EFFAN

PROJECT FINAL REPORT

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4.1 Final publishable summary report

Executive summary

On an electrical ECS pack, outside air is used to remove heat from the cooled system. The outside air flow is generated on ground thanks to a vacuum device. The present subject deals with electrical fan solution used as vacuum device for ram air flow generation. The challenge of optimizing such a component for this application is double.

First, from aerodynamic point of view, the fan shall be capable to generate pressure drop whatever the flow without surge issues. Indeed, the ram air fan is used to suck main air flow through ECS pack main heat exchanger for cabin cooling and in the meantime to suck small amount of flow through ECS pack electrical motor stator for cooling. Due to ECS control logics, the fan shall be also capable to ensure ECS motor stator cooling without any flow from main heat exchanger. In this case it shall provide the same pressure rise with a very limited flow.

Then, the fan is installed downstream of the ECS main heat exchanger. Therefore, high temperature air can enter the fan and specific concept shall be implemented for fan integration to enable fan mechanical and electrical subpart cooling.

Finally, technology and solution selected to comply with these last constraints shall minimize impact on performance efficiency and component reliability and availability so as to achieve global ECS objectives.

Considering these objectives, a new fan concept has been selected from available bibliographic and consortium expertise, and designed using the consortium skills in deep fundamental fluid mechanics and heat transfer knowledge (UniversitatPolitècnica de Catalunya- UPC), advanced CFD tools and aerodynamic know-how (Termo Fluids - TF) and engineering capacities of a fan manufacturer (LMB SAS).

After a careful selection of anti-surge technologies based on state of the art carried out within the first project period, some predesigns have been numerically tested and aerodynamically analyzed (WP2). A final modeling of the ram-air fan and the consequent prototype has been designed, constructed and successfully tested at both flow range conditions (WP3). The numerical results and the experimental data have assured that final proposed solution avoid surge problem under both flow conditions initially expected.

In a similar manner, a thermal analysis of the selected electric motor coupled with the fan designed has been thermally analyzed. The thermal design has been numerically modeled and experimentally tested under high temperature conditions in a climatic chamber. The fan thermal validation has allowed to numerically check the temperature level at the actual conditions indicated by the Topic Manager in the initial project requirements.

In conclusion, an adequate efficient fan design has been obtained to cover at the same time, both high and low flow rate working conditions and high inlet air temperatures. Thus, LMB has now this new efficient fan design, TF has improved its in-house CFD numerical tool capable to predict the surge effect under numerical simulation of fans, while UPC has developed a detailed thermal model capable to analyze thermal effects in electric motor driven fan configurations. Finally, Topic Managerhas acquired the know-how and the technological readiness to drive the ram-air flow with a wide flow spectrum fan, thus covering the initial objective of cooling the ECS main heat exchanger or alternatively the ECS electrical motor stator.

Summary description of project context and objectives

The conventional aircrafts engines, not only produce thrust to propel the aircraft, but also deliver electrical, pneumatic and hydraulic secondary power. The main secondary power and extra fuel consumer is the environmental control system (ECS), which is the responsible of providing a comfortable close environment for a given payload (people, goods and living matter) by keeping temperature, pressure and humidity within the required limits. ECS can reach the 75% of non-propulsive power on cruise.

With the aim of reducing the direct operating costs in the aircraft sector by means of decreasing maintenance costs and minimizing fuel consumption the adoption of all electric ECS has been considered as an alternative to the conventional bleed driven ECS. In an all- electric ECS the air that is used to cool the payload is air taken directly from outside, instead of bleeding it from the compressor (as in a conventional ECS system). Moreover, the ECS pack is electrically driven, what introduces the necessity of cooling such electrical motor. Boeing adopted the all-electric ECS in the B787 aircraft, being the first commercial aircraft using this technology.

When aircraft is on ground a vacuum device is needed for ram air flow generation. According to Topic Description the challenge of optimizing this fan for this application is double. First, from aerodynamic point of view, the fan shall be capable to generate pressure drop whatever the flow without surge issues. Indeed, the ram air fan is used to suck main air flow through ECS pack main heat exchanger for cabin cooling and in the meantime to suck small amount of flow through ECS pack electrical motor stator for cooling. Due to ECS control logics, the fan shall be also capable to ensure ECS motor stator cooling without any flow from main heat exchanger. In this case it shall provide the same pressure rise with a very limited flow.

In the present project a smart combination of numerical and experimental tools has been used for the design of a ram-air fan solution in order avoid or suppress stall and surge problems at low flow conditions. A similar approach has been employed to obtain an adequate solution for the ram-air fan electrical motor cooling at high inlet air temperatures.

After having an overview to the project main objectives within the framework of the more electric aircraft, the specific objectives for the whole period of the project have been:

WP1 Project management.

Control the tasks related to the technical coordination of the project, as well as the administrative and financial management within the consortium. Fulfillment of the reporting obligations towards EC and ITD members. Cover activities regarding the dissemination, exploitation and IPR management.

WP2 Selection of a technology for the solution of fan surge at low flow conditions.

On P1, Task 2.1 has provided a complete bibliographic study with proposal of the most promising technologies to solve the surge design problem, indicated on Deliverable 2.6. On P2, Task 2.2 a pre-design based on aerodynamic concepts and numerical simulation cases have been carried out and aredetailed on Deliverable D2.7.

WP3 Fan surge technical solution.

This WP has been fully developed within P2. This WP has been mainly oriented to the validation of the proposed aerodynamic solution by means of numerical simulations and laboratory test on a prototype. Task 3.1 is conceived for numerical simulation at different levels in order to refine the ram-air fan predesign and to confirm the new design ability to suppress the fan surge problem, (reported in Deliverable D3.8), while Task 3.2 has been focused on prototype manufacturing, described in Deliverable D3.9.Finally Task 3.3 has devoted on experimental test and validation comparisons, as it is explained in D3.10.

WP4 Fan thermal management.

Based on analysis and development of a solution enabling thermal management of the fan in hot air condition, Task 4.1 is devoted to the thermal analysis of the problem by a bibliographic search and identification of innovative ideas, finishing with the selection of the best concept. Deliverable 4.11 presents the bibliographic search, while D4.12 presents the selected solution/technology and the available software tools. This task started on P1 and has finished on P2.

During P2, Task 4.2 has been devoted to the detailed analysis of the actual fan thermal management concept to have a detailed and deep analysis. In a first phase, the preliminary design was based on a mixed flow fan (described in D4.13), but finally due to space and efficiency reasons, the design has been changed to an axial one (described in D4.14). During Task 4.3 the final solution has been tested not only to assure the thermal solution, but also to provide a full heat transfer physics understanding (details in D4.15).

S&T results and foregrounds description

EFFAN project was initially expected to be developed during a period of 18 months, staring on February 2014. After the first 3 months of the projects, and due to the unfortunate situation of Baltogar company partner bankruptcy, there was a stop on project work since May 2014 until May 2015 (12 months) looking for Baltogar partner replace, who finally was found with LMB company. After EFFAN amendment approval, the project was expected to restart on May 2015. However, REA validation of LMB company and some bureaucratic aspects obliges to finally restart the project on September 2015 (4 months later than was initially expected). A final amendment was needed to enlarge the second period of the project that finally started on September 2015 to end on September 2016 (both months included).

Thus, the final real period of EFFAN working project has been a first period (P1) from February 2014 to April 2014 (3 months) and a second period (P2) from September 2015 to September 2016 (12 months) a total period of 15 months within a period of 32 months.

A first period was reported in a Periodic Report P1 of 3 months February 2014 to April 2014, with UPC, TF and Baltogar as project partners. While a second period has been reported in a Periodic Report P2 of 12 months September 2015 to September 2016 (with a gap period of 16 months from May 2014 to May 2015 without partner replace, another gap period of 4 months from May 2015 to September 2016 due to bureaucratic problems and one amendment of two months extension from July 2016 to September 2016).

The Periodic Report P1 was mainly covering: mainly TASK 2.1 of State of the art on anti-surge technologies and a first part of TASK 4.1 of Fan thermal analysis. Within this P1, a deliverable D2.6 of anti-surge technologies and a D4.11 of bibliographic search of motor cooling technologies and high air temperature fan solutions were carried out.

The Period Report P2 has covered: TASK 2.2 on Predesign of several aerodynamic concepts, detailed within deliverable D2.7 of low flow range fan technologies description and selection; TASK 3.1 for the modeling of the ram fan air at low flow conditions within deliverable D3.8 of prototype fan design report, TASK 3.2 of the fan prototype (D3.9) and TASK 3.3 of fan test results and validation report (D3.10). TASK 4.1 and TASK 4.2 of fan thermal analysis and design were carried out and reported within D4.12 of fan thermal management solution, D4.13 preliminary design, D4.14 fan thermal solution, while TASK 4.3 finished with a numerical and experimental comparison of test results of TASK 3.3 together with numerical comparisons within D4.15 of thermal test performance validation.

The milestones of the project have been accomplished according the objectives initially planned:

MS4 a fan surge solution has been numerically obtained.

MS5 a fan prototype to avoid the surge problem has been designed; MS6 a fan prototype according the previous design has been constructed; MS7 the fan prototype has been tested for both high and low mass flow rates assuring the surge problem is avoided, thanks to anti-stall solution proposed, designed and proved.

MS8 a fan cooling solution is implemented based on LMB models; MS9 the actual design has been tested within the same prototype; MS10 a numerical simulation tool has predict how the actual design works, MS11 the fan prototype has been tested and validated according the simulation predictions.

WP2 Fan surge analysis

TASK 2.1 State of the art of anti-surge technologies

Deliverable 2.6 describes the state-of-the-art of the anti-surge technologies for axial fans. The content of the deliverable starts with an introduction with a description of the physics involved in rotating stall and surge phenomena. A summary of these contents is presentedin the following lines. Some comments coming from the brainstorming between the partners are given, outlining design strategies to achieve the anti-surge goal within reasonable cost and complexity.

Rotating stall and surge are flow instabilities that occur in turbomachinery, in particular in axial fans. Due to these instabilities the system efficiency falls dramatically and even mechanical failures may occur due to material fatigue. The main differences between the two phenomena are that rotating stall is steady in time and is not axisymmetric with respect to the stream wise direction while surge, is a periodic and axisymmetric event. Avoiding surge is of critical importance because its periodic behavior. Flow and pressure fluctuations do occur during surge event causing unsteady loads on the fan blades. These loads can reach dangerous amplitudes and may cause a fan blade failure. Since rotating stall is regarded as an inception of surge in axial fans, the understanding of the physics involved in this event is of key importance and will help us to develop efficient techniques in the surge avoidance field. The stall triggering mechanism is detailed below.

If the mass flow rate that passes across a fan stage decreases while the rotation speed remains constant, the angle of attack (i.e. the angle between the incident flow on the blade and the blade's chord) increases, and it may exceed the limit from which the flow separates from the blade surface. In Figure 1, a vector diagram of the flow velocities is depicted. As the mass flow rate drops at constant rotation speed due to the system strangulation, the inlet velocity moves from U1in to U2in being U2in smaller than U1in. This causes the rise of the angle of attack (AoA) enabling the stall event.

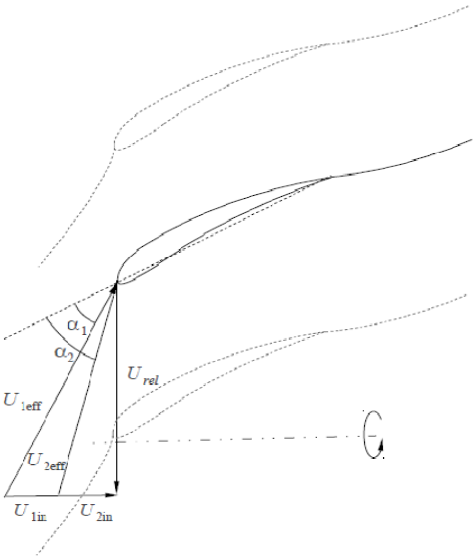


Figure 1: Velocity diagram at the blade cascade inlet. If U2in <U1in !_1 < _2 being _ the angle of attack of the flow with respect to the airfoil chord.

However, the blades of a given row do not stall at the same time but only part of the rotor circumference is stalled, and it moves about the blade row at a fraction of angular velocity (stall propagation, Figure 2). The angle of attack in the airfoil just above is increased while just the opposite occurs in the airfoil below. This causes the stalling of the airfoil above when the angle of attack reaches the critical value and the recovering of the airfoil below when the AoA is reduced enough.

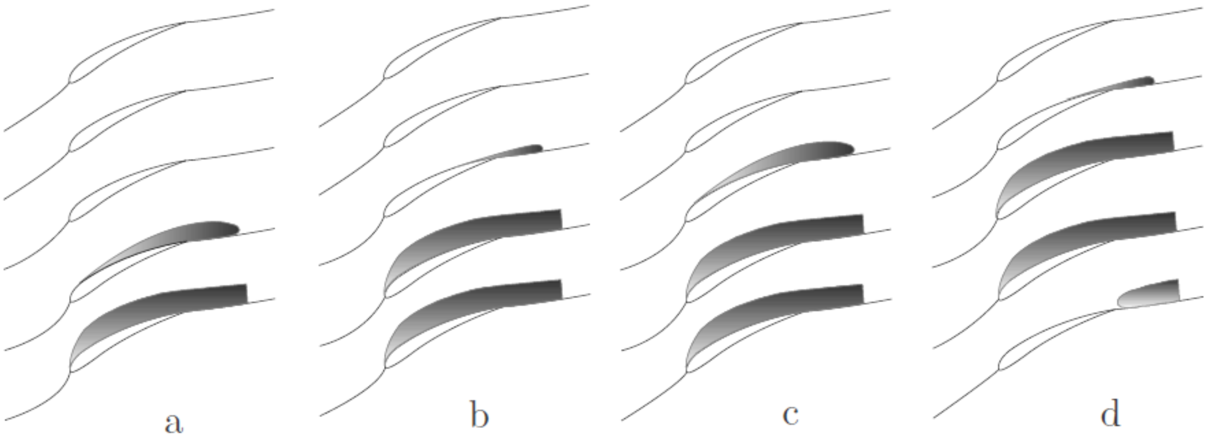


Figure 2: Stall propagation process.

As a consequence of the rotor stall a more severe phenomenon called surge may occur as an evolution of the rotating stall. From the physical point of view, surge is a self-excited cyclic phenomenon and it is characterized by large amplitude fluctuations of both, pressure rise and annulus averaged mass flow. Fan surge is triggered in the region of the characteristic fan curve with positive slope that exceeds a certain value that depends on the fan itself and the system load line. That means that the onset of surge is not only function of the fan design but also the characteristics of the system that it discharges into which is coherent with the blade stall process described previously.

It has been found that for high loaded operating points, the tip leakage flow is responsible for the occurrence of surge inception. The tip leakage rolls-up into the tip vortex as shown in figure 2c and blocks the main flow passage near the tip gap region reducing the flow speed at this location and the overall mass flow rate [1]. Controlling the tip leakage vortex evolution will induce the dissipation of the tip vortex and part of the flow features that causes the characteristic pressure pulse of surge.

Anti-surge technologies can act on two main aspects. The first one is the modification of the fan operating point to avoid unstable regions but keeping the shape of the original fan curve. On the other hand, the modification of the fan characteristic curve in order to eliminate unstable regions is another important approach to be taken into account. These modifications can be carried out by means two main groups of methodologies, passive or active anti-surge measures. Both families of methods have been used for industrial applications of fans and compressors. However, passive stall control techniques are the norm in fan applications.

Passive control techniques are based basically on a modification of the fan geometry in order to transform the flow field,specially in the tip-to-casing region. These geometrical features and modifications prevent the surge inception or it reduces its consequences. Because its low-cost and simplicity if compared with other methods, these techniques are the most commonly used in the fan industry. On the other hand, active techniques feature control systems that monitor the flow field and its physics to detect the stall event or its onset. Depending on the data provided by the control system, actions on the flow are carried out in order to modify the operating point of the fan and avoid the instability region.

Passive techniques

After the analysis of the surge/stall phenomena, the work has been focused on anti-surge passive methodologies. A general overview in what the passive technologies consist has been given in the deliverable. Different solutions are presented and its physical behaviour is described. Four of the presented passive techniques may help to achieve the desired steadily rising performance curve target: airfoil geometry optimization, low blade angles of attack, anti-stall rings and casing grooves. These four different techniques are compatible form the geometric and operational point of view and can be combined.

