. Additionally, the inlet system should not pose any threat to the operation of the engine [27 p. 4]. This might occur following a malfunction of the inlet, for example, if a part of the inlet separates and damages other components or if the airflow into the engine is blocked.

Reliability and cost include the amount of maintenance that is required to keep the inlet system in working condition as well as the life cycle cost of the system. Reliability is different from safety in the way that a system can be safe although non-critical malfunctions may occur, which create a need for maintenance and increase costs.

4.1.1. Inlet area

The most important trade-off, apart from the inlet type, is finding a suitable inlet area. During take-off, a large inlet is favourable because the air flow into the engine will be slower, thus producing lower pressure losses. Furthermore, high cooling air mass flows are required during that phase. If the inlet is too small, the inlet can become blocked, as the air flow is accelerated in the smallest cross section and could transition to supersonic speeds.

However, in cruise flight, a smaller inlet is advantageous to reduce drag. Especially if the engine only needs a small mass flow, a large inlet can create a significant amount of spillage drag. Following, the effects of the inlet area at take-off, see FIG 8, and in cruise flight, see FIG 9, are compared.

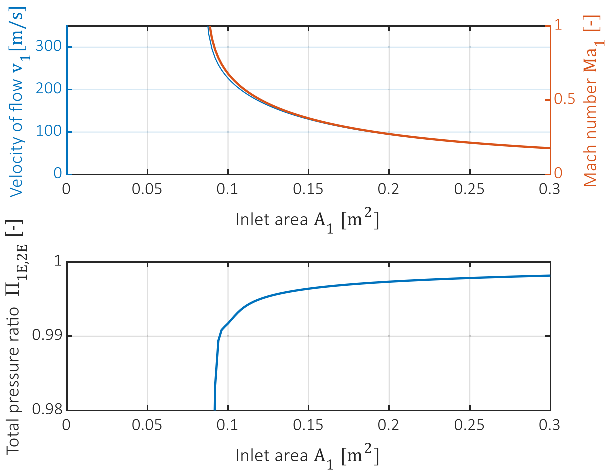

FIG 8. Flow velocity and total pressure ratio over cross sectional inlet area for an air mass flow of $\dot{m}_{Air} = 21.2\ kg/s$

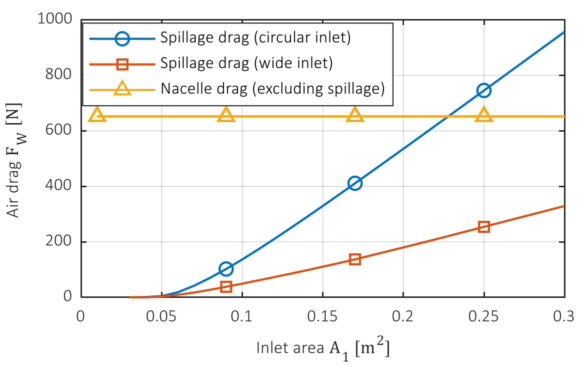

FIG 9. Aerodynamic drag in cruise flight over inlet area for $\dot{m}_{Air} = 2.57\ kg/s$, $v_0 = 169\ m/s$

The spillage drag is calculated with two separate methods for different inlet types. The boundary conditions for the surrounding air and mass flow requirements are taken from the cruise design point. For circular inlets, a factor K_{Add} that only depends on Ma is used to calculate the spillage drag from the theoretical additional drag as proposed by Mount [25]. For wide scoop inlets, where the square of the width is more than 2.5 times larger than the inlet area, a spillage drag coefficient is calculated from the Mach number, mass flow ratio and geometric parameters [19]. Wide inlets have a higher circumference for the same inlet area, which leads to decreased air spillage over the inlet lip per circumferential length. This helps to reduce the losses that occur, when too much air flows around the inlet.

These figures show that an inlet designed to deliver good air flow properties at take-off conditions may cause excessive drag during cruise.

4.1.2. Total Pressure Ratio

The total pressure ratio of the air inlet is a very important parameter for both the maximum power requirement of the fuel cell system and for the sizing of fans or blowers included in the thermal management system, see FIG 10. In cruise flight, the total pressure ratio influences the aerodynamic drag F_{WI} that the thermal management system of the reference engine causes due to the slowing of the internal air flow, see FIG 11.

