Rotor Cooling Concept for the ASuMED Superconductive Motor

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Abstract. The consortium of the Advanced Superconducting Motor Experimental Demonstrator (ASuMED) will develop, build and test the first fully superconductive motor for aerospace applications. The cryogenic topology of the motor is based on a dual-cryostat concept, which consists of two separate cryostats for the rotor and stator. The rotor cryostat design is particularly challenging because of the cryogenic operating temperatures, the cooling requirements and the rotating parts, which include a rotary seal. A number of alternatives based on different heat transfer mechanisms were considered. The feasibility of these options was assessed by preliminary analyses, which show that a forced convection based system is the optimal solution to achieve the required cooling power in the rotor. The forced convection cooling system is realised by the forced circulation of cooling gas (gaseous helium) in the system. This is the so-called externally controlled cooling system for the rotor. A detailed flow and heat transfer analysis shows that the system has the potential to achieve the required cooling power.

1. Introduction

The ASuMED fully superconductive (sc) motor will be able to achieve the power densities and efficiencies required for hybrid-electric distributed propulsion (HEDP) of future large civil aircraft. HEDP allows for the fuel burn and emission reductions targeted by Flightpath 2050, which include a reduction in CO_2 by 75%, NO_x and particulates by 90% and noise by 65% compared to 2000.

The motor will consist of sc stator coils and sc stacks on the rotor. A dual-cryostat concept in which two separate cryostats for rotor and stator are combined in one motor is chosen as the cryostat topology of the motor. This solution gives the possibility to use the most suitable technology for both rotor and stator and thus meet the most demanding requirements. The choice for a dual cryostat also makes it easier to select the most suitable coolant for each cooling system.

The stator cryostat is based on a capillary system which uses liquid hydrogen as the cooling fluid. The rotor cryostat uses gaseous helium and its design is presented in this paper. Apart from the cryogenic design, an important aspect of the rotor cryostat is the rotating seal between the cooling fluid and the vacuum. There is a preference for the use of ferrofluidic seals in the ASuMED motor because of their potential excellent performance even though their effectiveness still needs to be proven.

2. Rotor Cryostat Design Concepts

The rotor cryostat design is to a large extent determined by the cooling concept. The required cooling power (Q_{goal}) is defined by the heat generation in the sc stacks during operation and at this stage is estimated to be 150 W. The rotor cryostat design concepts are based on the reference model shown in Figure 1. The most relevant alternatives considered are presented in this section.

The rotor cooling system will be provided with helium at 25 K, which defines the operating temperature in the system. The operating temperature window of the sc rotor stacks is between 27 and 35 K. The analyses of the rotor cryostat design concepts are therefore based on temperature differences between the sc stacks and the cooling fluid (ΔT) from 2 to 10 K. The pressure in the system is 2 bar(a).

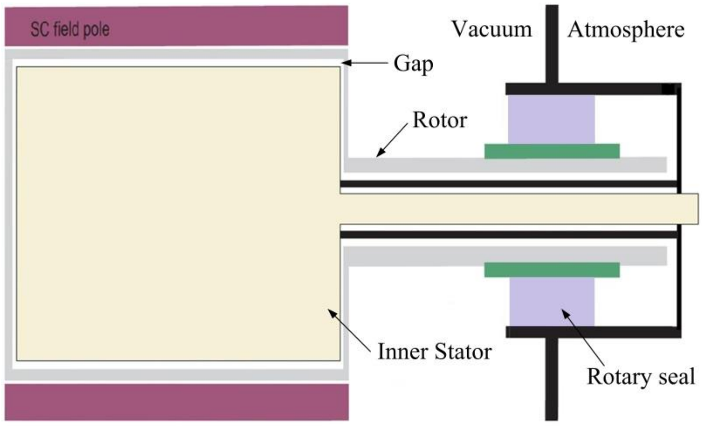

Figure 1. Rotor reference model. The main elements of the model are the rotor itself, the inner stator (stationary part inside the rotor) and the gap between them, which is 2 mm high.

2.1. Static Indirect Cooling System
The static indirect cooling system consists of an open circuit built in the inner stator. The gap is filled with contact gas, helium, which is the heat sink for the sc rotor stacks. The cooling fluid, also helium, is circulated through the cooling system and cools down the contact gas, which remains stationary along the gap. The heat transfer mechanism governing the system is conduction (Nusselt number = 1).

The results of the heat transfer through the gap (Q_{gap}), given in Table 1, show that the maximum cooling power achieved by this system is 15% of the requirement. The static indirect cooling system is therefore not a solution for the rotor cooling system.

Table 1. Heat transfer results, static indirect cooling system.

Scenario	ΔT (K)	Q_{gap} (W)	Q_{goal} ratio
1	2	4	3 %
2	5	11	7 %
3	10	22	15 %

2.2. Forced Circulation of Contact Gas
Forced circulation of the contact gas through the gap is a way of improving the heat transfer in the system and thus achieving the required cooling power. In order to demonstrate the feasibility of this solution, a preliminary heat transfer analysis is performed. This analysis consists, to a great extent, in the determination of the characteristic numbers that will define the system: the Reynolds (Re) and Nusselt (Nu) numbers.