Active techniques

Active stall methods are based in complex systems of detection and monitoring of the stalled flow characteristics such as pressure or mass flow fluctuations combined with different mechanisms and actuators that modify the fan geometry and/or the flow conditions. All these measures are intended to avoid the stall onset or to recover an already stalled fan. Some of these methodologies are quite complex and expensive and are mainly reserved for the compressors industry. However, a review of the current active techniques has also been studied in the first period of the project and integrated in deliverable 2.6 as well.

TASK 2.2 Pre-design of several aerodynamic concepts

The objective of this Task has been to obtain a pre-design of the fan which meets the different technical requirements of the project such as flow stability at different flow regimes, size restrictions, mechanical simplicity as well as energetic efficiency.

Several design configurations have been initially proposed by using combinations of different anti-stall methodologies. The proposals have been individually evaluated by taking into account their performance on the different design requirements, especially regarding flow stability. After this process, an optimal proposal is done in order to be studied in deeper detail by means numerical simulation.

An appropriate numerical model which could deal with the complex geometry and behavior of the mechanism has been selected. The model should deal with a domain, part of which is rotating while other zones are static. At the same time, the fan rotates at very high speed which causes that in the blade tips, the flow speed is close to the compressibility limit (i.e. Ma=0.3).

An existing LMB fan design with experimental data has been used in order to carry out the calibration of the model by matching the numerical and experimental results at different flow regimes.

Finally the numerical model has been applied to the proposed pre-design and different improvements have been implemented to the initial concept in order to meet the technical specifications.

Pre-design configuration

Different fan technologies and the evaluation of every configuration have been carried out: mixflow fan; centrifugal fan, and axial fan. The final selection comes from LMB, based on their background and experience. The best option has been selected considering dimensions, weight and efficiency needed to accomplish the initial. In this case, the axial fan with anti-stall device is the best solution considered and the ones proposed for prototype design.

Numerical model

In the proposed solution a high speed rotor is combined with stator vanes in order to correct the flow swirl and raise the output pressure. Therefore, a methodology able to deal with moving solid boundaries must be used together with an interpolation method between domains which have a relative movement between them.

In order to overcome the first problem of rotating boundaries, the Arbitrary LagrangianEulerian method (ALE) is used to simulate the rotating parts. This methodology allows the simulation with moving meshes by correcting the mass fluxes at the mesh cell faces, taking into account the displacement of the mesh and considering that this movement should only interact with the fluid at the solid boundaries.

However, not all the domain is rotating and therefore a new problem arises when having to deal with relative movement between different parts of the same domain.

The technique used to deal with this issue is called sliding meshes. The methodology is based on having different meshes for the static and rotating domains. A pre-process method is applied in order to join the different parts, obtaining a single mesh of the whole domain but with internal boundaries that allow the sliding of the rotating parts with respect to the static ones.

On the other hand, the communication between these parts must be ensured. To do that, the code internally interpolates form the rotating parts of the mesh to the static ones through parallel communications. However, since the relative position of the boundary static cells with respect of the rotating ones change at each iteration, the new connectivity of the cell nodes has to be evaluated periodically in order to guarantee a proper information flow through the inner boundaries. In the Termo Fluids case, this is performed by means an efficient particle tracking methodology.

The mathematical and numerical formulation of the physics involved in the simulation has been chosen according a calibration process that is reported in the following section.

In order to model the flow, Large Eddy Simulations (LES) with a compressible formulation are used. A time-accurate formulation was needed since the phenomenon that was intended to study is a highly unsteady behavior of the flow. The only available formulations which have enough temporal accuracy to capture a phenomenon of this nature were Direct Numerical Simulations (DNS) or LES. Unsteady Reynolds Averaged Navier-Stokes approach (URANS), methodology has also a relative temporal resolution but very far from the frequencies of the present problem. Since DNS is completely unaffordable in cases of industrial applications at high Reynolds Numbers and large domains (as it is this case) the only realistic option was LES.

In LES the contribution of the large, energy-carrying structures to momentum and energy transfer is computed exactly and only the effect of the smallest scales of turbulence is modeled which implies a reduction in the number of grid points needed to represent the flow.

Regarding numerical schemes, Termo Fluids is an unstructured parallel finite volume solver. After discretization of the computational domain in a finite number of control volumes (meshing), NS equations are solved for each volumen. A hybrid advection numerical scheme is used for the discretization of the convective flux. The scheme is based on a kinetic-energy preserving numerical scheme, that ensures kinetic-energy preserving at all scales, this is important for DNS and LES since numerical diffusion can dissipate the smallest scales altering the result. Convective terms are discretized in split form in order to ensure temporal stability. To avoid instabilities in the presence of shock-waves, a low-order upwind scheme, is used when a discontinuity in the flow is detected. The shock detection is carried out with a Larsson discontinuity sensor. Viscous terms are discretized with a central-difference approximation and a second-order Adam-Bashford scheme is used for the temporal integration.

Regarding turbulence model, the selected method has been the Variation Multi-scale closed with a Wall-Adapting Local Eddy-Viscosity (VMS-WALE). In the Variational Multi-scale approach three classes of scales are considered: large, small and unresolved scales. If a second filter with filter lengthis introduced (usually called test filter),a splitting of the scales can be performed. Neglecting the effect of unresolved scales, we only need to model the small scales. Here, we close these terms using the WALE model. The WALE model by Nicaud and Ducros is based on the square of the velocity gradient tensor. In its formulation the SGS viscosity accounts for the effects of both, the strain and the rotation rate of the smallest resolved turbulent fluctuations. In addition, the proportionality of the eddy viscosity near walls is recovered without any dynamic procedure.

Numerical model calibration

In order to evaluate the performance and accuracy of the numerical formulation, a reference case with experimental data provided by LMB was used. This case is referred as reference 1 fan. The model included also rotating and static parts and therefore the ALE and sliding meshes methodologies would be also tested along with the flow modeling.

Figure 3(a) shows the geometry of the reference case, 3(b) both the fan with rotor and static vanes; 3(c) the corresponding mesh.

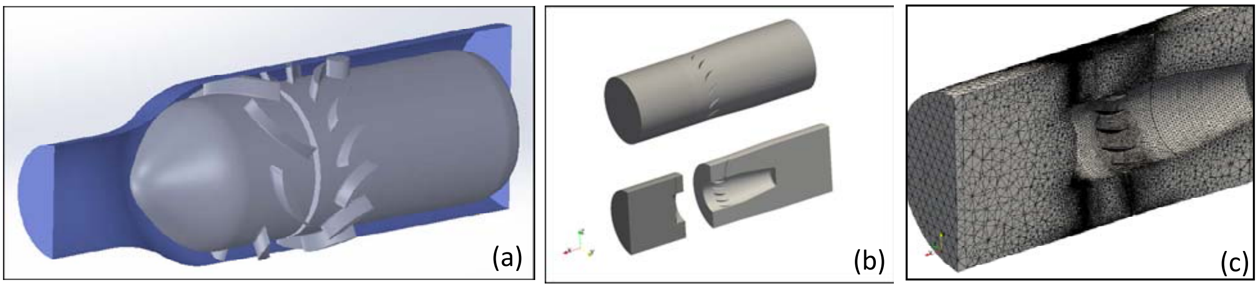


Figure 3.reference case geometry (left); fan with rotor and static vanes(center); mesh detail (right).

Table 1 shows the comparative results between the LMB axial fan reference case without anti-stall solution to assure that the numerical model is able to reproduce numerically the phenomena involved in high speed rotating fans..

Table 1. Comparisonbetween experimental and numerical results obtained with the selected case.

NON-DIMENSIONAL MASS FLOW RATE	EXPERIMENTAL PRESSURE DROP	NUMERICAL PRESSURE DROP	ABSOLUTE ERROR	RELATIVE ERROR [%]
0,90	1,036	1,015	0,021	2.0
1,00	1,000	0,944	0,056	5,6
1,23	0,657	0,659	0,002	0.2
1,43	0,131	0,127	0,004	3.4
1,44	0,074	0,077	0,003	3.9

As it can be seen in Table 1, the numerical results are very close to the experimental data even for low mass flow regime. At the same time, the flow was analyzed by means streamlines and pressure distribution observations and showed a coherent behavior throughout the domain as shown in Figure 4.

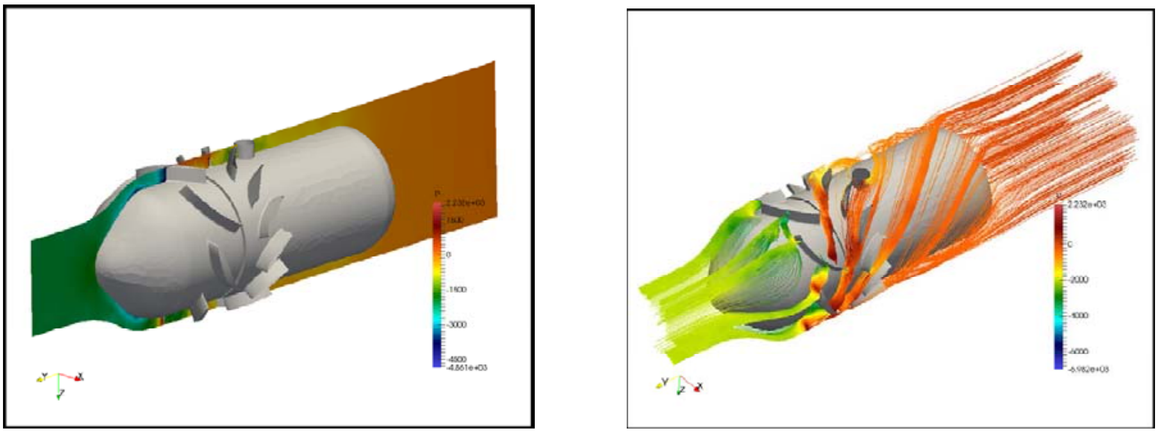


Figure 4.Pressure distribution (left) and stream-lines fan flow colored by pressure of Figure 3 case.

A final numerical methodology based on a compressible flow formulation discretized by means conservative numerical schemes which ensure numerical stability while avoiding numerical dissipation is used with successful results. As a LES model, the Variation Multi-scale closed with a Wall-Adapting Local Eddy-Viscosity model (VMS-WALE) has been used in order to obtain the sub-grid dissipation. Since the geometry to be simulated includes rotating parts, the Arbitrary LagrangianEulerian (ALE) methodology has been used to deal with this issue. This strategy subtracts the non-physical mass flows that are generated in the cell faces because of the mesh displacement when evaluating the convective flux. Another issue that has been solved is the coexistence of rotating and static parts in the same domain. A sliding meshes methodology has been used in order to communicate flow variables through the common surfaces of the different mesh parts. With this numerical tool both numerical cases without anti-stall solution and with the anti-stall solution has been numerically tested.

Numerical test without anti-stall solution

Once the numerical model has been validated against a reference LMB fan case, the numerical test of the final fan geometry has also performed (Figure 5).

Figure 5 shows the recirculation flow on the blade surface of the fan without anti-stall device in unstable flow conditions, while the normal behavior of the reference in nominal conditions is shown on Figure 6.

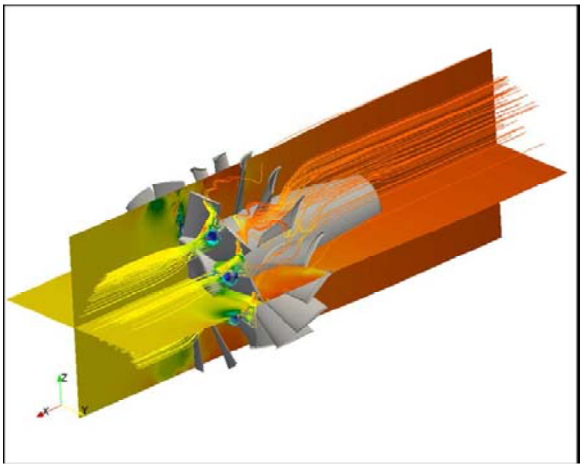


Figure 5–Recirculation unstable flow effect at whole fan level.

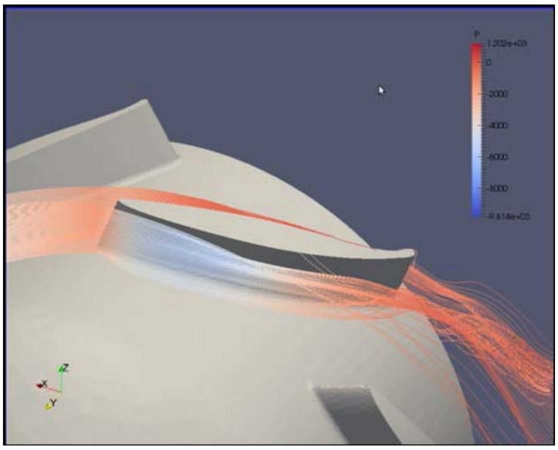


Figure 6 Recirculation normal flow behavior.

Numerical test case with anti-stall solution

The numerical experiments with the final fan design including the anti-stall ring have also been carried out. The results show that the solution proposed is ready to be prototyped and final validation is needed in WP3. The velocity field and the streamlines of the absolute velocity field of the numerical test cases assure that surge effect is avoided.

WP3 Fan surge technical solution

TASK 3.1 modelling and numerical simulation of the designed ram-air fan at low flow conditions.

Based on the numerical results of WP2, TASK 3.1 has been oriented to extend the numerical test cases from nominal conditions to lower mass flow ratesin order to evaluate whether surge phenomenon is avoided or not.

Figure 7 shows the pressure evolution with respect to the mass flow for the selected axial fan without anti-stall ring. The pressure clearly does not increase when airflow decreases below a certain mass flow rate of0.8. Instead, a drop of pressure do appear which is characteristic of the unstable working regions of the axial fans The new configuration has to assure a constant rising performance curve even al very low mass flow rates.

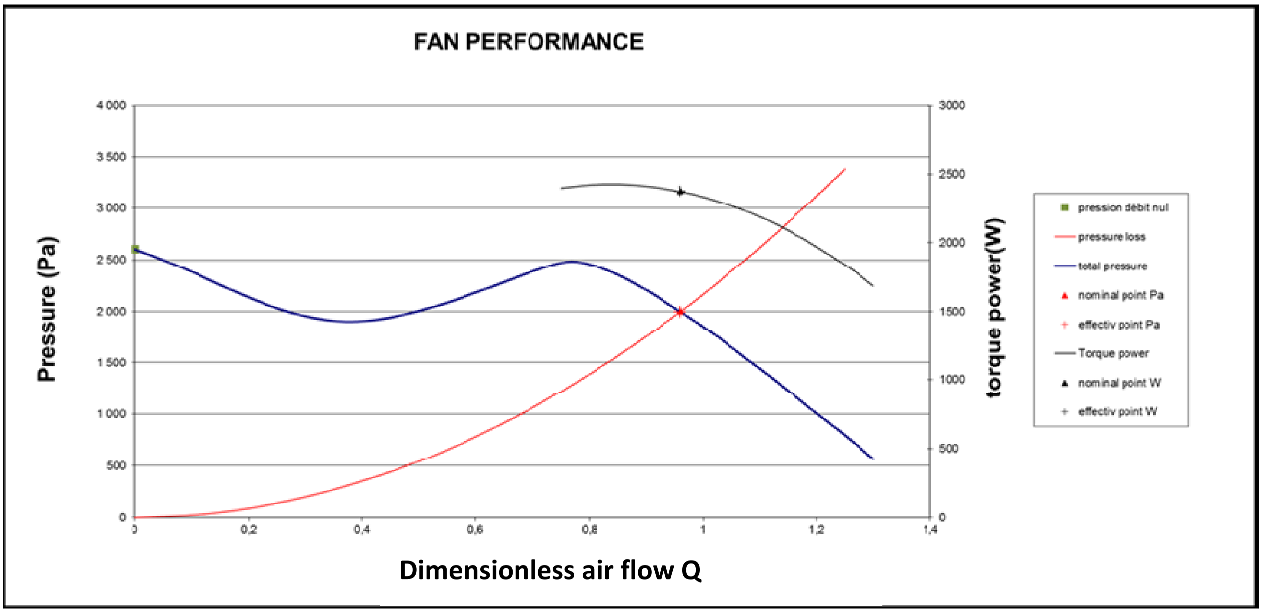


Figure 7.Numerical performance curve of the final proposal of axial fan without anti-stall devices.

With this information, the analysis strategy has been as follows: The full geometry including the anti-stall solution with skewed static vanes has been meshed and a first computation at the minimum stable airflow has been carried out in order to verify that the flow stability was kept.

Afterwards, the airflow amount has been reduced gradually with discrete steps of 0.1 m^3/swhile the pressure rise and axial velocities were monitored in order to verify the flow stability during the process.