At the start of the take-off roll, no ram pressure is available to move air through the thermal management system. Therefore, a fan with a maximum power demand P_K is required to draw air through the heat exchangers [3]. All pressure losses in the air system have to be compensated by this fan, which contributes significantly to the total power demand of the propulsion system $P_{FC,ref}$, see FIG 10. For this diagram, the total pressure ratio of the inlet system $\Pi_{0,2}$ and of the main heat exchanger $\Pi_{2,3}$ are taken into consideration.

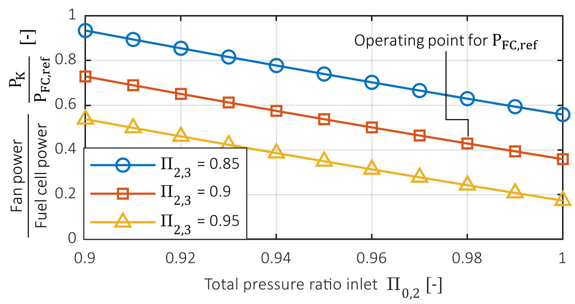

FIG 10. Required cooling fan power (normalised to total power delivered by the fuel cell) over inlet total pressure ratio

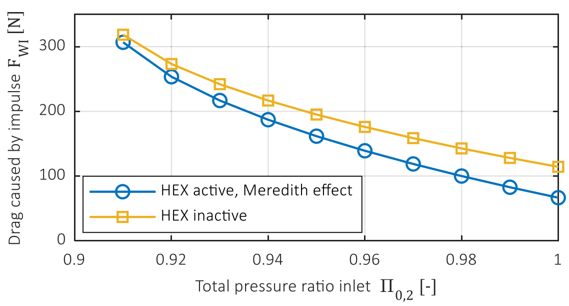

FIG 11. Influence of the total pressure ratio of the inlet on air drag in cruise flight with $\Pi_{2,3} = 0.9$

In cruise operation, the fan can be shut down and air will flow through the thermal management system purely by using ram pressure. In this mode of operation, pressure losses within the air system cause the air to slow down and act an impulse upon the engine. This speed reduction and therefore the impulse from the air becomes larger, the more pressure is lost when the air passes through the intake duct. This drag force F_{WI} can partially be counteracted by the Meredith-effect, see FIG 11. If air is heated up in a heat exchanger, the air will expand. By using a properly designed duct, this expansion can be used to accelerate the air after losing some total pressure within the heat exchanger.

An important result from these calculations is that during take-off a 1% decrease in the total pressure ratio of the air inlet causes a 10% increase in the necessary power to run the fan. In cruise, the same decrease in the total pressure would result in a neglectable additional drag of around 20 N per nacelle.

4.2. Concepts

This section describes selected concepts that were studied. All of the concepts that are displayed here were deemed to be viable during the preselection.

Concept 1 uses an annular inlet, which is integrated with a coaxial inertial particle separator, see FIG 12. Air and particles from the bypass channel of this separator are extracted by a fan. The mostly particle free air is then passed to the heat exchangers. Some air passes through a filter to be used by the fuel cells.

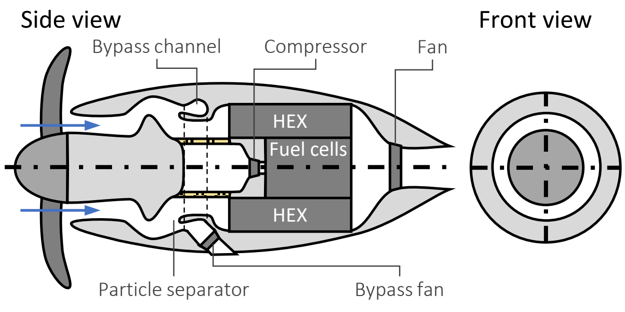

FIG 12. Concept 1 with annular inlet

Similar to many modern turboprop aircraft, concept 4 uses a scoop inlet. Behind the inlet, air passes through a passive inertial particle separator before reaching the heat exchangers and the fuel cell stack, see FIG 13.