The forced circulation cooling system relies on convective heat transfer to generate the required cooling power. In this respect, turbulence in the flow is an important parameter to increase the heat transfer rate. The Reynolds number that characterises the flow through the gap is set to 14000, which corresponds to the early turbulent regime region.

The determination of the Nusselt number is, due to the configuration of the system with a rotating outer cylinder (rotor) and a stationary inner cylinder (inner stator), more challenging. A study of the Nusselt number for different geometries is performed to define the system from a reasonable perspective in terms of heat transfer. The Nusselt number is calculated for three different geometries: turbulent flow over flat plate (Nu_{plate} = 70), turbulent flow through a pipe (Nu_{pipe} = 45) and annulus with walls at rest ($Nu_{annulus}$ = 35). It must be noted that $Nu_{annulus}$, determined using three different experimental correlations, corresponds to an annulus with both cylinders at rest and, at this stage, the influence on the heat transfer of having a rotating outer wall is unknown. For this reason, the Nusselt number in the system is set, using a conservative approach, to 20.

The results of the heat transfer through the gap in the forced circulation system, given in Table 2, show that the system has the potential to achieve the heat transfer rate needed to cool down the sc rotor stacks. In order to accomplish the circulation of the contact gas through the system, two options were considered: an internal fan based cooling system and an externally controlled cooling system.

Table 2. Heat transfer results, forced circulation of contact gas.

Scenario	ΔT (K)	Q_{gap} (W)	Q_{goal} ratio
1	2	41	28 %
2	5	107	71%
3	10	226	150 %

The fan based cooling system includes a fan attached to the rotor. The cooling fluid is circulated through a cooling system built in the inner stator and cools down the contact gas, which is in the gap. This is the same concept as for the indirect cooling system. The contact gas is circulated through a separate circuit, also built in the inner stator, by means of the fan. The gap is therefore filled with the contact gas, which is stationary when the rotor is at rest, and circulated during normal operation, when the motor rotates.

Regarding the externally controlled cooling system, the main difference with respect to the previous proposals lies in the fact that the cooling gas which the system is provided with is also the contact gas. In this way, helium at 25 K enters the inner stator through an inlet channel and is taken to the gap, where it receives the heat generated by the sc stacks. The warm helium leaves the gap through an outlet channel in the inner stator.

The externally controlled system is preferred over the internal fan based system and is therefore the chosen cooling system for the rotor in the ASuMED motor. The reasons for this are the possibility to adjust cooling parameters during operation and the fact that the performance is independent of the motor speed. In addition, the externally controlled cooling system uses the available helium supply and avoids the heat exchanger concept to cool down a second fluid, the contact gas.

3. Rotor Cryostat Design

The externally controlled rotor cooling system for the ASuMED motor is shown in Figure 2 together with its main components. The preliminary heat transfer analysis carried out to prove the feasibility of a forced convection based system is the basis for the design and sizing of the system.

3.1. Design sizing and flow characterisation

The Reynolds number in the system is Re = 14000 and is the base to determine the helium mass flow through the system, which is 20 g/s. The Nusselt number for the design analysis is Nu = 20. These are the starting points to perform a detailed heat transfer and flow analysis on the rotor cooling system.

The flow pattern in the system corresponds to a Taylor-Couette flow, which is the fluid flow that occurs between two coaxial and independently rotating cylinders. For a situation with stationary inner cylinder and rotating outer cylinder with increasingly rotational speed, the turbulence in the flow appears suddenly in the form of intermittent patches that coexist with the laminar flow. The turbulence in the flow increases as the rotation rate of the outer cylinder increases up to the point that the entire flow is filled with turbulence. This is the so-called subcritical transition to turbulence [1]. The influence of having a rotating outer cylinder is especially difficult to quantify in terms of heat transfer. A finite element analysis and analytical calculations supported by a literature study have been used to analyse the system.

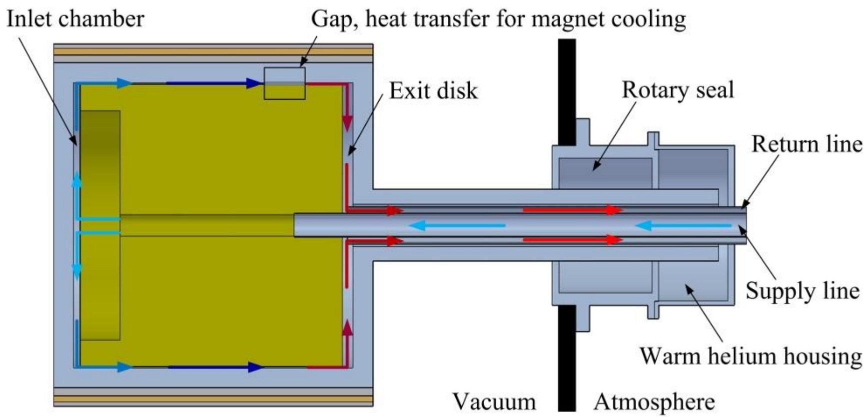

Figure 2. Overview of the externally controlled cooling system for the ASuMED rotor showing the design and main components.