Figure 8 shows the pressure evolution of the axial fan selected with and without anti-stall solution, where pressure clearly does not increase when airflow decreases after a certain point close to 0.8. The new configuration has to assure blue line continues increasing below this value.

In conclusion, numerical experiments have been performed with the final fan design. The improvement in the flow stability margin with respect to the same design but without any anti-stall device has been analyzed. It has been found that with the current design which includes an anti-stall with skewed static vanes, the anti-stall margin is improved by 50%.

In order to verify the project specification, experimental bench is being built in order to confirm the numerical data and also to test further design improvements which will allow meeting the specified requirements.

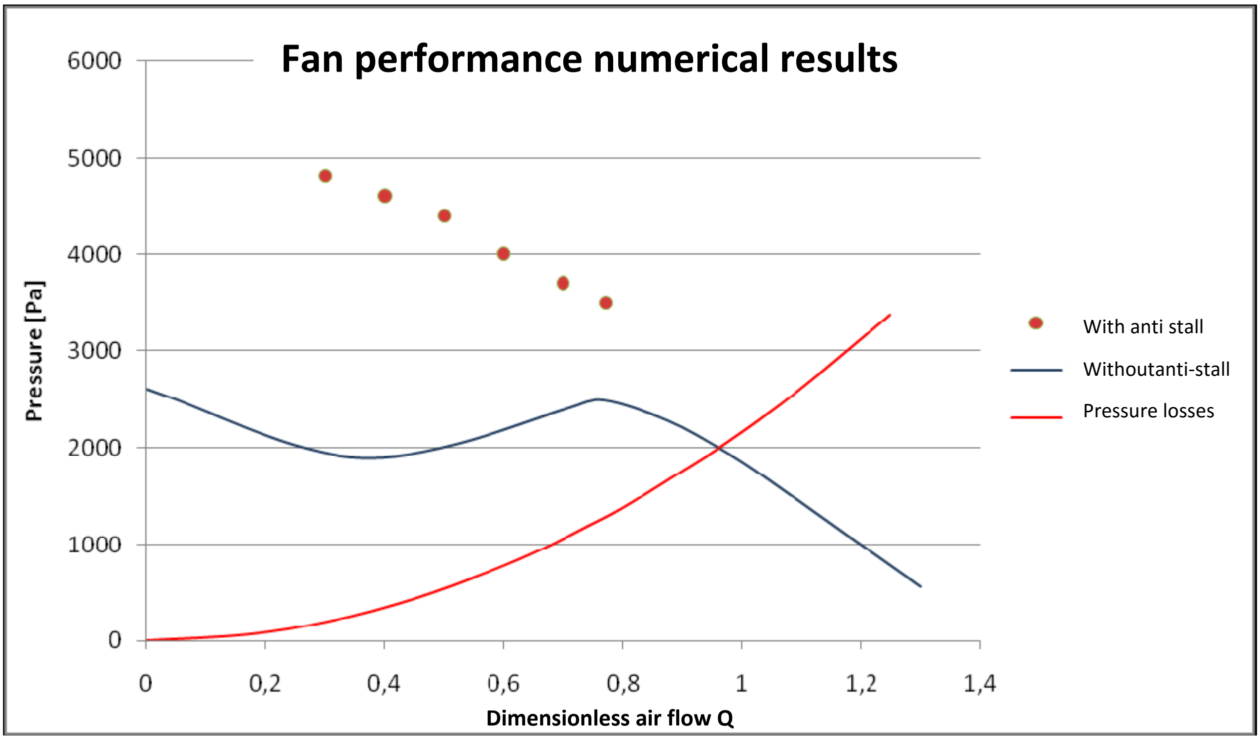


Figure 8.Numerical performance curve of the final proposal of axial fan with and without anti-stall devices.

TASK 3.2 Prototype manufacturing.

A prototype of an axial fan with a passive anti-stall device has been constructed based on the previous design selected (also previously numerically tested), according the methodology and the standards that follows. An experimental unit has been specifically adapted for this purpose.

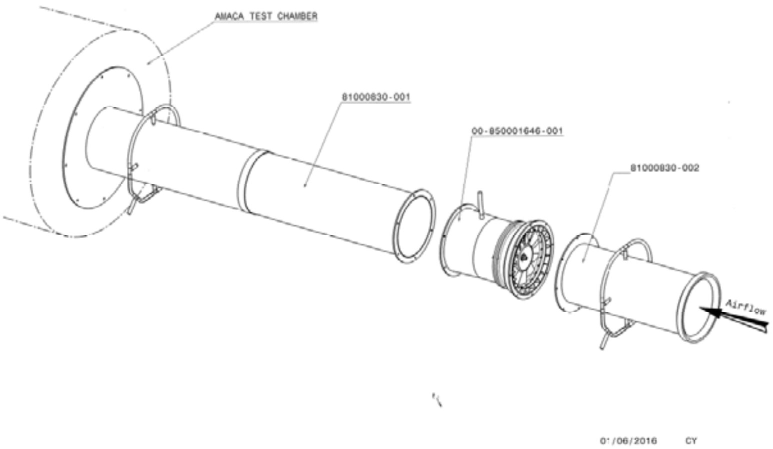


Figure 9.Fan position between duct.

Experimental test bench description

The aerodynamic test is according to the standard 5801 (total pressure measurement). In this case the fan is between an inlet and outlet duct. At each duct a sensor record the static pressure (P_{inlet} / P_{outlet}). The total pressure is the differences (P_{outlet} -P_{inlet}). Figure 9 shows the fan position between ducts.The airflow measurement is carried out in the AMCA chamber (pressure between specific nozzles). The variation of airflow is regulatedby means a variable exhaust system.

Figure 10 shows the test bench with the pressure sensors for the aerodynamic test purpose, while Figure 11 shows the same test bench indicating the airflow measurements.

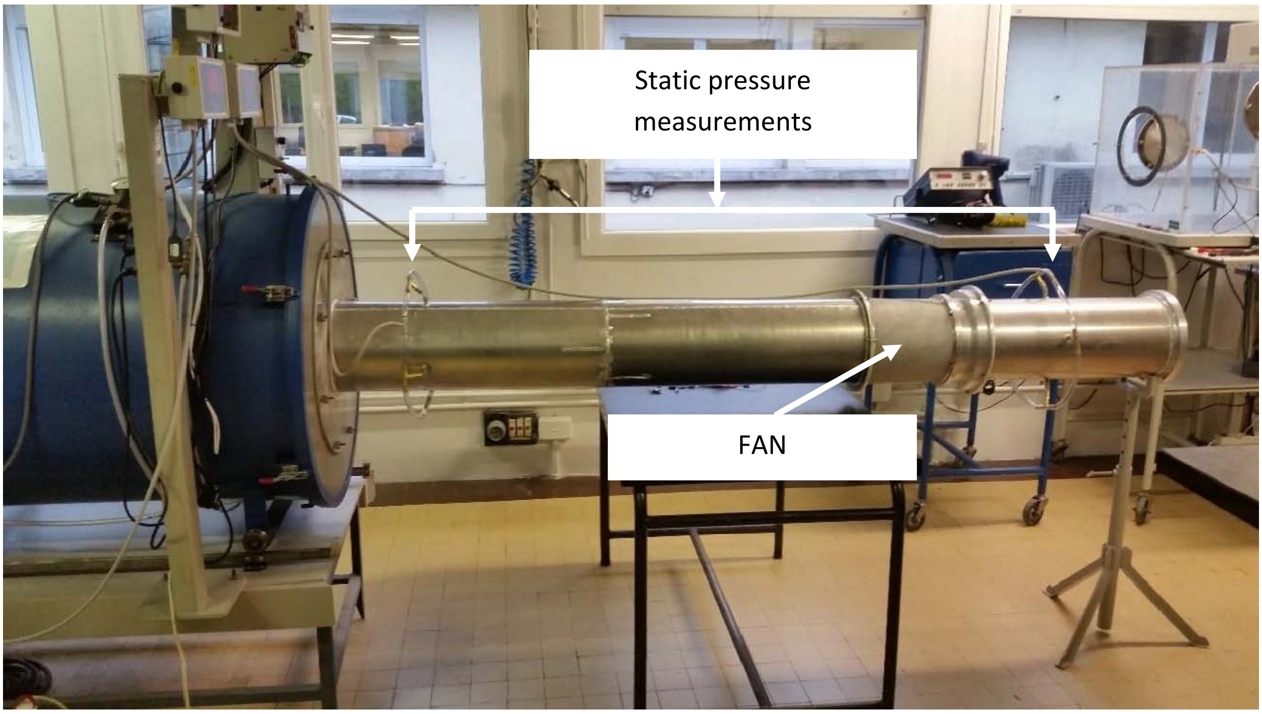


Figure 10.Fan position between duct.

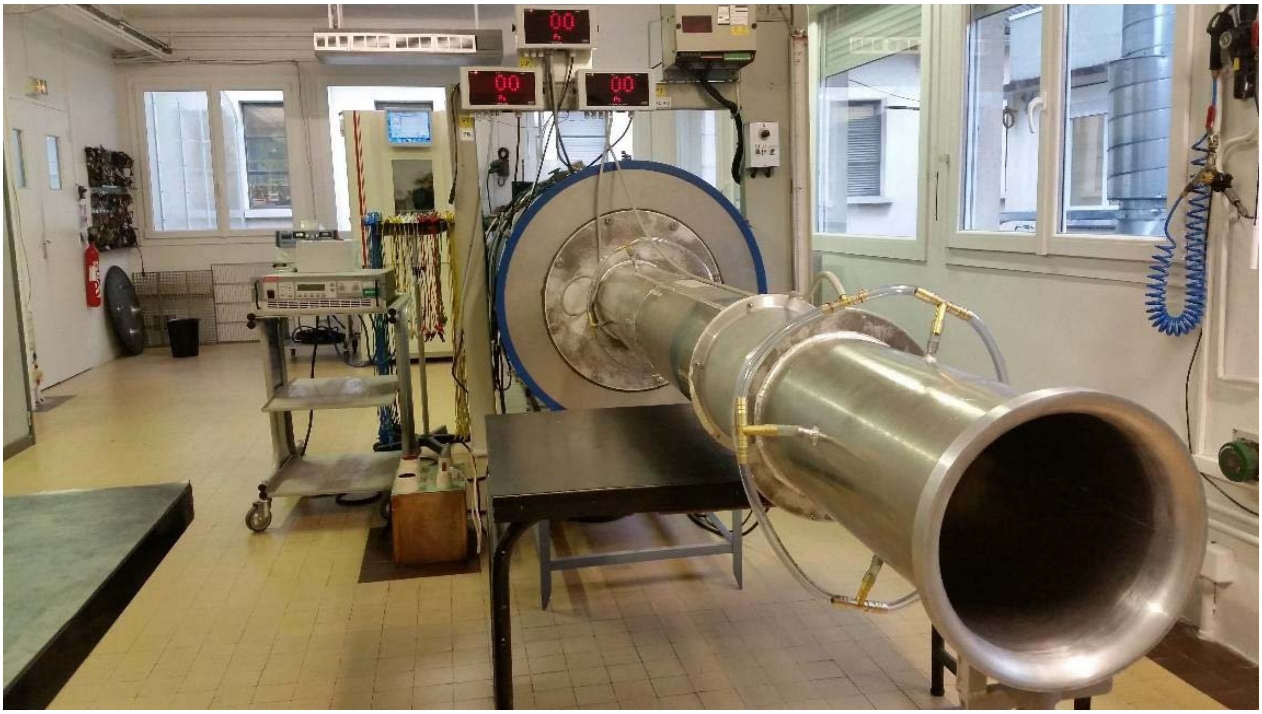


Figure 11.Fan position between duct.

TASK 3.3 Validation.

The results presented in this TASK 3.3 are a comparison between the experimental results obtained with the TASK 3.2 LMB experimental test bench and the numerical results obtained with the TASK 2.2 TF numerical tool.

In order to carry out the comparison, the performance curves obtained experimentally with and without stall ringare shown in Figure 12 together with de numerical data. The numerical results are represented with dots only for anti-stall configuration. As is can be observed, the absolute value of the pressure rise is higher than in the experiments. However, the curve trend follows fairly well the experimental behavior form a qualitative point of view, clearly avoiding the pressure-drop area that is a characteristic of the beginning of the unstable region.

Pressure values for air flow
calculations

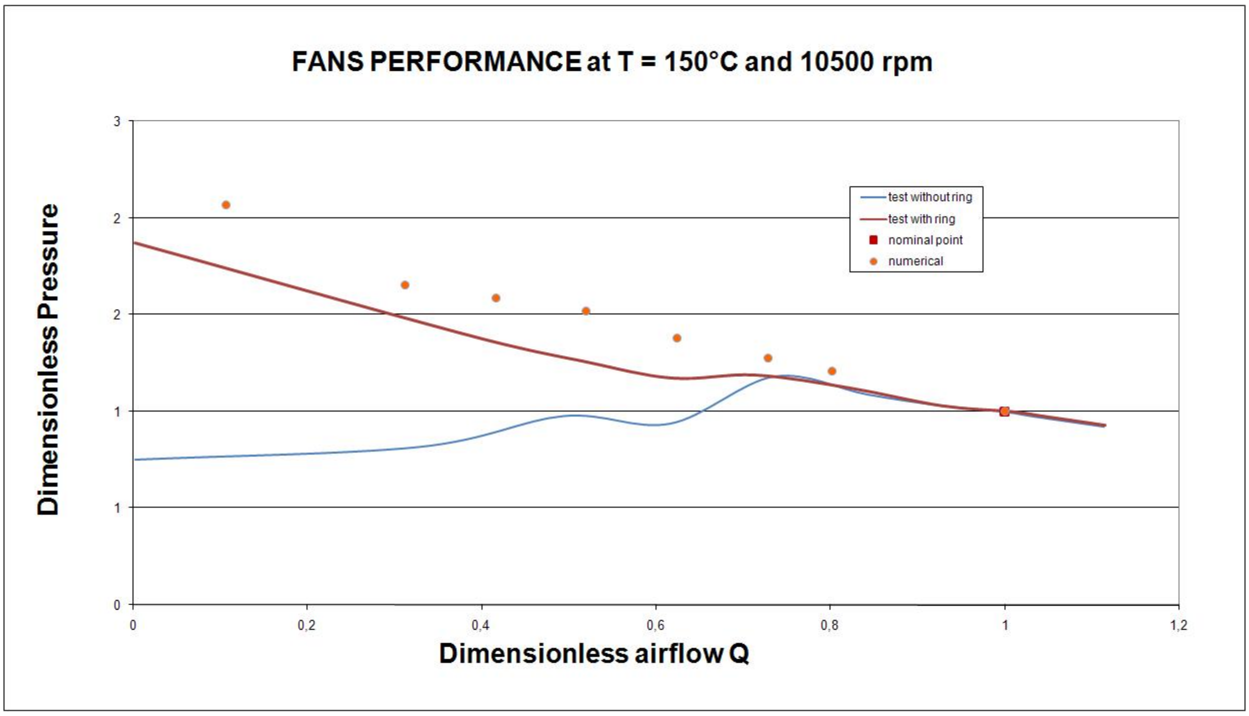


Figure 12.Fan curve performance.

The main conclusions derived from the experimental tests are that the proposed anti-stall device for the axial fan is able to avoid completely any flow instability at any flow rate and any rotation speed. Additionally, the aerodynamic efficiency is almost not affected by the addition of the anti-stall ring thus fulfilling another requirement of the project.

Therefore, the main purpose of the project has been achieved by obtaining a fan that can work in the whole range of flow regimes required in the project without aerodynamic instabilities and without losses of efficiency.

Regarding the numerical analysis, a correct qualitative analysis has also been achieved and it is confirmed that the numerical methodology has captured the effects of the anti-stall device properly.

WP4 Fan thermal management

TASK 4.1 Fan thermal analysis

This TASK4.1 has been centered within the first project period P1 to the generation of the bibliographic study on electric motor cooling. High temperature electric fan concept bibliography research aims at reviewing current technologies available for axial fan motor cooling, construction materials and corresponding adopted solutions. The state of the art deliverable 4.11 integrated the following objectives:

- Present different construction materials capable of high temperature operation for the different fan parts.
- Identify the different suppliers that deal with high temperature capable components.
- Understand the different motor cooling technologies available.
- Identification of new design concepts and available solutions for axial fans and cooling systems operating in high temperature conditions.

The work has been split in the three main components of the fan: the impeller, the motor and the bridge between them and the main structure/shaft, the bearings. On the other hand, a detailed review of available high temperature fans and corresponding cooling solutions/strategies has also been included.