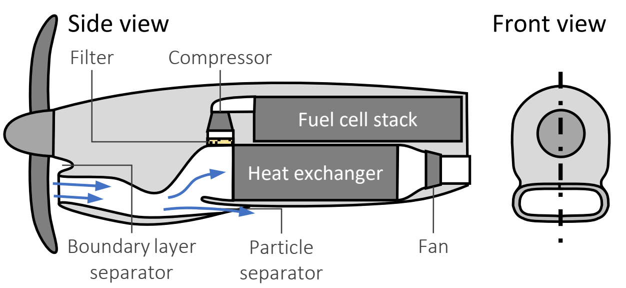

FIG 13. Concept 4 with fixed geometry scoop inlet

This design can be supplemented by a movable lip, see FIG 14, which can improve the total pressure ratio at take-off and reduce drag during cruise. However, the system complexity and most likely the system weight is increased.

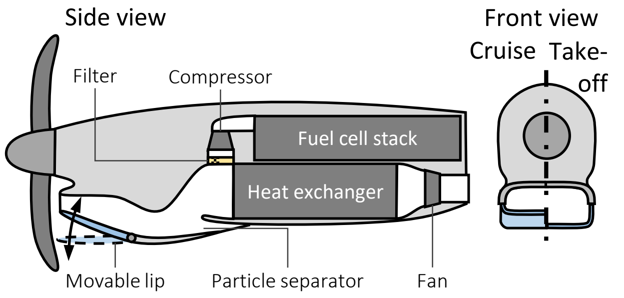

FIG 14. Concept 4a with scoop inlet and movable lip

The approach used by concept 5 is similar to concept 4, as it also incorporates a scoop inlet underneath the propeller cone. However, blow-in doors are located on the underside of the nacelle and a movable grid can be deployed to protect more sensitive components from foreign objects. This concept is displayed in FIG 15.

To integrate a NACA inlet into the nacelle, a reverse airflow system is chosen due to the long inlet ramp, that is required, see FIG 16. With this design, a particle separator can be integrated into the rear bend of the air duct. Air exits the nacelle through two nozzles located on either side of the nacelle. This design was considered to benefit from the low drag, that a NACA inlet can provide. However, the total pressure ratio is lower compared to scoop or annular inlets.