3.2. Operating modes

The ASuMED motor, and therefore the rotor cooling system, may be operated in two modes: normal operation and magnetisation mode. The normal operation mode corresponds to the steady state of the motor during flight with a maximum rotational speed of 6000 rpm. The speed of the motor (Ω) is expected to be between 1000 and 4000 rpm during transient operation events. The magnetisation mode depends strongly on the magnetic topology of the rotor, which is not yet defined. At this stage of the design, it is known that, during the magnetisation mode, both the rotor and inner stator will be stationary while, at the same time, the system needs to be provided with full cooling power.

4. Rotor Cooling System Detailed Analysis

A detailed heat transfer and flow analysis has been performed on the externally controlled cooling system using the finite element method. The model is based on the k-epsilon turbulence model.

The analysed cases may be divided into two groups: variable rotor speed for fixed temperature difference (Group 1) and variable temperature difference in the system for fixed rotor speed (Group 2).

4.1. Flow analysis

The flow pattern in the gap depends on the speed of the rotor. When the rotor is stationary (magnetisation mode), the flow through the system is a pure pressure driven flow and the flow velocity consists of only an axial component. The absolute (axial) velocity of the flow in the gap is 4.5 m/s. The pressure drop in the system for the magnetisation mode is 10 mbar.

The flow pattern during the normal operation cases consists, apart from the pressure driven flow, of a drag induced flow developed by the rotation of the outer cylinder. In the same way, the absolute velocity is composed of an axial component (similar as for the magnetisation mode) and a phi component. The absolute flow velocity in the gap for normal operation (Ω = 6000 rpm) is 50 m/s.

Due to the rotation of the outer cylinder during normal operation, a swirl in the flow is developed at the location of the exit disk. This swirl leads to a back pressure development that creates a pump action acting against the flow direction. The absolute flow velocity at the exit disk during normal operation (Ω = 6000 rpm) is 120 m/s and the pressure increase in the system is 0.5 bar. Since this effect puts the performance of the system at risk, a diffuser composed of six vanes will be included in the inner stator at the location of the exit disk. This solution is, however, difficult to quantify and analyse in detail and it will be implemented in the design for experimental verification.

4.2. Heat transfer analysis

The results of the heat transfer analysis for all the analysed cases, given in Table 3, show that the speed of the rotor determines the heat transfer through the gap. When the rotor is stationary, the heat transfer in the gap is determined by the pressure flow. On the other hand, the heat transfer for the normal operation cases (Ω > 0 rpm) is governed by the drag flow developed by the rotation of the outer cylinder. For the analysis case 1.2 (Ω = 1200 rpm), the heat transfer through the gap decreases with respect to the magnetisation mode. As the speed of the rotor increases, the heat transfer increases likewise as a result of the increase of turbulence in the system generated by the rotation of the outer cylinder. Regarding the group 2 analysis cases, an increase of the temperature difference in the system, and therefore of the sc rotor stacks, results in an increase of the heat transfer in the system.

Table 3. Heat transfer results for the externally controlled cooling system.

Analysis Case	ΔT (K)	Ω (rpm)	Q_{gap} (W)	Q_{goal} ratio
1.1	2	0	44	30 %
1.2	2	1200	31	21 %
1.3	2	3000	43	29 %
1.4	2	6000	58	39 %
2.1	2	6000	58	39%
2.2	5	6000	103	69 %
2.3	2	6000	150	100 %

The heat transfer through the gap is critical and only an increase of the sc rotor stacks operating temperature guarantees the required cooling power in the system. For this reason, six finlets will be included along the entire length of the rotor inner wall. Numerical simulations and experiments on Taylor-Couette flows prove that the increase of the wall roughness by means of these finlets will increase the turbulence [2]. This effect cannot be quantified in terms of heat transfer but the increase of turbulence, and therefore the improvement of the heat transfer in the system, is not in doubt. The finlets will be implemented in the design of the rotor for experimental verification.

5. Summary and conclusions

The cryogenic topology of the ASuMED motor is based on the dual cryostat concept, which consists of two separate cryostats for rotor and stator. The preliminary study to determine the rotor cryostat topology concludes that the externally controlled cooling system, based on the forced circulation of the cooling gas through the system, is the most suitable solution for the rotor cooling system.

The finite element method is used to perform a heat transfer and flow analysis on the externally controlled rotor cooling system. This analysis is based on the results of preliminary calculations that are supported by a literature study. The main assumption is the flow regime, which is placed at the early stages of the turbulent flow (Re = 14000). The helium mass flow rate through the system is defined from this assumption (ϕ_{He} = 20 g/s).

The detailed rotor cooling system analysis shows that the externally controlled cooling system has the potential to achieve the required cooling power. The following considerations must be taken into account:

- The heat transfer in the system is critical. The finlets placed on the inner wall of the rotor will increase the heat transfer through the gap but their effect cannot be quantified.
- An increase of the operating temperature of the rotor stacks increases the heat transfer rate of the rotor cooling system.

Acknowledgments

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