Impellers

Several aspects are to be considering when operating fan impellers at high temperatures: materials and failure mechanisms such as creep; high and low cycle fatigue in cyclical operation with speed variation and start-stop operation; thermal stresses in fans subject to rapid temperature changes; amongst others.

Depending on the operation temperature, the following are to be considered: construction materials, blade to hub attachment mechanism, bearings and lubrication, shaft seals and cooling. In standard fan impellers limiting operating temperature is usually given by the limiting temperature of the bearings.

The following references *“[1] High temperature fans.2011”*, *“[2] Multi wing international.Fan materials”,* and *“[3] Airap. Wheels and impellers”,* collect the main information obtained for impeller operation conditions and typical fan materials with the corresponding temperature operating range, like Table 2.

Table 2. Fan materials and temperature operating range

Material	*Temperature range*
Aluminum (Al)	-60ºC +245ºC
Glass reinforced polyamide (PAG)	-40ºC +120ºC
Anti static PAG (PAGAS)	-40ºC +110ºC
Glass reinforced polypropylene (PPG)	-10ºC +90ºC
Steel	-60ºC +1050ºC

The field of impeller design, with the advances in computational power in the last few decades, has turned to computer simulations for state-of-the-art accuracy and assistance in solving all sorts of flow related problems. Typical goals in impeller design include increased efficiency, manufacturing optimization, decreasing noise levels and lower blade stresses.

The following references show the influence of numerical computation tools on impeller design *“[4] Shmotin Y. N. Fedechkin K. S. Egorov, I. N. Increasing of axial fan efficiency basing on optimization technology. In 6th world congresses of structural and multidisciplinaryoptimization,* *Rio de Janeiro, Brazil, 2005"*; *"[5] Bakir F. kouidri S. Younsi, M. and R. Rey. Influence of impeller geometry on the unsteady flow in a centrifugal fan: numerical and experimental analysis. Int. J. of Rotatingmachinery, 2007*"; *"[6] Hua O. Yang, L. and D. Zhao-Hui.Optimization design and experimental study of lowpressureaxial fan with forward-skewed blades.Int. J. of Rotating machinery, 2007"*; *"[7] Choi Y.-S. Kim Y.-L. Lee, K.-Y.and J.-H. Yun.Design of an axial fan using inverse design method.J. of mechanical sciences and technology, 22, 2008"*; *"[8] V.-Hosangadi A. Slipper-M.E. Mulvihill L. P. Birkbeck R. Lee Y.-T., Ahuda and R. M. Coleman.Impeller design of a centrifugal fan with blade optimization.Int. J. of Rotatingmachinery, 2011"*.

Electrical motor and cooling systems

Standard electric motor operating conditions are defined by the IEC [9] International electrotechnicalcommision. *Rotating electrical machines international standard IEC60034*: maximum altitude: 1000 m above sea-level, maximum ambient air temperature: 40º*C* and minimum ambient air temperature: 15º*C*. Electric motors operating in a wider temperature range need special consideration. There are several effects of temperature affecting the performance of electrical motors. First and most notorious is the insulation life. As temperature increases insulation degradation accelerates reducing the operational life of the motor. Other effects of temperature on electric motors are as follows:

- Bearings: Lubricant also deteriorates with temperature so operation in high ambient temperatures and forces the use of proper heat resisting lubricants, additionally cold temperatures reduces the ability of some oils to flow, if cold temperatures are encountered special lubricants are to be used. Additionally, bearing materials must also vary to withstand the heightened demands of high/low temperature operation.
- Metallurgy and Thermal stresses: Basic materials such as tin solder loose resistance when exposed to temperatures over 150ºC. In addition, hardened steel, such as those present in bearings and shafts, gradually soften at high temperature operations. Thermal expansion is also an issue that can lead to cracking and failure in bearing housings, shafts and frame, amongst other motor components, especially for operation in a large temperature range.

A major concern in motor design and application is the heat regulation within the motor itself. Excessive temperature will degrade motor insulation and cause motor failure. High temperatures can also breakdown lubrication grease, leading to bearing damage. Two factors influence motor temperature, ambient temperature and motor temperature rise. Usually, electric motors are designed to operate in ambient temperatures not exceeding 40º*C*. In hotter environments motors may need modifications in key aspects to withstand these harsher operating conditions.

Operating temperature plays a vital role in the efficient performance of electrical motors. Increasing outputs and heavy electrical and magnetic loading have forced cooling techniques to advance in order to properly remove excess heat. Heat generated in the motor core, windings and bearings limit the capacity of the electric motor. This heat comes mostly from resistance losses in the stator winding itself. Additional energy loses include: core losses consisting in hysteresis and eddy current losses mainly in the stator core, windage and friction losses due to bearing friction and rotation of the rotor and fan in the air, rotor winding losses occurring in the rotor conductors and end rings; and stray load losses from slot openings, leakage flux and harmonic fields. Core, friction and windage losses are considered as fixed losses as they do not vary significantly with load.

Two types of cooling circuit can be used: open circuit where coolant enters and exits the system and closed circuit where cooling flow is recirculated and heat exchangers are used to get rid of waste heat. Additionally, a cooling classification is done identifying the source of the power and some major characteristics in the cooling system. There are four basic mechanisms: Natural cooling, self-cooling, frame cooling and separate cooling.

Natural cooling

Natural cooling method relies on natural convection and radiation to cool down the parts of the motor. Natural convection takes place between the motor housing and parts (in open motors) with its surroundings. Fins can be added to the frame in order to increase its heat transfer capacity. Additionally, cooling may come by relative movement between the machine and its environment

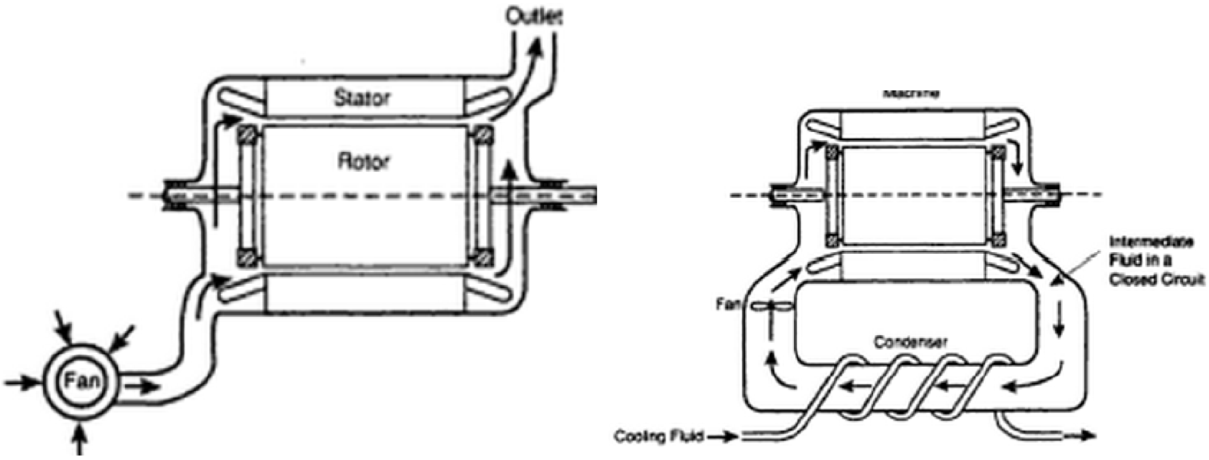


Figure 13.Cooling circuit types: open (left); close (right)

Self-Cooling, frame cooling and separate cooling

In the self-cooling, the medium is moved by the motor due to the flow induced by the rotor, by fans mounted on the shaft or external fans or pumps driven by the motor. This cooling mechanism moves air directly into the parts involved in the heat emission. Casing shape greatly influences the cooling capacities of the air within, being the thermal and aerodynamic coefficients highly correlated. Casing design influences the overall operating temperature.In the frame cooling, the external surface of the frame is cooled by means of built in fans, usually mounted on the motor shaft using this way part of the output power to move the cooling fluid and cool the motor. Fans can be inside, and/or outside the motor frame, Fig. 14 shows a sketch of this type of ventilation scheme. Air flow characteristics play a major role in this method of cooling. Both, experimental and numerical studies have been used to improve cooling efficiency in this type of motors. In this cooling method there can be two stages, internal cooling and external cooling. Internal cooling most affects the coil temperatures, additionally efficiency is highly dependent on this temperature. Just as in self-cooling, secondary systems may be used.In the separate cooling, the flow of coolant is powered by and external source. Figure 14 shows illustrative schemes of these three types of cooling.

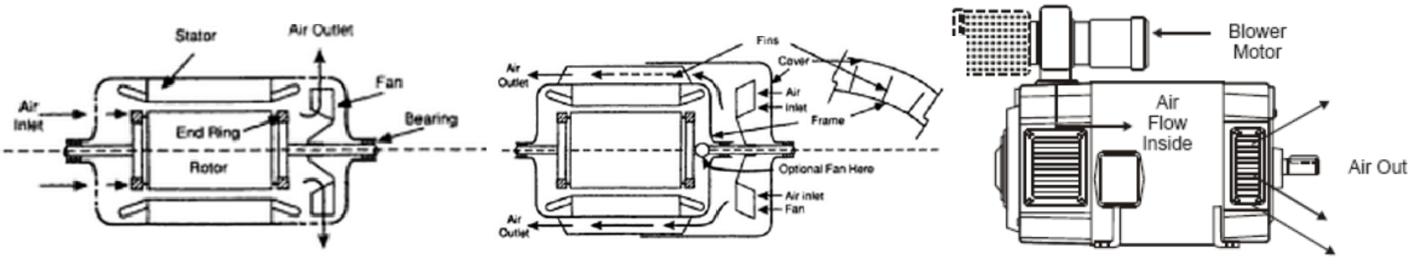


Figure 14.Cooling mechanisms: self-cooled (left); frame-cooled (center) and separate cooled (right)

Liquid cooling

Cooling can also be classified by the cooling fluid’s phase, gas (usually air) cooled and liquid cooled. Liquid cooled motors achieve a higher cooling ratio than air cooled counterparts. In contrast, the building of such machines is considerably more complicated, needing auxiliary systems to handle the cooling fluid and far more complicated motor frames and shafts. Fluid cooling is very effective due to the high heat capacity and heat transfer coefficients of cooling fluids. It is important to note, as stated before, that for implementing liquid cooling far more complex frames and support structures have to be used, increasing manufacturing costs. Additionally, coolant flow has to be dealt with, using heat exchangers, pumps, filters, etc.

Enclosure

Finally, enclosure types greatly influence the performance of the cooling mechanism. Three basic types exist: open, totally enclosed and encapsulated. Open motors have a ventilation opening that permit the flow of air from outside to the inside of the motor. Different configurations exist to protect the motor from environmental factors such as humidity, dust, etc. The classification of the environmental protection and methods of cooling has been standardized by NEMA and are as follows for open machines: Open, drip-proof, splash-proof, semi-guarded, guarded, dripproof guarded, open independently-ventilated, open pipe-ventilated and weather-protected.

On the other hand, totally enclosed machines separate the inside medium from the environment, not being air tight. Different types of totally enclosed frames are as follows: totally enclosed nonventilated, totally enclosed fan cooled, totally enclosed fan cooled guarded, totally enclosed pipe ventilated, totally enclosed water cooled, water-proof, totally enclosed air-to-water-cooled, totally enclosed air-to-air cooled, totally enclosed air-over, explosion proof, dust ignition proof.

Finally, encapsulated machines are: sealed windings and moisture resistant. Three different typical enclosures are: drip-proof fully guarded (DPFG), totally enclosed fan cooled (TEFC) and totally enclosed air over (TEAO). The DPFG enclosure is self-ventilated and has no other means of cooling, the TEFC enclosure has an external fan used to cool the frame. It can optionally mount a fan on the inside of the frame. Since cooling air flow is a direct result of motor rotation these two enclosures are not recommended for low-speed applications. The TEAO enclosure has a blower attached directly to the machine. This element allows air to be constantly refrigerating the motor frame (this type of enclosure has no internal cooling). Since air flow does not depend on rotation speed this type of enclosure would be more recommended for low-speed applications.

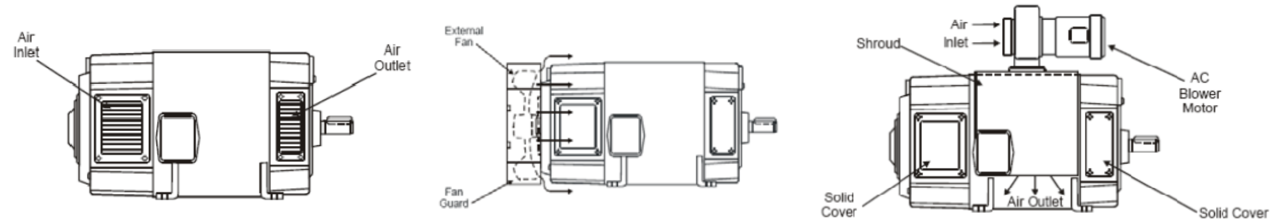


Figure 15.Typical types of enclosures: DPFG (left), TEFC (center) and TEAO (right)

Bearings

Outside bearings also pose a difficulty in electrical motor operation. Just as the problems encountered with bearings inside the motor, the auxiliary bearings that support the shaft and other rotating elements connected to it are subjected to the harsh conditions of elevated temperature operation. Due to the large number of applications concerning bearings and high temperatures this mechanical element is much more common and several bearing manufacturers offer adequate bearings. Roller bearings, air bearings and magnetic bearings are the more common types.

Available high temperature fan solutions and cooling methods

Regarding available high temperature fan solutions and cooling methods some few options have been encountered from some companies oriented to axial fans.

Milowent S.C company from Poland offers axial fans having an operating temperature range between -20ºC and 100ºC and between -20ºC and 150ºC. This axial fan is designed for continuous operation at high temperatures, equipped with a high-temperature Siemens electric motor, aluminum (150_C) or PAG blades and aluminum hub (100ºC) impeller and powder-coated steel enclosures. Flow rates available range from 600 l/s to 14800 l/s.

Mmotors JSC, a company from Bulgaria offers axial fans for operations in temperatures up 150ºC. Impellersare manufactured from aluminum alloy sealed maintenance free electric motors, however, these fans are small, designed for a flow rate up to 80 l/s.

HSC also patented a RAM fan system for an aircraft environmental control system, as shown in Fig. 16. The fan rotor (86) is driven by the ram air fan (RAF) electric motor (80). The RAF electric motor includes a rotor (102) mounted within a stator (104) inside a housing (84). Foil bearings (88, 90, 92) are used which permits effective operation of the RAF downstream of the respective heat exchanger (HX) in the high temperature RAM exhaust.

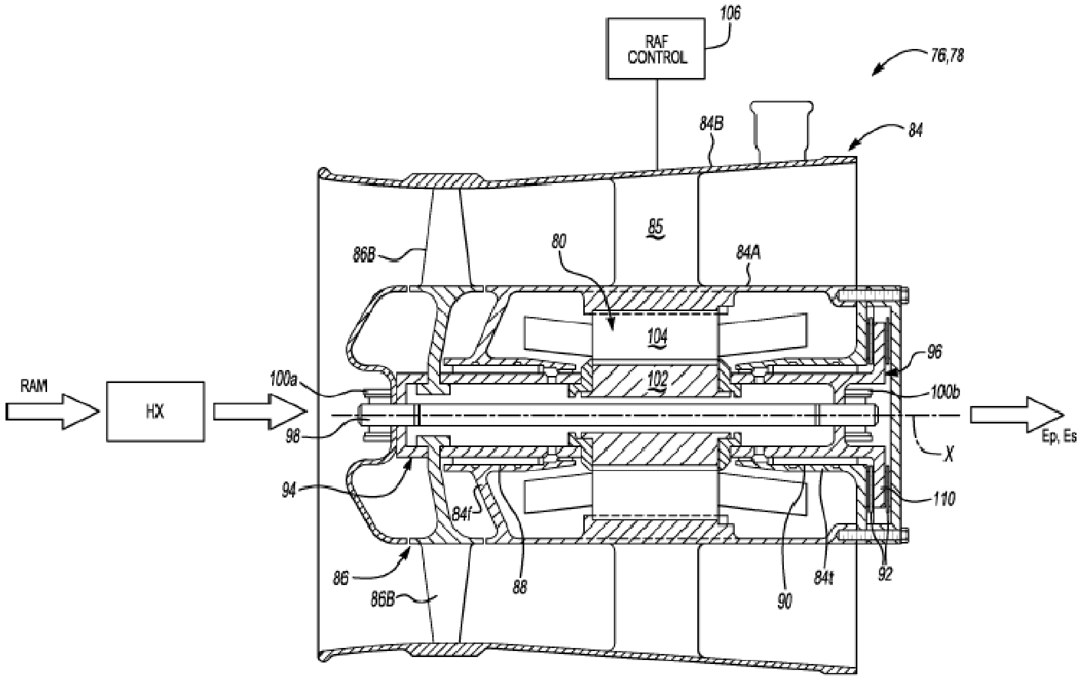


Figure 16.Hamilton Sundstrand RAM air fan for ECS.