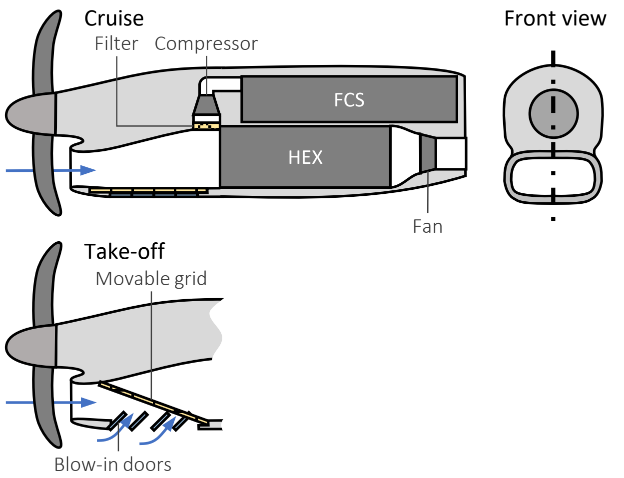

FIG 15. Concept 5: Scoop inlet with blow-in doors and a movable FOD grid

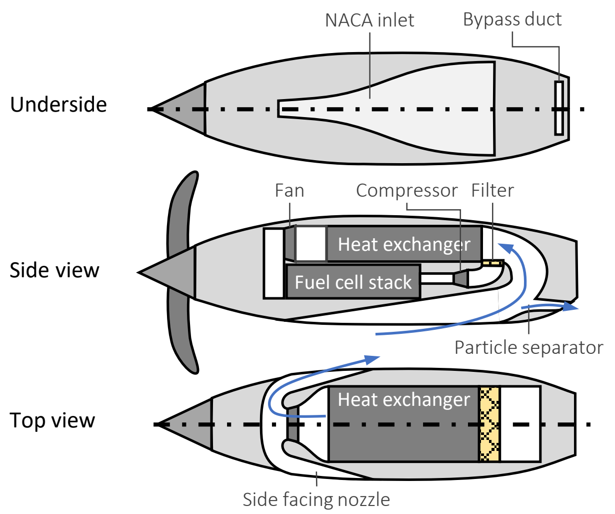

FIG 16. Concept 8: NACA inlet with reverse airflow

4.3. Preselection

All identified concepts are evaluated in the selection list in TAB 3 regarding their ability to potentially fulfil the following mandatory requirements:

- Aerodynamics **(A)** — Can the concept deliver the required air mass flow and performance?
- Mass **(M)** — Is it possible to design the concept to have an acceptable mass?
- Installation space **(I)** — Can the concept be integrated into the available installation space?
- Safety **(S)** — Can the system fulfil the safety requirements in aviation?
- Reliability **(R)** — Is the system durable, maintainable and fault-tolerant?
- Cost **(C)** — Can the system be developed, manufactured and operated with acceptable cost?

TAB 3. Selection list

Concept		A	M	I	S	R	C	Remarks	
1	Annular inlet	+	+	+	+	+	+		**+**
1a	Annular with blow-in doors	+	+	+	+	+	+		**+**
1b	Annular with translating ring	+	+	+	+	+	+		**+**
2a	C-Doors and filter	?	-	+	-	+	+	Filter can become blocked in icing conditions, aerodynamics around doors	**-**
2b	C-Doors and movable heat exchanger	?	-	?	?	+	+	Doors have to move weight of HEX	**-**
3	Ducted spinner integrated with IPS	+	?	+	-	+	+	Foreign object may be propelled towards other parts of the aircraft	**-**
4	Scoop inlet	+	+	+	+	+	+		**+**
4a	Scoop with movable lip	+	+	+	+	+	+		**+**
4b	Scoop with blow-in doors	+	+	+	+	+	+		**+**
4c	Scoop with vent door	-	+	+	+	+	+	Flow separation and mixing behind vent-door lead to bad aerodynamic properties	**-**
5	Scoop with blow-in door and mesh	+	+	+	+	+	+		**+**
6	Scoop with split heat exchangers	+	+	+	+	+	+		**+**
7	Scoop with reverse airflow	+	+	-	+	+	+	Duct takes up too much internal volume	**-**
7a	Reverse scoop with movable lip	+	+	-	+	+	+	Duct takes up too much internal volume	**-**
7b	Reverse scoop with blow-in doors	+	+	-	+	+	+	Duct takes up too much internal volume	**-**
8	NACA inlet with reverse airflow	+	+	+	+	+	+		**+**

4.4. Evaluation with Weighted Point Rating

4.4.1. Criteria

For the weighted point rating, the criteria are derived from the requirements list. The aerodynamic properties are split into three criteria: total pressure ratio, external drag and flow distortions & acoustics. This is done for two reasons. First, a compromise is needed between the total pressure ratio and the external drag created by an inlet. For example, a boundary layer diverter can improve the total pressure ratio but increases the drag of the nacelle. The second reason is that an air inlet is primarily an aerodynamic component. Therefore, having three criteria in that category puts more emphasis on the inlet aerodynamics. TAB 4 shows the pairwise comparison of the respective criteria.

TAB 4. Pairwise comparison for criteria weighting

		P	D	A	M	S	R	Weight g_i
Total pressure ratio	**P**	o	+	+	+	o	+	28%
External drag	**D**	-	o	+	o	-	+	17%
Distortion and acoustics	**A**	-	-	o	-	-	o	6%
Mass and installation space	**M**	-	o	+	o	-	o	14%
Safety	**S**	o	+	+	+	o	+	28%
Reliability and cost	**R**	-	-	o	o	-	o	8%

The criteria weights that result from the pairwise comparison highlight the importance of the total pressure ratio and safety of the inlet system. All weights are also displayed in FIG 17.

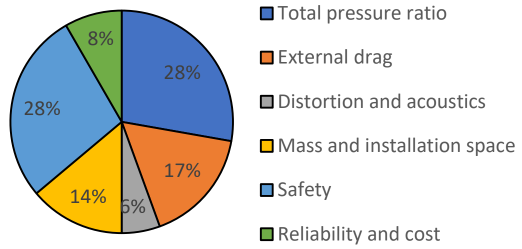

FIG 17. Criteria weights for the weighted point rating

4.4.2. Main Inlet Type

First, the primary inlets are evaluated, see TAB 5. For the total pressure ratio and the spillage drag, the values are based on the described analytical calculations. All other points are distributed based on information available in literature [5], [7], [10].

TAB 5. Point ratings for primary air inlets

		P	D	A	M	S	R	Rating
		28%	17%	6%	14%	28%	8%	$w_{j,Primary}$
Annular	**K**	-	+	- -	++	++	++	0.69
Scoop	**S**	++	- -	+	o	++	++	0.75
NACA	**N**	- -	++	-	-	o	o	0.40

The results from this evaluation show, that a scoop inlet is the preferred solution followed by an annular inlet, see FIG 18. NACA inlets are not preferred as primary engine inlets [7] due to their bad pressure recovery.

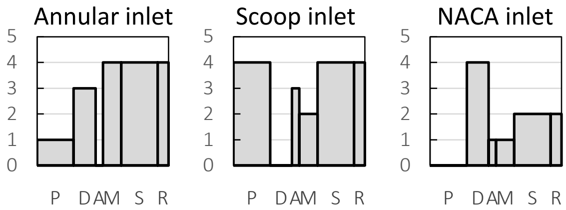

FIG 18. Utility value profiles for primary air inlets

4.4.3. Variable Geometry Inlet Type

Secondly, different options to adjust the inlet geometry and one fixed geometry inlet are considered, see TAB 6. The fixed reference represents an inlet without any variable geometry and is included to verify whether variable geometry inlets offer a benefit considering all criteria.

TAB 6. Point ratings for variable geometry inlets

		P	D	A	M	S	R	Rating
		28%	17%	6%	14%	28%	8%	$w_{j,Variable}$
Blow-in doors	**B**	o	++	-	o	o	-	0.55
Movable lip	**L**	++	++	++	+	-	o	0.72
Fixed reference	**X**	-	- -	++	++	++	++	0.63
Translating ring	**R**	-	++	o	- -	- -	- -	0.26

According to this evaluation, variable geometry inlets and movable lips in particular, offer performance benefits, but also introduce challenges, such as increased complexity, cost and weight, as well as lower reliability, see FIG 19.

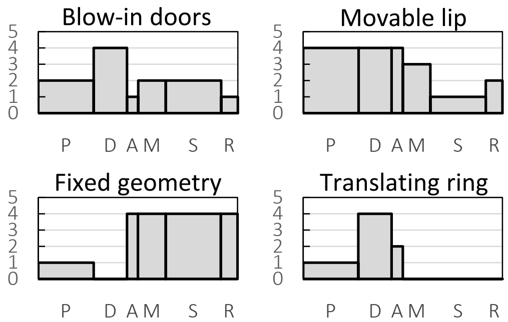

FIG 19. Utility value profiles for different options to adjust the inlet geometry and a fixed geometry

4.4.4. Engine Air Protection System Type

The last subsystem, that is evaluated, is the engine air protection system, see TAB 7. To achieve the goal of providing protection for the fuel cell, in two of the three concepts, that are evaluated here, the protection system consists of two parts. The first part is either an IPS or a mesh to avoid damage due to larger objects and particles. The second part is a filter to separate finer particles from the air that flows into the fuel cell.

TAB 7. Point ratings for engine air protection systems

		P	D	A	M	S	R	Rating
		28%	17%	6%	14%	28%	8%	$w_{j,EAPS}$
IPS only	**I**	o	+	o	o	o	++	0.58
IPS & filter	**IF**	-	+	+	-	++	o	0.59
Mesh & filter	**GF**	o	++	- -	-	-	-	0.43

The most promising solution for an engine air protection system is an IPS coupled with a filter for the fuel cell, see FIG 20. This combination allows for good protection against all types of foreign objects from sand up to larger debris on the runway or bird strike remains [28].