In conclusion, the fan thermal analysis carried out, based on the actual state of the art has shown the actual electrical motor cooling techniques, their main problems and challenges at high operation temperatures, while available actual technologies have been described.

The final part of this task is related to the selection of the best thermal management concept. In this particular case, the fan is subjected to exigent temperature working conditions. As LMB partner has a good technological level to withstand these conditions, the work here has been focused in the identification and description of LMB capacities, and to the tuning of UPC modelling tools and expertise to this specific situation.

Therefore, the objective has been to have a clear overview of the capacities of the consortium regarding the thermal design and modelling tools to develop the high technical thermal management solution that the project demands.

In a very summarised way, the LMB capacity regarding high temperature electric motors is based on the use of high temperature constitutive parts: High temperature enamelled copper wire (Class H); high temperature insulation varnish (Class H); high temperature slot insulation (300°C); high temperature IronSilicon lamination (725°C typical); high temperature magnets (350°C), and high temperature bearings.

Considering the availability from LMB of a background technology for high temperature use, instead of developing full new concepts to withstand the required high temperatures, the focus has moved towards the detailed characterization of the selected fan and electric motor design. With the detailed knowledge of the electric motor thermal map a further improvement of the thermal dissipation is expected in order to reduce the temperature in the selected motor, with the subsequent improvement in motor reliability and safety. Another very interesting working line in this TASK 4.2 has been to improve to the limit the current thermal dissipation capacity in order to check the feasibility of the implementation of the power electronics within the motor.

Therefore, the fan thermal management approach has been:

1. Identify and quantify LMB capacities regarding HT fans and electric motors.
2. UPC and TF adaptation of numerical simulation platform to allow future detailed analysis of the selected preliminary and final designs.
3. Define thermal objectives for the selected designs.
4. Identify and quantify possible improvements regarding thermal dissipation

Examples of meshes for the solid fan and for the fluid flow are presented in Figure 17.

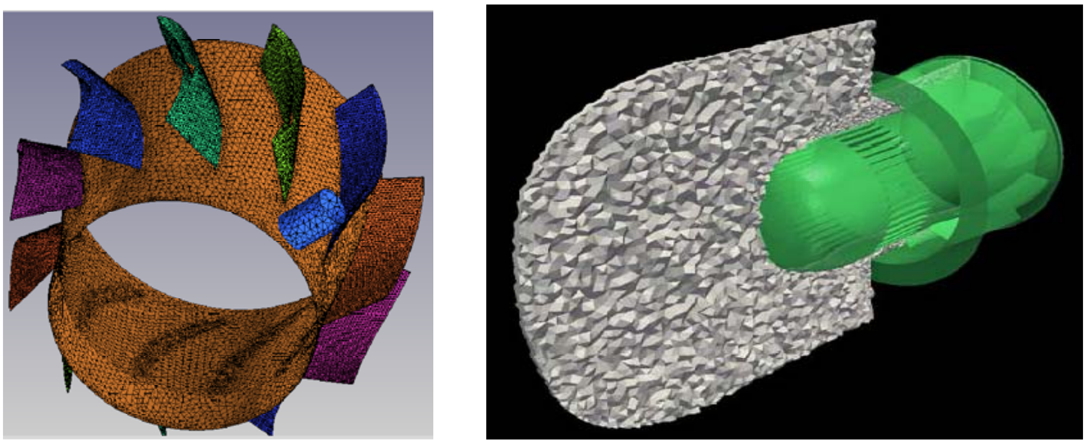


Figure 17.Unstructured mesh for the fan (left), fluid meshes for the air (right)

A first step has been oriented on different meshes influence analysis, to overcome numerical instabilities and spurious results identified under non-physical details.

A second step to avoid convergence problems and CPU time reduction, the UPC solution adopted has been to decouple the CFD problem from the energy solid problem. Given the velocity of the airflow in the region of interest, the effect of natural convection (which acts as a coupling between the energy and momentum equations) is expected to be very low.

In that sense, and thanks to the complete aerodynamic analysis developed by TF in TASK 2.2 and TASK 2.3, the solid thermal analysis tool here presented have been adapted to be able to use TF data as the input data.

To summarize, the tool developed for the study of the thermal behaviour of the electric motor is based on: i) use of the Inverse Boundary Method (IBM) methodology for the accurate estimation of heat transfer from solids to the surrounding fluid; ii) decouple of energy and momentum, and therefore solve only the energy equation in a region around the electric motor, so only a small domain is considered; and iii) take input flow field data from a CFD simulation of the complete fan where the accurate physics of flow behaviour have been taken into account

In the case of internal motor analysis, the intricate geometry and small thickness elements in the motor internal part creates strong mesh problem transitions if tetrahedral elements are selected. As an alternative, Adaptive mesh Refinement (AMR) method using structured Cartesian mesh has been implemented. The convective fluid dynamic map in the annular flow is interpolated from previous unstructured mesh simulations (fully compatible with TF pressure-velocity simulation in WP3).

The cells in the vicinity of the thin bodies are divided to have a good resolution (Figure 18, left). Meanwhile the solution is reconstructed in the cells cut by the bodies using immersed-boundary method (Figure 18, right).

On the other hand, regarding the boundary conditions, the tool has also been prepared to have full flexibility in terms of materials and heat generation. Different elements have independent heating rates (windings, front bearings, rear bearings), while each element has its own material with the corresponding thermal conductivity.

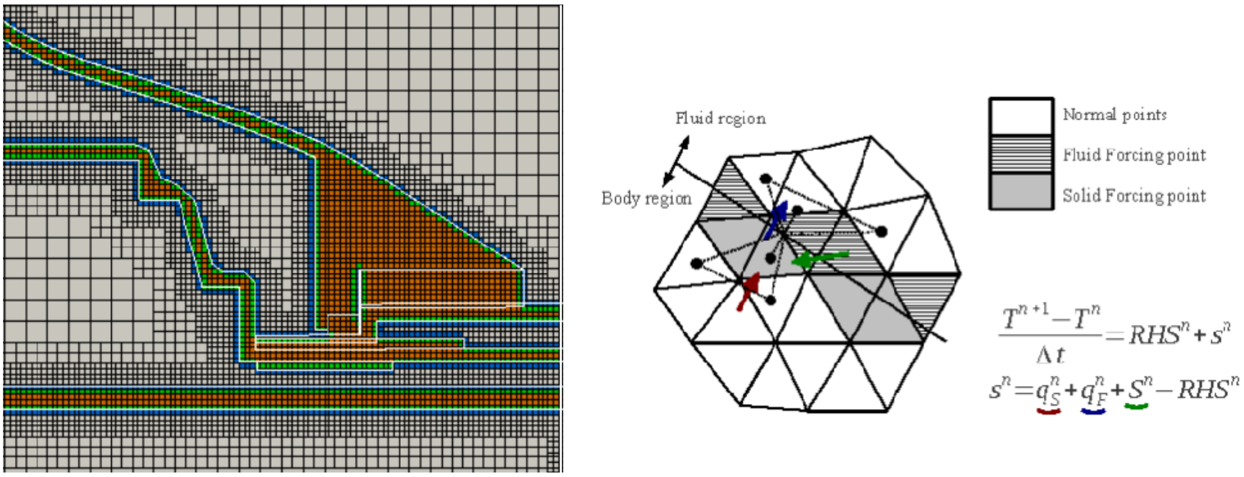


Figure 18.AMR mesh local densification around thin elements (left); IBM cell reconstruction in intersection boundaries (right).

After the selection of the best numerical methodologies for the thermal analysis of the fan, and with the corresponding material and boundary conditions requirements covered, the tool has been applied and checked in a real LMB geometry, in order to have everything ready for further simulations within WP4 (Figure 19). The tool has revealed as a smart option to deal with the complex geometry with a great flexibility. Its ability to interact with TF pressure-velocity simulations of the rotor-stator system has avoided the duplicity of simulations in this sense.

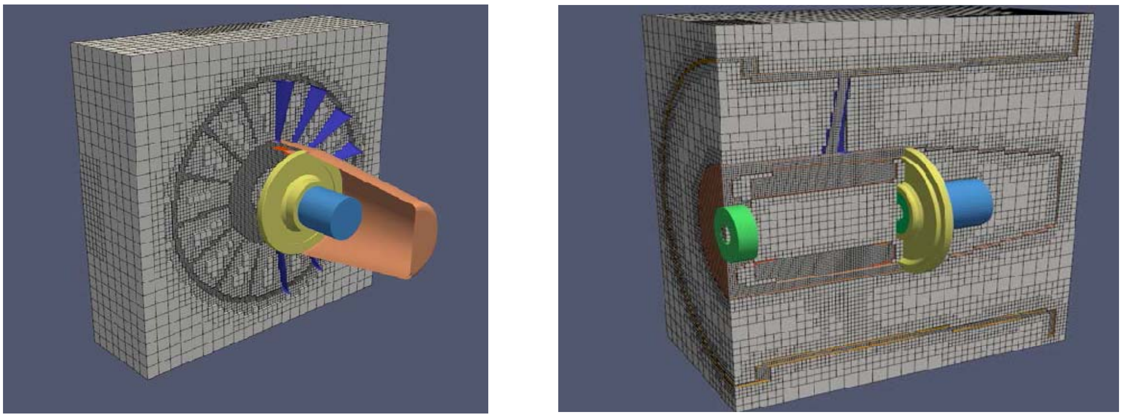


Figure 19.Implementation of the numerical methodology to an LMB electric motor.

TASK 4.2 Fan thermal design

This task is related to the thermal analysis and design of the fan thermal management. In particular, has been focused on the description of the preliminary design step, where a mixed flow fan was selected as thought to be a good solution for the surge issues. On a second iteration, during the final design step, the design has shifted towards an axial flow fan solution, as having some benefits in terms of size and performance.

The LMB design process has been also outlined, giving some details of the most important motor parameters. On the other hand, the simulations and numerical strategies developed and applied by UPC and TF have been described in detail.

The main thermal management structure, common to both mixed and axial flow fan configurations, is based on an annular channel where the stator blades are simultaneously used as thermal dissipating fins. The flow circulating along this annulus is the same air displaced by the fan.

Numerical model of the mixed flow fan

For the mixed flow fan, only the hull surrounding the electric motor, hereinafter referred to as the “inner hull”, and the hull supporting the stator blades, hereinafter referred to as the “outer hull”, are considered. These are modeled as a solid element, and the heat conduction equation is solved within them. For the remaining part of the domain, the convection-diffusion equation is solved

All solids are assumed to be made of aluminum, with the thermal conductivity of 121W/mK. The internal elements of the motor are not simulated for this fan. The effect of the motor is introduced via a heat flux through the boundary. The values used for the power coming from the electric motor were provided by LMB and are 45.3 W for the stator and 71.7 W for the winding. Figure 20 shows the solved domain selection.

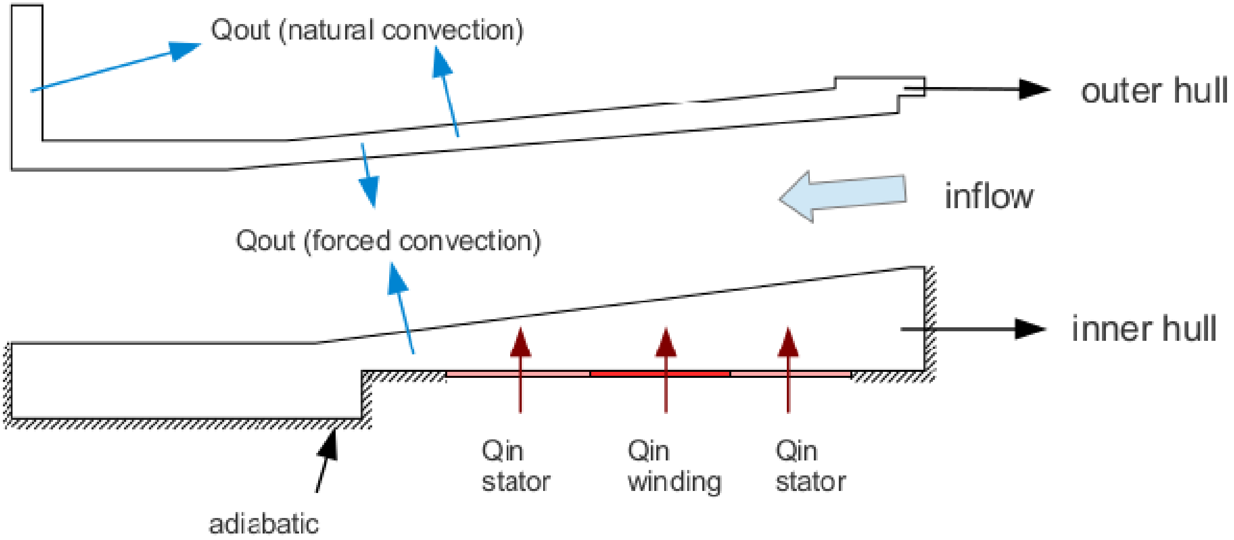


Figure 20.A section of the solved domain.Description of the problem and boundary conditions used.

To speed up the tool assessment for the thermal analysis of the electric motor of the mixed flow fan, a reduced domain including all the relevant physics is used as a numerical test bank. The purpose of this strategy is to reduce the computational cost and to be able to run the simulations in desktop computers instead of a more powerful cluster, where more users are competing for a limited amount of computational resources.

The reduced computational domain consists on the geometry sketched in Figure 20, rotationally extruded by 60 degrees, with a single fin in the middle of the domain. Several simulations were carried out in order to ensure that all parameters, materials and boundary conditions were set properly. A result of one such simulation is shown in Figure 21 left.

This result was also compared to the complete simulation with the reduced domain in Figure 21 right. Both kinds of simulations exhibit a close behaviour, and at this point the attention was focused to the complete domain. Note that, being the results of the only-solid approach similar to the detailed fluid-solid model, the door is opened to very fast simulations where only solids are considered, with heat transfer coefficients estimated from a detailed simulation.

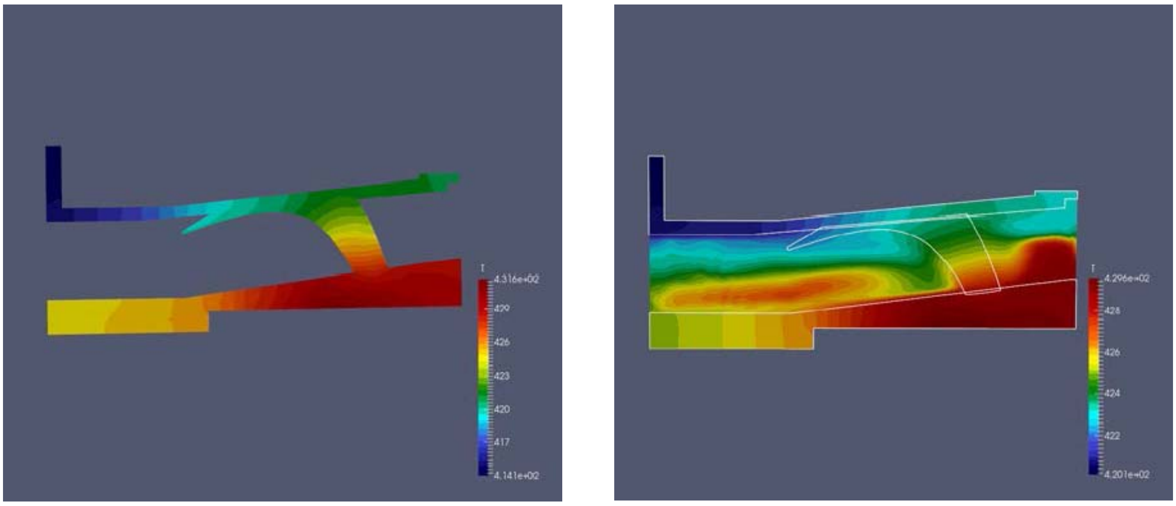


Figure 21.Temperature distribution:simplified model (left); complete (right).

From this design process, the dissipation levels are determined, and used for the simulations carried out, which give a very detailed information of the thermal behaviour of the unit, the temperature levels, the heat flux distribution between hulls and blades, etc. However, as explained before, the mixed flow fan design was discarded in favor of the axial flow design.