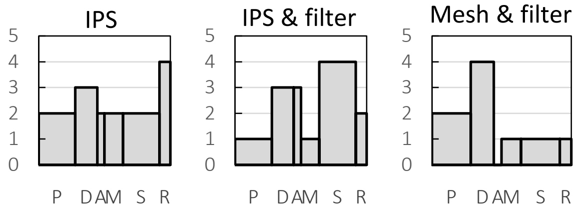

FIG 20. Utility value profiles for different engine air protection system options

4.4.5. Results from the Evaluation

Using the evaluation carried out for the subsystems, all concepts receive a rating. Additional points for synergetic or detrimental interactions between the included subsystems are added to this rating to achieve the final score. The interactions or differences to other systems that were identified during the evaluation are summarised in TAB 8.

TAB 8. Summary of additional points given to concepts

Concept 1	**Annular inlet**
+1 (Drag)	Reduced spillage drag for fixed geometry in combination with annular inlets
Concept 5	**Scoop with Blow-in doors and mesh**
+1 (installation space)	Reduced installation space due to integration of mesh with blow-in doors
Concept 6	**Scoop with split heat exchangers**
-1 (Drag)	Very large open blow-in doors during climb
-1 (Distortion)	Different airflow through different heat exchangers
-1 (mass & installation space)	Many channels have to be integrated in the Nacelle
+1 (safety)	Redundant heat exchangers
-1 (reliability)	More variable components that can fail
Concept 8	**NACA inlet with reverse airflow**
-1 (installation space)	Space requirements for the reverse airflow system

The final ratings are calculated from the previous ratings for the subsystems TAB 5, TAB 6, TAB 7 and the additional points in TAB 8 and are listed in TAB 9.

According to these results, a scoop inlet with a movable lip is the most promising concept. The inlet system will include a particle separator, which is also found on many turboprop aircraft and an IBF to protect the fuel cells. Other promising variants are a scoop inlet with a movable lip to adjust the inlet area and an annular inlet, which has the benefit of decreasing the aerodynamic drag of the inlet but achieves this at the cost of higher total pressure losses.

TAB 9. Final ratings for concepts

Concept		P 28 %	D 17 %	A 6 %	M 14 %	S 28 %	R 8 %	Total Rating Gw_j
1	Annular inlet	3	7	7	9	12	10	0.65
1a	Annular with Blow-in doors	4	10	4	7	10	7	0.61
1b	Annular with translating ring	3	10	5	5	8	6	0.52
4	Scoop inlet	6	3	10	7	12	10	0.66
4a	Scoop with movable lip	9	7	10	6	9	8	0.69
4b	Scoop with Blow-in doors	7	7	7	5	10	7	0.63
5	Scoop with Blow-in door and mesh	8	8	4	6	7	6	0.59
6	Scoop with split heat exchangers	7	6	6	4	11	6	0.62
8	NACA inlet with reverse airflow	2	7	8	5	10	8	0.53

4.5. Preliminary Design of the Concept

The outer dimensions of the nacelle are chosen to match those of the pre-design for the complete aircraft model. To maximise the space inside the nacelle, an almost rectangular cross section is chosen, see FIG 21. Behind the propeller cone, a small auxiliary inlet is added to ventilate and cool the nacelle.

Initial models of the components of the propulsion system are shown in FIG 22 to display their sizes and a possible propulsion system layout. The electric motor and a gearbox are placed in the front of the nacelle. Below these, the power electronics are placed. The fuel cell stack takes up most of the space in the upper half of the nacelle. Behind the inlet and the particle separator, air passes through the main heat exchanger and exits the nacelle through a fan.