Numerical model of the axial flow fan

After the previous model, an updated version has been developed for the final design step, where an axial flow fan with anti-stall ring was selected to cope with the surge issues while maintaining an acceptable size and performance for the Topic Manager requirements. The LMB design process has been outlined, giving some details of the most important motor parameters. On the other hand, the simulations and numerical studies carried out by UPC and TF has allowed a model tool ready for validation purposes.

Therefore, the objective of this task for the final fan thermal management solution has been to model the thermal dissipation behaviour to predict in an accurate and detailed way, the temperature map. Further studies are also given, exploring future designs integrating the electronics inside the fan, or about design modifications to increase the heat dissipation capacity.

The solution provided by the LMB company regarding the axial flow fan adopted in this project has been meshed using the Cartesian discretization method using Adaptive Mesh Refinement around thin elements. From its geometry, UPC has simplified the level of detail to create a model suitable for an adequate and efficient CFD simulation shown in Figure 22.

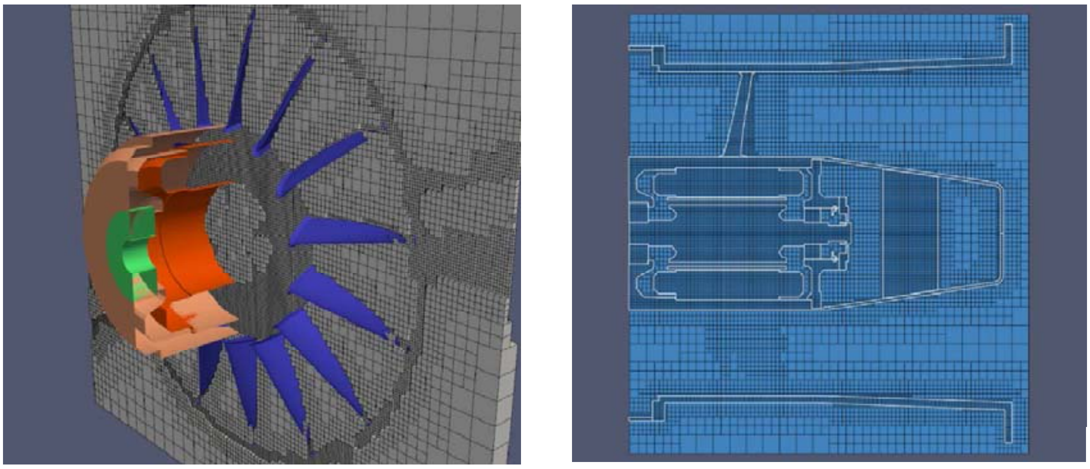


Figure 22.Cartesian based mesh using Adaptive Mesh Refinement around thin elements.

Regarding the internal heat dissipation, the solids have the ability to generate heat in an independent form. In this way, the values given by LMB,have been uniformly distributed in the specified elements (front and rear bearings, stator, electronics).

Regarding working conditions, the work has been focused on the high inlet temperature, where the effect of varying external temperature has been analysed. On the other hand, in order to be aligned with LMB initial test campaign, a set of results with low inlet and ambient temperatures has also been considered.

In all cases, including the ones with a high inlet temperature, the obtained bearing temperatures are just below the limit of 250ºC, which could be seen as adequate even being quite close to this value that can be considered as a limit.

Improved numerical designs with intensified heat transfer

UPC and TF have dedicated part of the work to find alternative feasible and cost-effective designs that could reduce the temperature level of the fan. In this sense, some what-if scenarios have been proposed: i) Fins on the outer hull to increase dissipation area (heat transfer coefficient increased by a factor of 4); ii) Stator blades made of a high thermal conductivity material (blades thermal conductivity increased by a factor of ~4) or iii) A combination of the two above scenarios

The simulation of all these possible solutions has been carried out for the worst scenario with the maximum temperatures. In this case, the temperatures within the motor are greatly reduced by the introduction of the proposed design alternatives. The temperature levels in the motor core (bearings, stator, inner hull) reduce in the order of 10ºC with the improved outer hull heat transfer, 45ºC with the improved conductivity, and 60ºC with the combined proposal. Although these proposals feasibility and cost-effectiveness have to be confirmed by LMB designers, the obtained temperature drops are really important, indicating that the proposed baseline design has margin to be improved if the final tests confirm that we are working at limiting temperature values. Figure 23 shows all these for scenarios from a qualitative point of view.

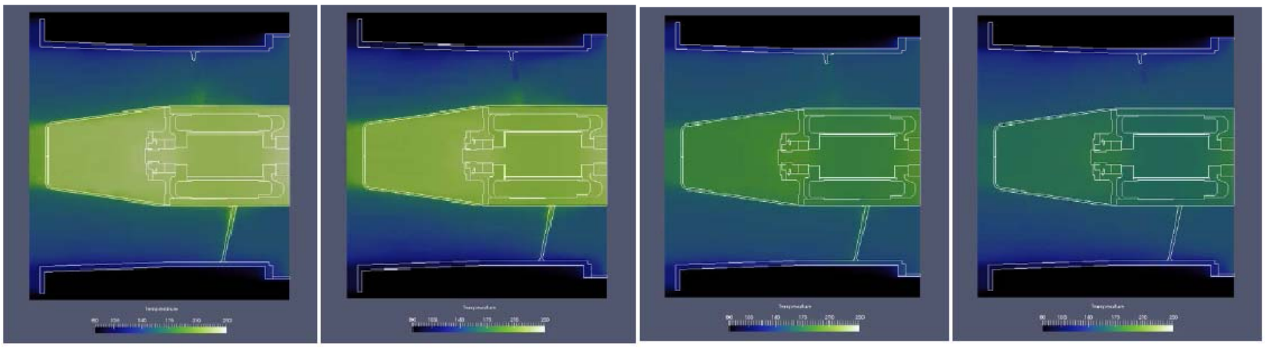


Figure 23.Temperature maps for the four situations: baseline design, improved hull heat transfer, increased fin conductivity, and combined design..

Thermal analysis with the electronics embedded in the fan

During the project evolution, and considering the LMB capacities, one additional interesting aspect regarding the thermal management has been the investigation of the effect of having the electronics inside the motor casing. As a first step, the electronics have been considered inside the casing in OFF conditions, to check their impact in the thermal dissipation of the whole fan.
On a second iteration, the electronics have been switched on to describe the current obtained temperatures in this exigent test.

The numerical comparative results withIN-OFF electronics under different limits of inlet working conditions observe a certain temperature division effect in the electronics casing compared to the cases with electronics OUT of the fan. This blockage in the heat transport along the electronics casing seems to have a small heating effect (5 to 10ºC) in the internal parts of the motor bearings.

The numerical comparative results with the electronics IN-OFF in comparison with electronic IN-ON, confirms the important temperature increase in the motor elements. For the average temperatures, an increase of about 25/30ºC is observed for the internal elements as bearings and stator. Regarding the maximum temperatures, we can see that they are quite close to the average for the bearings and stator, while notably higher for both hulls (specially for the inner hull with 292 ºC maximum vs. 232ºC average), as being longer and thinner elements with higher temperature differences. Figure 24 illustrates this important increase, to conclude that too high temperatures are reached and that new actions should be taken to improve the thermal dissipation, specially around the electronics capsule if electronic wants to be included.

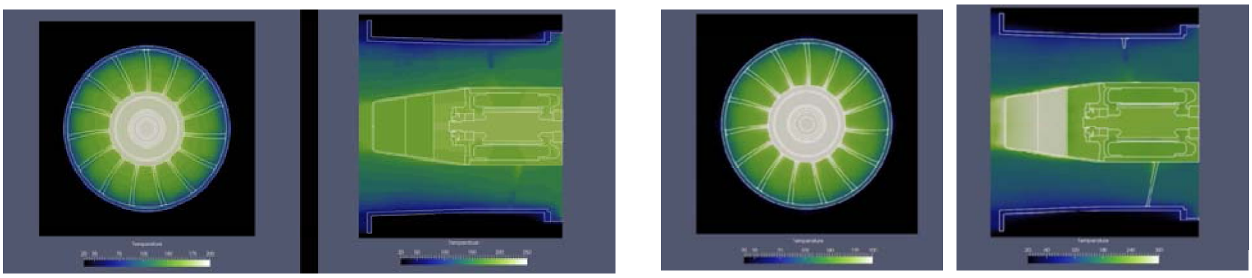


Figure 24.*Temperature maps with electronics IN-OFF (left) and IN-ON (right)*.

TASK 4.3 Fan thermal validation

The EFFAN project goals were double: on one side the design of a fan that could operate in a very wide flow regime without stall-surge instabilities. On the other hand, the operation at very high air inlet temperatures was required, what ask for a very specific design in terms of fan electric motor thermal management.

As illustrated in the previous WP4 deliverables, thanks to LMB in-house technical know-how on high temperature electric motors, the EFFAN solution has been the development of an ex-professo electric motor with high quality high temperature components. This solution is based on an axial fan that uses the annular displaced airflow as the motor cooling medium, with the help of the stator vanes and external hull as additional heat transfer surface. This solution is similar to some of those identified solutions in the bibliographic study (D4.11).

During the last part of the project, the fan prototype has been constructed, and tested aerodynamically to confirm stall-surge avoidance. Finally, its thermal performance has also to be verified, which is the objective of this last thermal-side deliverable.

Accordingly to previous comments, this section shows first the experimental LMB facilities and then the thermal experimental performance tests carried out. Finally it depicts the numerical tests carried out at those experimental conditions, analysing the goodness of the numerical predictions.

Experimental methodology and bench description

LMB has an adequate set of equipment and infrastructure to thermally test the fans it produces (Figure 25). For the EFFAN requirements, it has used an environmental test chamber to test high-temperature conditions, while for low temperature cases, open-channel experiments within the Lab room have been conducted (more freedom to analyse the unit, free test chamber for other uses).

Figure 25 – LMB environmental test chamber to conduct the high temperatura tests required within EFFAN. In the picture below we can see the EFFAN fan prototype ready for testing

It must be considered that the external ambient conditions during the thermal tests in the environmental chamber differ from those outside the chamber, and from those during aircraft operation. The airflow in the environmental chamber circulates through a limited area, looping from the outlet to the inlet of the fan, at high velocities.

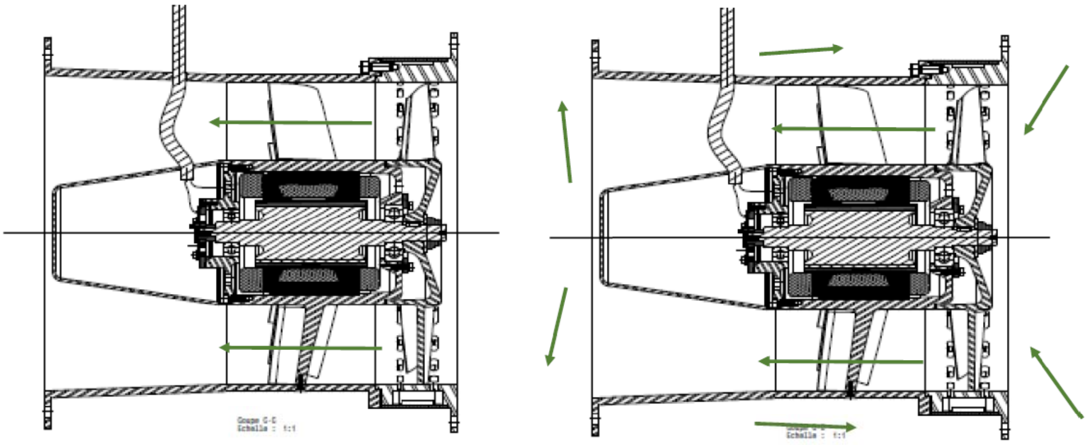


Figure 26- Thermal tests airflow circulation in the external environment. On the left, case outside the environmental chamber. On the right, case within the environmental chamber, which creates a high velocity airflow along the external part of the fan.

Figure 27 – Rear flange view, where the thermocouple wires (in White-green thin cable) can be identified. Thick power cables to the stator can be identified as well.

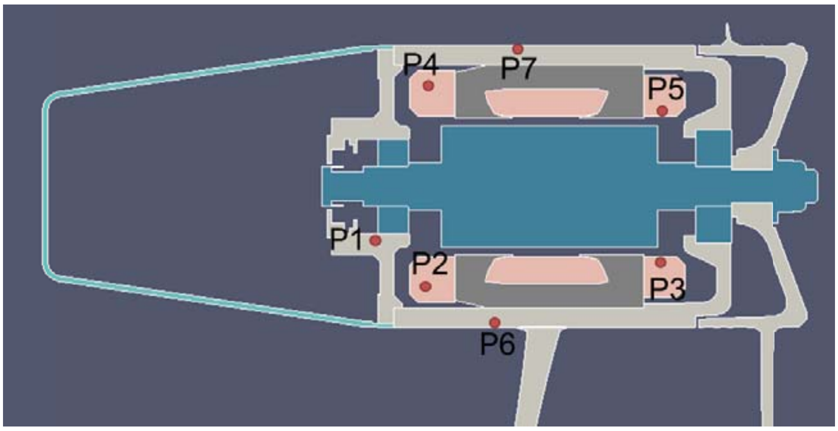


Figure 28 – Thermocouples measurement position within the EFFAN fan motor prototype.

Regarding the measurements to be done, a set of priority positions has been defined by UPC and LMB. In a first attempt, only three points where included (P1 to P3). After the first numerical comparisons, additional points have been included to have a more detailed picture of the whole fan-motor temperature map (P4 to P7), specially covering the inner hull temperature and additional measurements on the windings.

Experimental results

After the experimental campaign on the aerodynamic side, the thermal tests were also carried out. The attention has been finally focused on two tests.

The first test has been done at lower airflow conditions and low inlet and ambient temperature (see Table 3 for description of the case)..This case is complementary to the second one in terms of airflow influence to the electric motor cooling, analysing the overheating value respect to the inlet temperature in this alternative point (low flow, lower dissipation in motor core, lower heat transfer coefficient in the annulus).

Table 3 – Definition of test number 1 (cold).

Test place	*Laboratory room*
Flow conditions	*N= 5435 rpm*
	Airflow velocity between motor and housing = 15 m/s
	Return Airflow velocity on housing = 0 m/s. Natural convection.
Power loss estimated	*Rear bearing: 20 W*
	Lamination and windings: 28 W (20+8)
	Front bearing: 23 W

The second experimental validation performance case is defined at the limiting high air inlet and external environment temperature, and high airflow conditions (nominal point, high dissipation in motor core, high heat transfer coefficient in the annulus) (see Table 4 for full description of the case). This test is conceived to validate the performance of the selected fan high temperature materials and the selected thermal management solution, in an operating point close to the Topic Manager requirements on the thermal side.

One important remark to be done regarding the given case definition tables is that the high temperature decreases the grease viscosity, thus decreasing the power loss of the bearing in the same time. This can be observed in the heat dissipation lower values in the bearings for the test number 2.

Table 4 – Definition of test number 2 (hot).

Test place	*Inside climatic chamber*
Flow conditions	*Near the nominal point, N= 10700 rpm*
	Airflow velocity between motor and housing = 33 m/s
	Return Airflow velocity on housing = 20 m/s
Power loss estimated	*Rear bearing: 15 W*
	Lamination and windings: 180 W
	Front bearing: 17 W

Figures 29 and 30 show the diagram of the fan, with green arrows to indicate the flow direction, including the overheating values measured at rear bearing and at two positions of the windings for the test 1 and 2, and some additional measurement points for test 1.

Regarding the test number 1, Figure 29 provides the overheating values at different locations. For this test, the number of measurements has been extended to cover not only the functionality required as in test number 2, but also to have some additional measurements that allow a better understanding of the fan thermal management behaviour, and a more detailed numerical vs. experimental comparison.

As can be seen in the Figure 29, for this case the overheating values are very reduced, as the power dissipated in the windings and laminations is much lower (lower airflow) than in test 2. The higher dissipation at the bearings for this case seems to not have a great impact on the main electric motor solid body.
The fan fulfils the requirements in this case, as even though the test have been carried at low inlet temperature, the overheating of less than 10ºC assures that even if the inlet temperature rises to the hot inlet value the operating limits will not be reached.
On the other hand, looking at Figure 30, the overheating values observed in test number 2 (+22ºC) for the bearings are within the limiting temperature range given by LMB thanks to the special components under use, integrating a high-tech lubricant grease. Copper wire is using an enamelled protection qualified at very high temperatures, being capable to withstand the measured overheating (+51ºC).