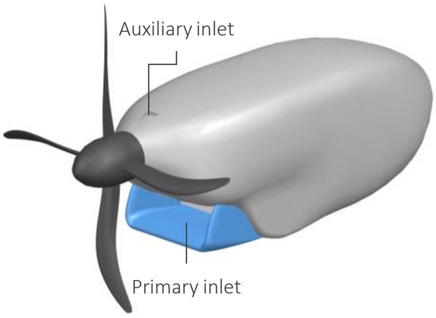

FIG 21. External view of the inlet system and nacelle

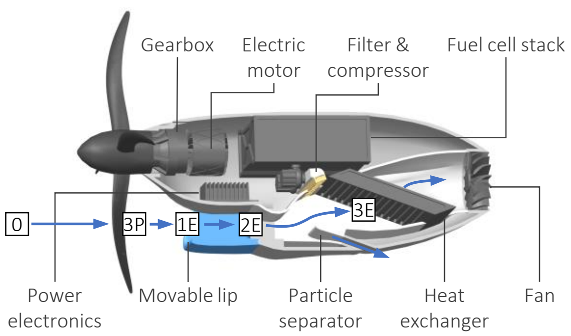

FIG 22. Sectional view of the inlet system and nacelle, with inlet levels

4.5.1. Estimated Total Pressure Ratio

The total pressure ratio of the complete inlet system can be calculated by multiplying the different total pressure ratios, that were obtained for separate sections of the inlet system. All corresponding levels are marked in FIG 22. These include:

- Losses while approaching the inlet $\Pi_{3P,1E}$ [10], [19],
- Losses while passing the smallest cross section $\Pi_{1E,2E}$ [20],
- Losses in the particle separator $\Pi_{2E,3E}$ [21], [22],
- and losses due to wall friction Π_W [10].

FIG 23 illustrates the predicted drop in total pressure over the separate sections. By multiplying the separate total pressure ratios for the sections, a total pressure ratio for the full inlet system $\Pi_{3P,2}$ can be calculated.

(4) $\Pi_{3P,2} = \Pi_{3P,1E} \cdot \Pi_{1E,2E} \cdot \Pi_{2E,3E} \cdot \Pi_W$

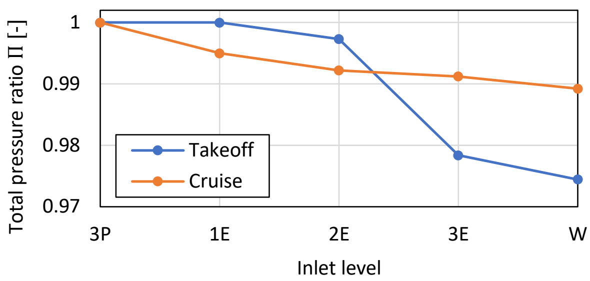

FIG 23. Predicted total pressure ratios at different levels of the inlet system

The resulting total pressure ratios of about 0.975 to 0.99 are good values for a scoop inlet with an integrated particle separator compared to existing applications [29]. However, these results should be verified by further analyses. Some phenomena that can appear in airflows, are very difficult to predict using analytical methods. For example, flow separation can occur and cause additional pressure losses.

4.5.2. Mass Estimate

To gain an understanding of the rough mass of the inlet system, surface areas from the CAD Model are used. The skin thickness is assumed to be 1 mm in most areas, only the inlet lip and the parts in the IPS that may be subjected to direct impacts from foreign objects, hail and birds are reinforced and have a skin thickness of 3 mm [27 p. 310]. Initial sizing calculations were also conducted for the structural components and actuators, resulting in the masses displayed in FIG 24.

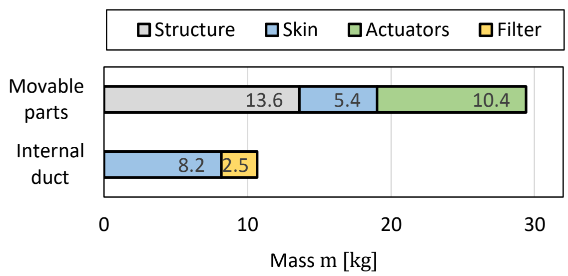

FIG 24. Mass predictions for the inlet system

Based on these predictions, the mass savings of a fixed geometry air inlet can be quantified to be at least 10 kg, which is the mass of the actuators. Most likely the structure of a fixed inlet will also be lighter, as no bearings are needed and vertical loads can be transmitted through multiple beams instead of just the actuator. Furthermore, no actuator control system has been included in the weight estimation.

4.6. Effects of Improved Fuel Cell Performance

If the operating temperature of the PEM-FC would be increased from about 80° C to 90 °C, the maximum air mass flow during take-off could be decreased by about 25% for the reference system. This would change the boundary conditions for the inlet system and could result in a different outcome of the evaluation process.

During the first design iteration, the spillage drag of a fixed geometry was evaluated based on data for a pitot or circular scoop inlet. If a wide scoop inlet or an annular inlet is used, the spillage drag will be significantly reduced, see FIG 9. The performance margins at take-off are extremely small for the studied fuel cell-powered topology. With the total pressure ratio being similar, mass savings should therefore be prioritised over lower drag in cruise flight. These considerations lead to different results of the points rating, which is shown in TAB 10.

TAB 10. Final ratings for concepts with new boundary conditions and updated drag data

Concept		P 28 %	D 17 %	A 6 %	M 14 %	S 28 %	R 8 %	Total Rating Gw_j
1	Annular inlet	4	9	7	9	12	10	0.70
1a	Annular with Blow-in doors	4	10	4	7	10	7	0.61
1b	Annular with translating ring	3	10	5	5	8	6	0.52
4	Scoop inlet	7	7	10	7	12	10	0.73
4a	Scoop with movable lip	9	9	10	6	9	8	0.71
4b	Scoop with Blow-in doors	7	9	7	5	10	7	0.66
5	Scoop with Blow-in door and mesh	8	10	4	6	7	6	0.62
6	Scoop with split heat exchangers	7	8	6	4	11	6	0.64
8	NACA inlet with reverse airflow	3	9	8	5	10	8	0.58

These results imply, that a fixed geometry scoop inlet, as used on most modern turboprop aircraft, could be the best choice for future fuel cell-powered regional aircraft. The updated inlet design eliminates all moving parts in the inlet, improving reliability and reducing complexity. Also, no actuators are needed, which reduces the mass of the inlet system.

5. CONCLUSIONS

First, different air inlet types, variable geometry inlets and engine air protection systems were summarised. To design a suitable inlet for a fuel cell-powered engine, requirements for this system were elaborated. Based on previously identified systems and a morphological box, multiple concepts for the inlet system were generated. In total, 16 variants were studied, 9 of which were evaluated to be potentially viable. The most promising concept was then further detailed, sized and analysed. During this process, a CAD model of the inlet integrated into the nacelle was created. The most important performance data were then estimated based on empirical data from literature.

To achieve a good inlet performance at all flight conditions, variable geometries can offer performance benefits at the cost of higher complexity and mass. However, fixed geometry inlets offer lower complexity and mass.

The developed CAD model provides a visual representation of the sizes and possible placement of the largest engine components. The distribution of components within the nacelle is subject to change, as the studied engine topology is still in an early design phase. Integrating some components into the wing may reduce the size of the nacelle and therefore reduce the aircraft drag. In this case, the inlet system has to be adapted.

Analytical assumptions used in this work simplify the complex effects of the airflow around the air inlet and inside the internal duct. To verify the results gained from these calculations, CFD simulations will follow. These analyses may include a parametric optimisation of the inlet and internal ducts. Furthermore, the effectiveness of the inertial particle separator at removing particles and foreign objects from the airstream should be investigated. Another subject for future investigation is the effect that the propeller has on the inlet system. If the pressure rise through the propeller can be captured, the total power required to draw air through the thermal management system could be reduced. However, the propeller also causes a swirling flow and distortions downstream the blades, which might negatively affect the air flow through the thermal management system. The design of the air inlet system strongly depends on the layout of the thermal management system. In future design iterations, changes may be made to the inlet system to accommodate distributed heat exchangers within the nacelle or the wing.

This study is part of a process, during which the components of fuel cell-powered propulsion systems are optimised and adapted to operate conjointly in flying conditions. This way, a contribution to fuel cell-powered aero engines in regional aircraft and thereby sustainable aviation could be achieved.

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