Summarising, the measured values indicate that the thermal management solution proposed fulfils the project requirements, as accomplishing the necessity to run the fan at hot inlet conditions by maintaining admissible temperature limits within its electrical motor (as described by manufacturer operating conditions).

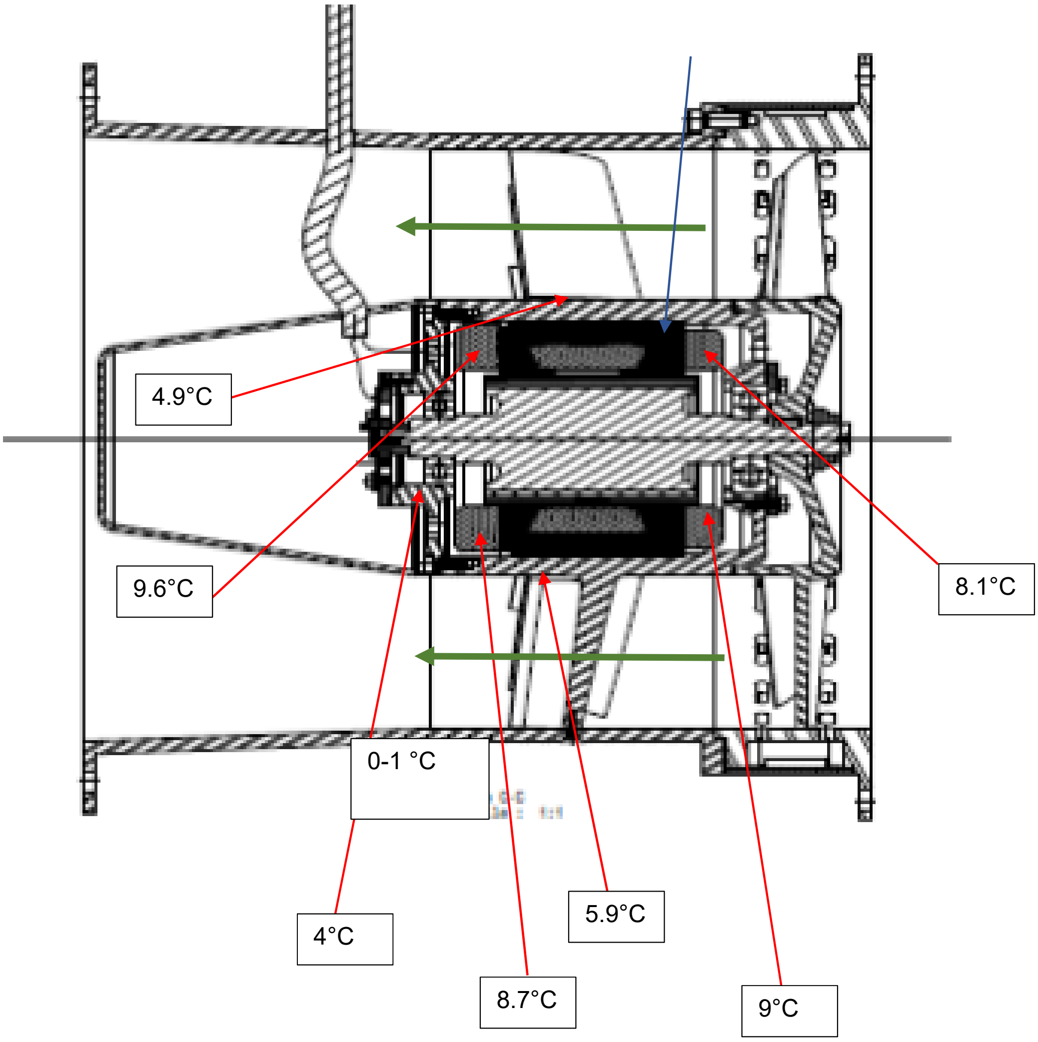


Figure 29 – Overheating values for the test number 1 (low T and low airflow).

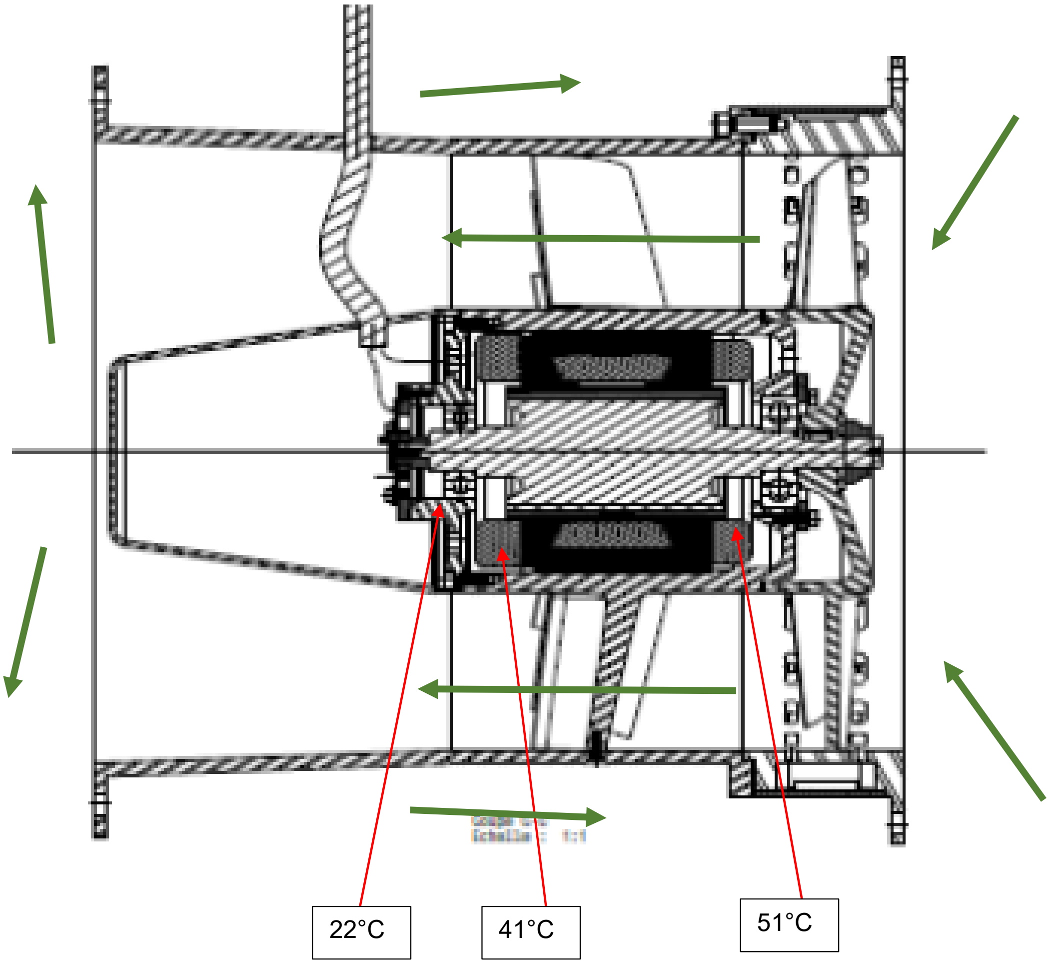


Figure 30 – Overheating values for the test number 2 (high T and high airflow).

Numerical complementary validation of fan thermal performance

As introduced in the previous thermal deliverables, the application of numerical thermal analysis along the project has been useful to identify the power dissipation mechanisms and to provide a full understanding of the physics involved. At the same time, they have been an alternative tool to propose future improvements as well.
The final project meeting was used as an intensive technical meeting, where the available numerical results at that level were commented in detail. Some improvement actions were identified and have been applied during this last reporting extra time, obtaining the last results presented in this deliverable.
Considering the project evolution, the partners have decided to do this additional effort to close this task in the best way.
The following aspects have been updated in this last simulation loop:

- Thermal conductivity of aluminium changed to 180 W/mK (LMB estimation)
- Front bearings, rear bearings, and rotor shaft made of stainless steel (therm. cond. 26 W/mK)
- Different distribution of power generated in windings and stator laminations
- Refined geometry of flange
- Refined contact resistance values. Special attention to avoid contact between impeller and inner hull, and on the contact quality between the windings and laminations.

In the following content, the numerical tests are described in detail. On one hand, the materials and their properties are given in Table 5. Then, regarding the contact thermal resistance, the contacts considered are depicted in Figure 31. Finally, the three numerical tests considered are described in Table 6, indicating the values of contact resistances. Tests 1 and 2 coincide with the experimental tests 1 and 2 introduced in previous section. Test 3 corresponds to the Topic Manager limiting requirement. Tests 1 and 2 will be presented in the following lines.

Table 5 – Description of materials and properties considered in the simulations.

Material	Therm. cond. (W/mK)
Aluminium (inner and outer hull, impeller, blades, flange)	180
Iron (stator laminations)	60
Copper (windings)	380
Stainless steel (rotor shaft, front and rear bearings)	26
Plastic (rear ogive)	0.5

C1	Contact between flange and inner hull
C2	Contact between laminations and inner hull
C3	Insulation between windings and laminations
C4	Contact between bearings and flange
C5	same as C4

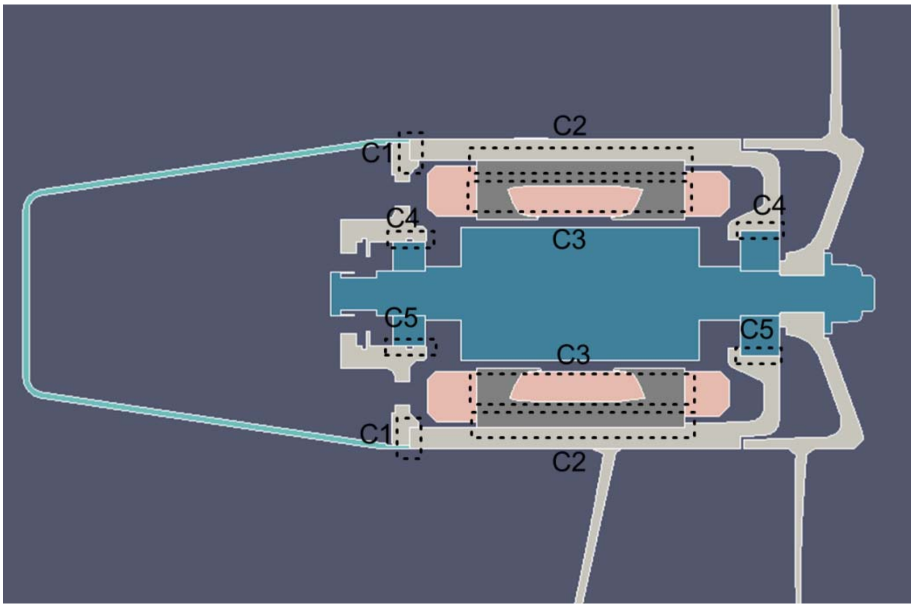


Figure 31 – Description of the thermal contacts considered.

Table 6 – Description of the three numerical tests considered.

Case	**TEST1**	**TEST2**	**TEST3**
Contact C1 (W/m^{2}K)①	450	450	450
Contact C2 (W/m^{2}K)②	45000	45000	45000
Contact C3 (W/m^{2}K)③	333.3	333.3	333.3
Contact C4 (W/m^{2}K)④	2500	2500	2500
Contact C5 (W/m^{2}K)④	2500	2500	2500

Test1 – Cold inlet –experimental conditions

The test 1 has been numerically simulated using the highest level of detail, which is, using a full CFD simulation on the airside.

The obtained values are depicted in Table 7 and Figure 32. As can be observed, the winding temperatures (P2 to P5) are predicted within a narrow range of deviation, although not observing the scattering seen in the experimental values.

Regarding point P1 near the rear bearing, the numerical prediction does not show the low value observed experimentally. This simulation is considering a relatively bad contact thermal resistance between the inner hull and the flange. It will be seen later in the convective condition simulations how a better contact in this point allows obtaining better predictions.

For points P6 and P7, it seems that the current simulation also overpredicts the temperature level. During the last simulations under convective condition the new set of empirical information also improves the prediction for these points.

Test 2 – Hot inlet – experimental conditions

For the test 2, again the maximum level of simulation using full CFD has been applied to get the corresponding maps of motor and airflow temperatures.

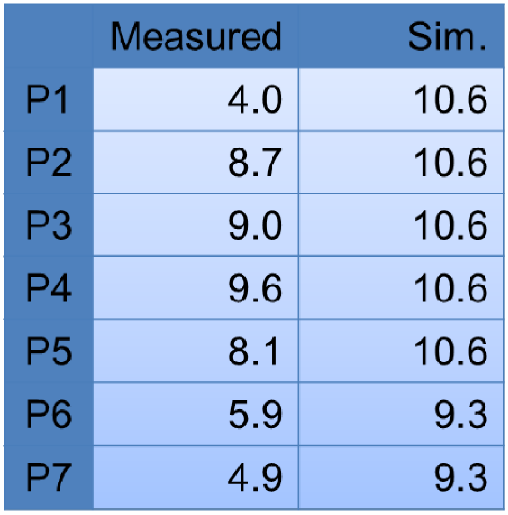
The obtained values are depicted in Table 8 and Figure 33, also showing the values presented from the simulation stage shown during the final meeting.

From that meeting technical discussion, several points have been adapted, specifically:

a) Avoid contact between impeller body and inner hull body, impeller only contacts the rest of the motor through the shaft.
b) Implementation of adequate insulation level between the windings and the laminations

As can be observed from the given values, the temperature level has been clearly improved compared to previous results, showing a better prediction of the experimental values in the windings. However, the low temperature seen experimentally in P1 is again not fully followed by the simulations (although the difference between P1 and P2-P3 has increased in a noticeable level, from 3 to 13ºC). As already commented for test 1, during the last convective condition simulation tests, the new set of empirical information, improving the contact between the flange and the inner hull, has allowed a better prediction for this temperature. In this sense, the same correction for both tests 1 and 2 allow to refine the corresponding numerical prediction.

Table 7 – Overheating values for TEST 1.



	Measured	Sim.
P1	4.0	10.6
P2	8.7	10.6
P3	9.0	10.6
P4	9.6	10.6
P5	8.1	10.6
P6	5.9	9.3
P7	4.9	9.3

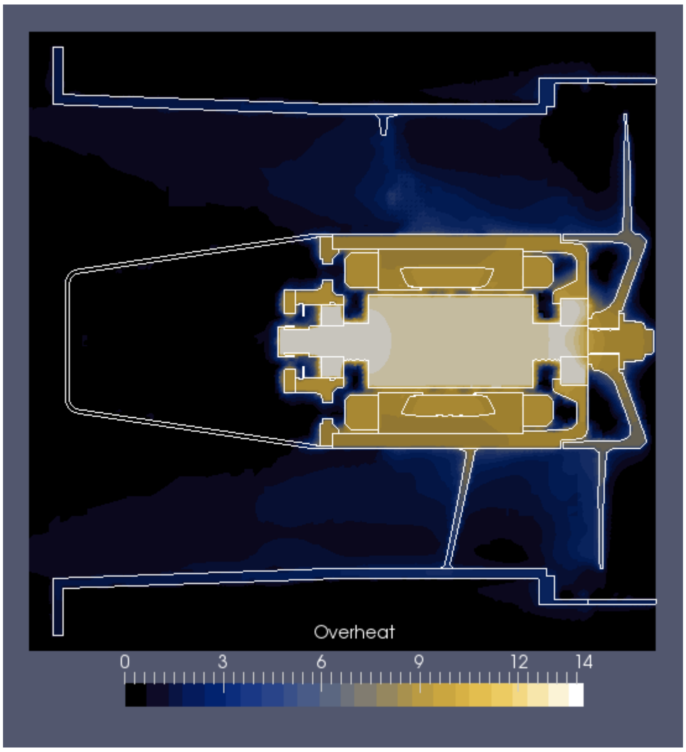


Figure 32 – Overheating map obtained with the simulation for TEST 1..

Table 8 – Overheating values for TEST 2.

	Measured	Prev. sim	New sim.
P1	22	34.5	41.4
P2	41	37.6	54.6
P3	51	37.2	54.4

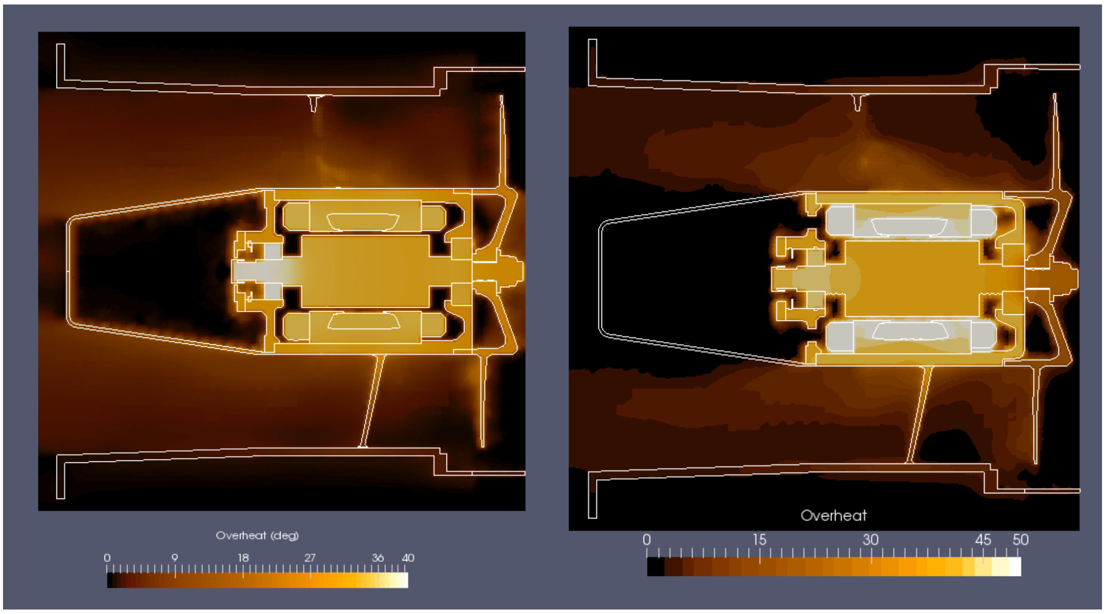


Figure 33 - Overheating map obtained with the simulation for TEST 2. Left: values obtained at Final Meeting. Right: improved values obtained after several upgrades.

Potential impact

The EFFAN project has succeeded in its main target, the design and performance validation of a new fan to cover the specific necessities that appeared with the more electric aircraft ECS design. The developed fan covers the expected wide airflow range without stall/surge issues, lowering the noise comparing to a standard fan, as having much less flow instabilities. Moreover, the efficiency of the fan is not affected by the integrated anti-stall device. On the other hand, the electric motor that drives the fan has a design capable to withstand the high air inlet temperatures required by the Topic Manager, by means of high temperature components, avoiding the introduction of complex cooling systems, alternative cooling airflow means, etc.

The success in covering the project requirements means that the project can really have an impact on the final new electric-ECS designs, providing a reliable (no instabilities, withstanding high temperatures without adding complexities) and efficient (same fan efficiency, one single fan to cover two very different tasks) component to cover such a critical task (cooling of air cycle machine, cooling of electronic devices, etc.).

Once seen the specific impact of the new fan at ECS design level, let us analyse the impact from a more general perspective. Thanks to its impact on the aircraft implementation of the electric ECS, the EFFAN project will have a high contribution to the European competitiveness with a potential for a reduction of energy consumption and environmental pollution while developing a new ram-air fan to be integrated in the ECS system with large possibilities of industrial and sector-wide applications.

The effect of aircraft emissions on the environment is complex and not fully understood. In absolute terms, it is clear that aviation will have a significant effect on climate change, greater than that suggested by the industry's CO_2 emissions alone. Worldwide air passenger traffic is forecast to grow by 4 to 5% per annum. This growth needs to be met whilst minimizing its negative impact on the environment. Air travel in 2050 will need to look very different than that of today. For the mitigation of the negative environmental effects, the target for 2050 is to employ technologies and procedures for reducing a 75% the CO_2 emissions per passenger kilometre, and a 90% of the nitrogen oxide (NOx) emissions. To achieve such a goal, a large number of solutions and approaches must be utilized. As it is well known, the impact of increasing fuel prices is fostering an additional effort in the aircraft industry in order to reduce the weight of the airplanes and to improve the efficiency of the main engines and the auxiliary equipment as well. Despite the continuous improvement of turbofan and turboprop engines efficiency, the rapid growth of air travel in recent years contributes to an increase in total fuel consumption. In the European Union, greenhouse gas emissions from aviation increased by 87% between 1990 and 2006. Today, aviation contributes to approximately 2% of the total man made CO_2. There are various factors that contribute to the release of GHG form aviation including frequency of travel, type of fuel, aircraft design, among others.

When focusing on the environment, the main targets for the year 2020 as defined in **the Strategic Research Agenda (SRA) for aeronautics in Europe** –the SRA of the **Advisory Council for Aeronautics Research in Europe (ACARE)**, the EuropeanTechnology Platform for aeronautics- are the following:

- 50% reduction in CO_2 emissions per passenger kilometre (i.e. 50% reduction in fuel consumption in the new 2020 aircraft compared to 2000)
- 80% reduction in NOx emissions
- 50% reduction of perceived aircraft noise.

The project appears to be in line with the environmental targets of the SRA of ACARE. On the other hand, **the Clean SKY SGO initiative** aims to meet the increasing social demand to reduce fuel consumption, emissions and noise through the adoption ofa new approach when designing systems. More specifically, SGO environmental objective consists in the reduction of NOX and

CO_2 emissions (between a 5 and 9% of reduction) through an improved energy management and systems weight reduction.

While this project does not directly tackle all these issues, it is fully in line with the strategic objective of both the SRA of ACARE and the SGO initiatives, as it will firmly contribute to the reduction of emissions, contributing to the European Competitiveness. In fact, the project has acoomplished with the objective to develop a **new ram-air fan integrated in the ECS system, which has a high degree ofimportance to improve the energy efficiency of the system as a whole**. Two main aspects have been identified regarding **energy efficiency** of the fan. The first one refers to the improvement of the fan at low-speed conditions where fan surge has been eliminated. Any reduction of these instabilities would have a clear impact on the fan efficiency at those conditions. The advanced and detailed analysis of the fan fluid-dynamic and turbulence behaviour would also introduce efficiency improvements in the rest of flow conditions where the fan is expected to work. The second aspect to be addressed during the project that has an impact on energy efficiency of the fan is related with the thermal management of the corresponding electrical motor. Apart of assuring the thermal control at the high temperature conditions, the proposed improvement of the cooling process by the detailed study carried out can also reduce the motor core temperature, which has a direct impact on its energy efficiency. Publishedworks indicate an achievable improvement in efficiency of around 1.5% [Yoon et al., 2002]. The conclusions on this electric motor would have obviously an impact on the rest of electric motors that the all-electrical aircraft design integrates in the system.

In relation to the **environmental pollution**, as previously mentioned, the in-flight civil aircraft is estimated to contribute to global CO_2 emissions at around 2%. However, non-CO_2 contaminant effects may increase the total impact for high-altitude flights near or in the stratosphere. The Intergovernmental Panel on Climate Change (IPCC) has estimated that aircrafts are responsible for around 3.5% of climate change of anthropogenic origin (including both CO2 and non-CO2 effects). The IPCC estimates are that aviation’s contribution could grow from 5% to 15% of the total contribution by 2050 if action is not taken to reduce these emissions.

From a general CleanSky point of view, it is interesting to highlight that the fact that the main engines could work in a more stable manner in the all-electrical aircraft would probably derive in an optimisation of the combustion processes and thereforein the reduction of NOx and other contaminants emission levels. Considering previous statements, it is clear that any measure that can contribute to an improvement in the energy efficiency of the aircraft components would derive in a reduction in the CO_2 emissions level. Then, related specifically to current project, the ram-air fan integrated in the ECS system has an importance in order to improve the energy efficiency of the system as a whole. Two main aspects have been obtained regarding energy efficiency of the fan: i) the improvement of the performance by surge-condition mitigation; ii) the assess of motor performance byactual expected temperature conditions.

Apart from efficiency/emissions aspects, there is another important issue related to pollution that should be analysed: noise. The Clean SKY SGO initiative objective in terms of noise consists in its reduction between -2 to –5 dBA (in phase of approach/landing) and -2 to -3dB (in phase of take-off/climb). The project is in line with these objectives as the reduction/mitigation of the surge effect has an impact in this sense, as it permits avoiding conditions with higher pressure/velocity non-uniformities and less instability that generate noise. CFD work on the fan blades around surge problems is also detecting noise sources and developing ways intended for its reduction. The project contributes to the European transport policy which is in line with the Euro 2020 initiative in working towards “**resource efficient Europe**”. This is achieved by facilitating economic progress, enhancing competitiveness and offering highquality mobility while using resources more efficiently. The project has certainly enhanced European competitiveness and facilitate economic progress as the innovative **ram-air fan,developed in the project, has a high degree of importance to improve the energy efficiency of the system as a whole**. Europe is home to approximately 448 airlines and 701 commercial airports which in 2010 supported 606 million passengers allowing the free movement of people and goods across borders. The European Air Transport sector has an annual turnover of more than € 95 billion and employs over half a million people directly with another 2.6 million indirect jobs. Research and development helps develop Europe's competitive advantage - on average almost 7 billion euros are reinvested every year in civil aeronautics R&D. The European Vision for Aeronautics and Air Transport in 2020 set targets to facilitates needs of society, while maintaining European global leadership in aeronautics especially against the US market. Competition to provide the products and services to meet that growth is also intensifying. This competition comes not just from traditional rivals, such as the US, but increasingly from strong challengers from Brazil, Canada, China, India and Russia.

With the new **innovative ram-air fan developed** while improving the whole system energy efficiency and reducing CO2 emissions, the project can highly contribute to the RTD European targets for strengthening the European competitiveness in the Aeronautics sector. Therefore, the project's results will have an important number of **economic contributions** The synergies created during the project, and the obtained fan design, have an important economic potential impact as enhancing the competitiveness of the Topic Manager (having an electric ECS with a single ram-air fan to cover very different cooling necessities), and of fan manufacturer LMB (developed a ram-air fan with outstanding capabilities in terms of stabilityand high temperature operation).

Since ram air fan are not included in the ECS baseline configuration for large aircraft, the project results will have major impact on the regional aircraft market. Regional aviation plays a very important role in Air Transport System. Regional fleet (9000 aircraft) accounts for 37% of world fleet. About 42% of the total departures are to attribute to Regional air transport while about 26%of the total flown hours are to attribute to Regional air transport. Regional carriers typically operate aircraft, such as regional jets and turboprops, with fewer than 120 seats, on short to medium-haul routes. Regional airlines mission is focused on operate aircraft to provide passenger air service to places/cities/communities without sufficient demand to attract mainline service. The regional aircraft market continues to be a key growth sector of the airline industry. Taking into consideration traffic developed by regional aircraft (capacity ranging in the 30-120 seat segment), in the last year more than 660000 million ASK (Available Seat Kilometre) were offered worldwide. Only in Europe regional carriers were able to offer more than 120000 million ASK to passengers interested short-time intra-continental connections with average distance of 320NM (about 600 km). Slight less than 200mln people in the last year flew on regional aircraft within European network. Regional traffic is expected to triplicate in the next 20 years. It is forecasted about 9300 new regional aircraft (both turboprop and jet) will be delivered worldwide in the next 20 years for a value of about €280 Billion (EC 2012), avg. €14Billions per year. Therefore, with a turnover of 110 billion euro, the European Regional Aviation market offer a huge potential for the strategic impact and market up-take of the project results.

In addition, this project has a great potential in extending the conclusions or improvements achieved in the design of aircraft fans to other applications where fans are being used. It is clear that this equipment is broadly used in a great quantity of applications: ventilation, air-conditioning, refrigeration, process industry, automotive industry, etc. It is expected that know-how generated under the severe and exigent conditions found in aircraft operation could be implemented in other applications. For instance, the reduction of surge problems and related noise will be for sure crucial in low-noise applications such as domestic air-conditioning using variable speed fans. On the other hand, any improvement in the design of the cooling system of the electrical motor would have an impact not only in the fan industry, but also to a much wider market as electrical motors are used in many other applications (electric vehicles, pumps, industrial machines, automation equipment, etc.).

Finally, the project will have significant secondary impacts through positive interactions with other programmes of work within the areas of aeronautics. Due to the initial partners' situation, the project extension and the extended deadlines, it has not beenpossible to have results until the end.At current stage, when we have finally a successful fan design and simulation tools, the partners will be able it to establish relationsand synergies outside of project consortium. In a similar way, different proposals of conferences, papers and fairs are expected in the next few months after the end of the project.

Dissemination and exploitation of the results

The dissemination of the results of the project is an important action once the intellectual property has been protected, in order to reach the widest possible impact to facilitate the take-up of the new technology. Dissemination has tried to be promoted at all levels, in order to spread, in accordance with IPR restrictions, the main innovative aspects which evolve during the development of the project. However, and due to all problems carried out (Baltogarbankrupty, the different extended period of time needed, and the impossibility to have some results to be disseminated until the end of the project with the prototype tested), has not allowed to have a lot of dissemination activities and only one conference paper from UPC and TF has been developed during this period and mainly focused on numerical aspects.

A **Dissemination Plan** has been developed. The purpose of the Dissemination Plan was to provide a formal planning document for using and disseminating knowledge throughout the project. The plan has tried to facilitate the common understanding of the aims of the dissemination activities, and assure the dissemination does not interfere with the IPR management but serve it.However, as it has been explained dissemination purposes has been postponed until now, where different conferences, papers and fairs are planned for the next few months.

The **website** has been created at the beginning of the project. In fact, it is assumed that the results will not only be interesting to the scientific community but also to a great number of SMEs and public aeronautic actors. The dedicated website has not produced an extensive record of all publications and communications originated on the course of the project due to the problems explained above. However,.a public area containing general information on the project, useful links tothe EC services, etc., has been continuously updated with the public results obtained, deliverables, news for communication of events. No workshops and conferences related to the project have been possible, although contacts to allow the website visitors to have a direct link to the Consortium has been available.

On a scientific level, the dissemination activities are now ready to be carried out through publications in specialized journal of aeronautics/aerospace and thermal engineering related journals – for example, *AIAA Journal, Computer&Fluids, Journal ofFluid Mechanics, ASME Journal of Turbomachinery, IEEE Transactions on Industrial Electronics, IEEE Transactions on EnergyConversion, Applied Thermal Engineering, Heat Transfer Engineering,* etc.

The project will address only publications that reach a wide spectrum both of the scientific and technical community. The results of the project are now ready to be presented at different events (workshops, technical conferences, fairs and exhibitions) organized by the consortium and in other potentially interesting events that could be planned by interested organizations. In particular, the consortium has already planned to attend and present partial project **results to the following events**:*Aerodays, Paris AirShow, Toulouse Air Show, including IEEE Aerospace Conference, Farnborough International Air Show, etc.*

On a second level, wider dissemination will be achieved via a more general strategy for attaining a broad coverage of the project to a wide range of European aeronautic public and private actors. This strategy includes the following activities:
- The diffusion of knowledge in cooperation with European organisations, such as the **Advisory Council for AeronauticsResearch in Europe (ACARE)**, the European Technology Platform for aeronautics and the **Aerospace and DefenceIndustry Association for Europe** (ASD Europe**).** Through the websites and annual meetings of these organizations, the present project can have

a direct link with their related scientific community, public aeronautics actors, industry, and affiliations. In general, any useful contacts and coordination/networking with national programs, industrial associations and related consortia within and outside Europe will be pursued in the aeronautics sector.
- **Direct mail to targeted organisations and groups**, based on target groups selected from relevant organizations for the use and spreading of the research results, as the existing aeronautic clusters.

Exploitation of the project results will be conducted by identification and protection of generated IPR, market needs assessment and communication with the stakeholders. In this case, each one of the partners in the consortium has made a significant effort in order to define as detailed as possible their exploitation interests and possibilities. For the results obtained, ownership, protection and use will be considered in detail. So, the basic IPR framework agreed by the partners considers: i) a final ram fan air prototype to be exploited by LMB and an updated numerical simulation tool for aerodynamic analysis to be exploited by TF. The numerical analysis tool for the thermal management is also exploitable opportunity for UPC:

At this point and with the exploitation opportunities of the project results finished, the partners are ready to analyse and validate the primary and secondary market potential, and structure a market penetration &development plan accordingly. Cooperation with regulatory bodies and third party sales and distribution licensees in the aeronautics markets can also used. This process has already begun through the concept development and pre-project market validation work carried out by the consortium within its existing customer bases. The final “Plan for the use and dissemination of the foreground” has been prepared in the last trimester of the project not including patent applications due to patents are not necessary, but with considering the use of the results considering:

- The knowledge in the field of aeronautics;
- Evaluation of possible industrial outcome for the research results obtained during this project;
- Estimation of the economic impact of the technologies and processes developed under the project;
- Observation of market trends and positioning of project results;
- Market analysis (actual market needs and size in Europe).

WEBSITE

www.effan.eu

Home page: