ELUBSYS

Final Reporting (1 June 2009 to 30 November 2012)

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ABSTRACT	This final report comprises three separate parts: a final publishable summary report covering results, conclusions and socio-economic impact of the project, a plan for use and dissemination of foreground and a report covering the wider societal implications of the project. It also includes the final report on the distribution of the European Union financial distribution
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Abbreviations Used in this Document

Abbreviation / acronym	**Description**
AN	Acid Number
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
DPM	Discrete Phase Model
DSC	Differential Scanning Calorimetry
FEM	Finite Element Model
FTIR	Infrared Spectroscopy
GA	Genetic Algorithms
LSIS	Lubricant System Interaction
MPI	Message Passing Interface
NIR	Near Infrared sensor
ODE	Ordinary Differential Equation
OPD	Optical Particle Detector
QCM	Quartz Micro Balance
REB	Rolling Element Bearings
RF	Radio Frequency
SFC	Specific Fuel Consumption
SPH	Smooth Particle Hydrodynamics
TBH	Tail Bearing Housing
VOF	Volume of Fluids

1. Final Publishable Summary Report

Executive summary

The overall objective of project ELUBSYS is to research, develop and validate a new architectural approach towards the design of high performance aircraft lubrication systems with the aim of reducing fuel and oil consumption by focusing on four key goals:

1. Reduce the air bleed with high performance seals and improve thermal management of housings.
2. Reduce the oil quantity rejected overboard by 60%.
3. Reduce mass of lubrication system.
4. Improve the oil quality monitoring.

During the project, work and main results achieved are:

Three types of brush seals (Kevlar, carbon, metallic) for sealing a bearing chamber were tested. Considerable reduction (75-95%) in air consumption is achieved compared to labyrinth seals. On the endurance side the lubrication of the seals is crucial. They also confirm performance results of MTU.

In order to better understand and model the complex two-phase flows in bearing chambers, scavenge and vent ports, and adjacent pipes.

Experiments on scavenge and vent port performance have been conducted on a generic rig for several geometries and boundary conditions such as air and oil flows. Detailed measurements of air and oil flows, film thickness, and pressures in the ports and adjacent pipe work have been performed.

Physical models for CFD predictions such as Volume of Fluids (VOF) and wall film models and a more advanced approach called Smoothed Particles Hydrodynamics (SPH) have been applied to simulate the complex two-phase flow to account for the high proportion of oil.

Experimental and numerical work on heat generation in bearings under normal operating and no lubrication conditions have been studied.

The models developed have been validated by the rig tests. A set of design rules and guidelines has been derived to enable design of better lubrication systems to handle the new challenges of modern gas turbine engines.

Testing has been performed In order to optimize the supply system components. Main conclusions are, clear influence of the piping and Flow Velocity on pump performance and oil gas content.

Design and testing of multi-inlet and ejector scavenge pump have been performed. Some working limitations on the bearing chamber pressure have been discovered that require future research work.

Oil Quality and Coking

Artificial ageing and chemical characterization of oil were performed. RULER, FTIR, and AN revealed to be the most representative analytical tools.

Development of following oil health sensors was made: OPD (Optical Particle Detector), NIR (Near Infrared sensor) water content and magnetostrictive viscosity sensors, QCM sensors. OPD and NIR went through validation tests in hostile environment. The robustness of the sensors was observed up to 15 bars and 150°C.

At this end of the project, results from the overall innovations in Elubsys could yield a reduction of: 60 % in Oil Consumption and 90 % in air consumption. These results for the ELUBSYS project will support the needs of future engine generations.

Summary description of project context and objectives

In aeronautics, gas turbine engines need the assistance of systems that have to guarantee performance throughout the whole flight envelope of the aircrafts for which they are designed. One of these systems is the lubrication system and its role is twofold: firstly to remove the heat generated in the highly loaded rolling bearings and the gears found in the power and accessory gearboxes via heat exchangers; secondly to lubricate these parts.

The current trend of developing aircraft turbine engines that consume less fuel increases the cooling requirements from the lubrication systems due to higher speeds, loads and temperatures in engines as well as the integration of high-power gearboxes (allowing high by-pass ratio) and high-power starter-generators. For manufacturers there is significant pressure for developing new lubrication system architectures that are able to meet the new cooling and lubricating requirements without negatively impacting the mass of the systems or the operational and maintenance costs of engines.

Current lubrication systems in turbine engines are based on architectures and technologies that have not significantly evolved over the last thirty years. Despite improvements and advances made on components of these systems, the technological limit is being reached. In other words, new technologies are required to face the challenge of the future engine requirements (higher cooling, higher thermal efficiency, lower Specific Fuel Consumption (SFC) impact, unchanged high-level of reliability, improved mass).

The overall objective of project ELUBSYS is to research, develop and validate a new architectural approach towards the design of high performance aircraft lubrication systems with the aim of reducing fuel and oil consumption. The project intends to reach this objective by focusing on four key goals:

1. Reduce engine SFC and the CO2 emissions by:

- Significantly reducing (target of 60%) the requirement for bleed air from the engine to pressurise the bearing chambers through introduction of new high performance seals;

- Improving thermal management of housings (and ports) by adapting these to the presence of high performance seals.

2. Reduce the oil quantity rejected overboard by 60%, thus reducing both, the consumption of oil which is a non-renewable energy, and the associated atmospheric pollution (currently 0.3 l/h average oil consumption per engine for a short-haul or a long-haul aircraft), through introduction of high performance brush seals and improvement of the supply pump capability.

3. Optimise the architecture of lubrication systems (taking into account the introduction of high performance brush seals) by reducing their complexity and mass. This will be done by integrating several lubrication functions into one single component and by re-designing other external components.

4. Develop solutions to improve the monitoring of engine oil quality with a particular focus on the anti-coking capabilities of the lubrication system. This will allow higher oil temperatures to be sustained for longer periods of time, and contribute towards higher allowable engine turbine inlet temperatures.

ELUBSYS organised its activities around four technical work packages (WP):

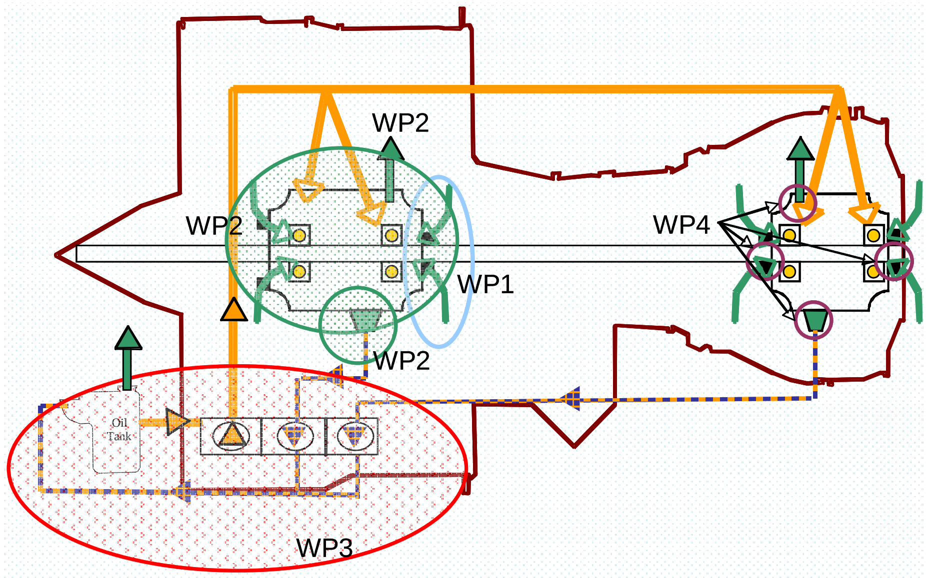
WP1: Advanced Brush Seals for Bearing Chambers

WP2: Bearing Chamber Flow and Heat Transfer

WP3: Externals

WP4: Oil and Coking

As shown in the diagram below representing a simplified schematic view of a lubrication system, the research that will take place in each WP is targeted at one particular area of the system. Seen as a whole, the project will address all of the key elements of a typical lubrication system.



WP1 – Advanced Brush Seals for Bearing Chambers

Work package 1 addresses the sealing element of bearing chambers

The objectives can be summarized as follow:

- Investigate the performance and reliability of advanced brush seals for bearing chamber sealing
- Study the two-phase flow behaviour, heat transfer and pressure loss in the scavenge pipe when brush seals are used and the vent pipes removed using CFD analysis.
- Investigate the effect on bearing chamber thermal behaviour of the reduced air flow anticipated through brush seals compared to labyrinth using CFD analysis and optimise the bearing chamber thermal design.

WP2 – Bearing Chamber Flow and Heat Transfer

Work package 2 deals with improved understanding and modelling the complex two-phase flows in bearing chambers, scavenge and vent ports, and adjacent pipes. It intends to establish CFD capability for realistic geometries typical for lubrication systems in gas turbines and produce new design rules which will enable lubrication systems that are better adapted to handle the new challenges of modern gas turbine engines. These engines run at higher operating temperatures and shaft speeds leading to higher thermal loads within bearing chambers and risk of overheating the oil.

The objectives can be summarised as follows:

- Improve scavenge and vent port performance
- Develop and optimise CFD modelling strategy for two-phase flows in bearing chambers
- Improve understanding of heat transfer in bearing chamber walls
- Predict heat transfer in bearings during oil flow interruption

The expected results will allow both, a more detailed understanding of flow and heat transfer phenomena and two-phase flow prediction capability. Correlations will be developed based on test results and CFD predictions to support the engine design process.

The derived design guidelines for chamber ports are expected to support the engine design process to account for advanced technologies such as contra-rotating shafts for improved turbine performance, less fuel burn and green house gases.

WP3 – Externals

Externals mean here “elements of the oil system out of bearing chambers”. This includes supply and scavenge systems and all the related components.

With the trend in aero-engine development towards higher power, higher speeds and a more electrical engine, the adequate global cooling of the bearings and electrical equipments has become an element of key importance. The introduction of innovative and advanced seals (WP1) and the new understanding of heat management (WP2) will lead to an optimisation of the supply oil flow for different engine speeds and for different bearing types. The advanced sealing behaviour may drastically change the scavenging system and elements by changing the proportion of mixed air in the oil. As a result, the design rules for external elements such as pumps, injectors and manifolds will need to be redefined with respect to the current aero-engine technological way forward.

The purpose of WP3 is therefore to concentrate activities on the externals parts of the lubrication system, i.e. all the elements in which the oil flows through: pipes and equipment responsible for delivering, extracting, cooling, de-aerating the oil of the bearing chambers.

The objectives can be summarized as follow:

- Design Rules for Lubrication Equipment considering the effect of effect of advanced sealing architecture from WP1 and heat management data from WP2
- Supply Oil Pump performance optimization.
- Scavenge System and Vents Components Simplification. Testing prototypes of multi inlet scavenge pumps and ejector pumps with objectives to reduce the mass of the system.

WP4 – Oil Quality and Coking

The trend towards hotter engines and lower oil consumption highlights the importance of efficient tools for the prediction and detection of oil quality.

Optimised heat management that will be developed in WP2, in combination with determination of oil ageing under different conditions (temperature, oil mist, oil films…) will allow predicting oil behaviour into the engine, which will be taken into account in the design of bearing sumps.

Heat management will also be used to identify regions of the sumps prone to coking (low oils flows, high temperatures). Formation of oil coking may also occur under specific conditions, for example after engine shut-down (thermal soak-back from hot parts of the engine). Specific work will therefore be performed on “in-situ” detection of oil degradation in the engine (first step before coking) and coking itself.

The objectives can be summarized as follow:

- Develop and validate numerical methods of characterising and predicting oil ageing and degradation in complex aero-transmission systems.
- Develop a method and a device to monitor oil health in the engine.
- Develop an anti-coking coating.

Description of the main S&T results / foregrounds

WP1 – Advanced Brush Seals for Bearing Chambers (MTU, RR-UK, SN, ITP, ULB, FIT, UNOTT)

A. Performance & ReliabilityTesting on brush seals at MTU & Snecma:

At MTU the rig was modified to be capable of conducting testing of brush seals, investigations of two phase flows in scavenge pipes and also testing of an ejector as a substitute for a scavenge pump (see figure below).

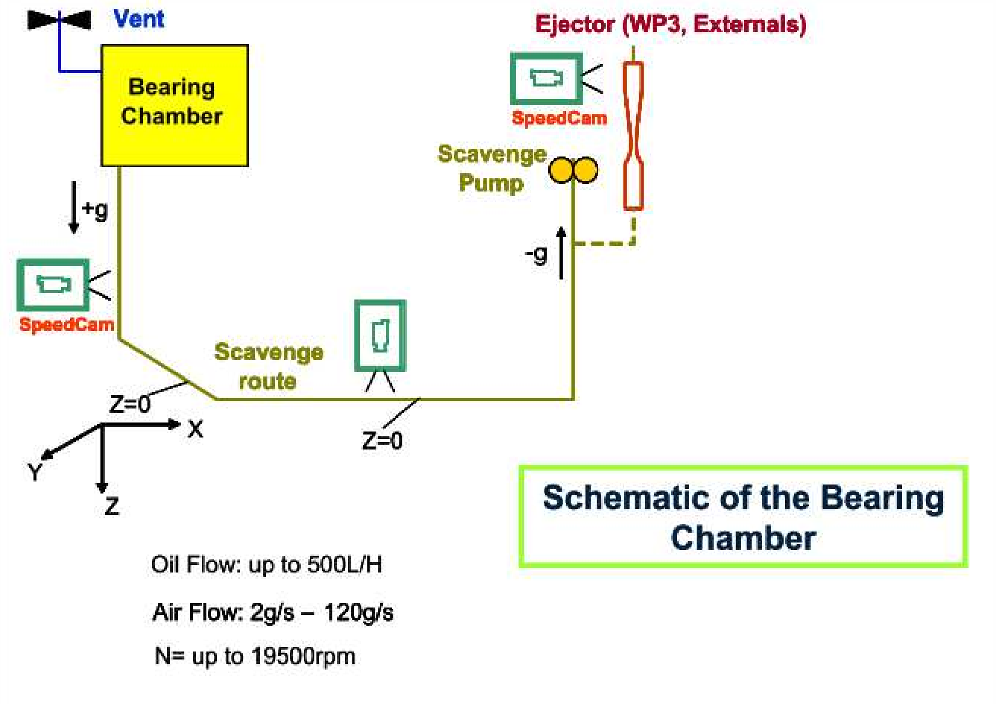


Fig. 1 The schematic of the test facility

Two brush seal types were used for the testing a) with bristles made of Kevlar and b) with bristles made of steel. The targets of the testing were to transiently record the thermal interaction between the seals and the rotor, to measure the air flow rate through the seals.

The conclusions of the testing were the following:

1) Brush seals of metallic, Kevlar and of carbon fiber's type can be used for sealing bearing chambers. They can be installed with an overlap of up to 0.2mm to the rotating part without concerns for elevated heat production in the contact area

2) Kevlar and carbon fiber type brush seals are much tighter than metallic brush seals. Compared to the traditional three fin labyrinth seal, brush seals can reduce the sealing air consumption up to 97%

3) Kevlar and carbon fiber type seals should be preferred only if the sealing air temperature is below 250°C, so that thermal degradation of Kevlar is avoided

4) The minimum delta pressure across the seal should be greater than 1kPa in order to avoid lubricant migration to the ambient

5) Through the reduction in sealing air consumption the omission of the bearing chamber vent pipe is possible

While MTU selected metallic and Kevlar brush seals, Snecma opted for carbon brush seals.

The main objectives of the testing were to investigate the endurance of the seals. Performances were also measured. Snecma rig used for this endurance test is normally used to test a bearing chamber under different conditions. In order to make this rig functioning, the rig has been installed in a test bench, fitted with all the devices necessary Motor drive, Oil supply system, Oil scavenge system, Vent system with de-oiler capability (in order not to give off oil fumes outside) .

The bearing chamber was sealed by a brush seal upstream the bearing#1 (see figure below).

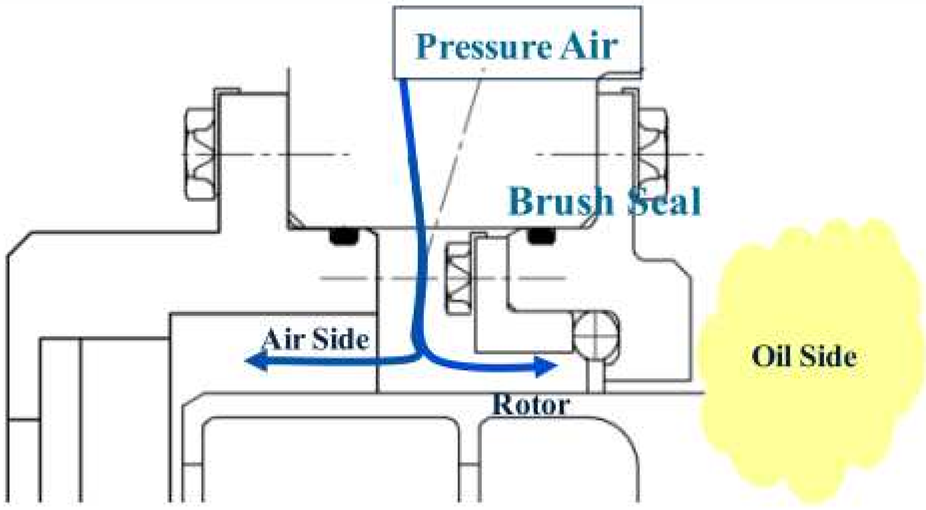


Fig. 2: close view of the carbon brush seal location

The main conclusions of the testing were the following:

Carbon brush seal performances have been evaluated. Compared to classic labyrinth seals, a 60% air flow reduction has been achieved. This gain, while participating to the global performance of the engine, will mainly permit to reduce the oil consumption (by reducing the amount of air to be treated by de-oilers).

Although the number of endurance tests that was planned was not achieved, it has been confirmed that a good lubrication of the seal was crucial to reduce the wear. It has also been demonstrated that a "controlled" lubrication of the seal was necessary in order to avoid oil oxidation in the seal, as well as coking after engine shut-down (soak-back conditions).

B. CFD Study of the aerodynamic characteristics in the brush seals tip region (ULB)

A CFD model and a FE model of a brush seal have been implemented with the aim of evaluating the contact forces between the shaft or contact disk surface and the bristles tip. The CFD model has been successfully validated with experimental and numerical results found in the literature. The results of the FE model are encouraging compared with manufacturers' data but the model still does not allow the usage of periodic boundary conditions if friction is included in the numerical simulations.

Further Work:
The two models (a CFD and a FEA) needs to be combined, by importing the loads (pressure and thermal) on the bristles calculated with the CFD model (see section 2.1) into the FEA model. The contact forces between the shaft surface and the bristles tip will then be calculated for various pressure ratio's across the seal pack. A parametric study (including the geometry and materials aspects) could ultimately be conducted.

C. CFD Results for the scavenge pipe (FIT)

Scope of the current work is to utilize an industrial –state of the art- CFD package for analyzing the three dimensional (3D) flow and the corresponding heat transfer of the air-oil mixture in the scavenge pipe. More specific, we are interested in:

- Developing a CFD model which approximates the kinematics of the air and oil in a complex real aero engine lubrication pipework. The pipework has an approximate length of 4.5 m and is a combination of straight, vertical and inclined segments with bends, expansion & contraction singularities. The major challenge is to identify the different flow patterns (annular, stratified, slug) at different pipework locations using a unified CFD model.
- Identifying recirculation and high pressure drop zones that may cause a pressure reversal. The final aim is to improve the design of the particular geometry in order to minimize pressure losses.
- Identifying hot spots in the pipework which in combination with stagnant or slow motion of oil may cause deposit formation. The final aim is to improve the design of the particular geometry in order to reduce the potential for oil coking.
- Understanding the limitations of current multiphase formulations.
- Developing design guidelines.

For the first time, a complete pipework (not a single part) including all flow resistance elements (contractions, enlargements, bows etc.) was modeled and simulated for two phase flow. The simulation has matched the experimental results with high fidelity (see figure below).

Fig. 3: Three dimensional model of a scavenge pipe

D. Tail Bearing Housing (TBH) Thermomechanical model (ITP)

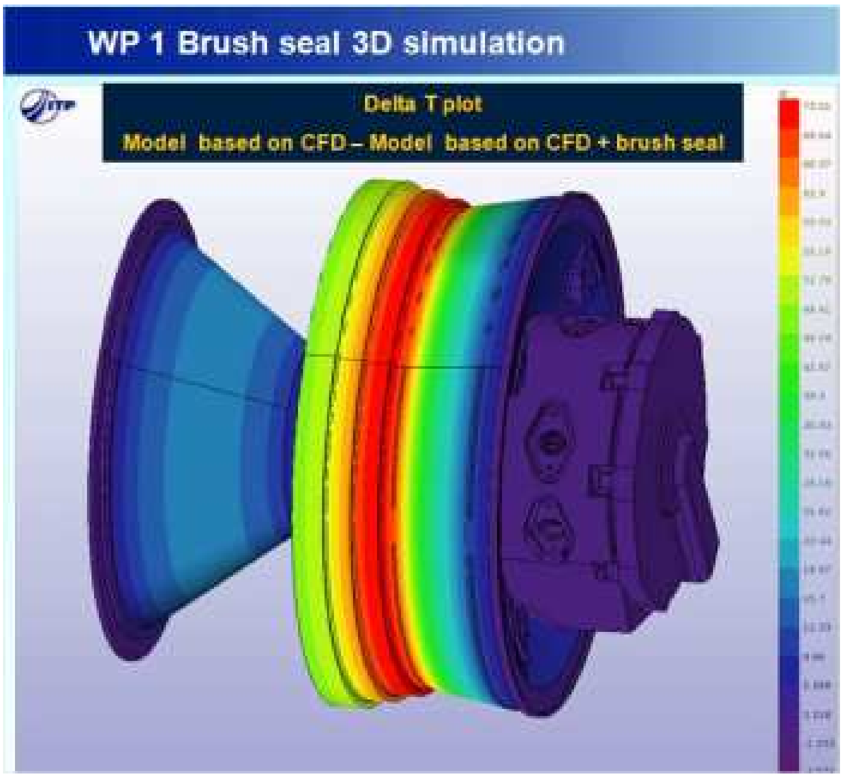
ITP work was focused on the bearing chamber design optimisation. For this case study, a real state of the art engine bearing chamber was used. A thermal 3D FEM model was generated taking on board 2-phase CFD analysis performed by RRUK and UNOTT in terms of oil flow distribution.

Nowadays, for most designs, 2D thermo-mechanical axisymmetric models are performed; bearing chambers are clearly non-axisymmetric components so the 3D model helps to identify the potential deviations or 3D effects that are not captured by the 2D.

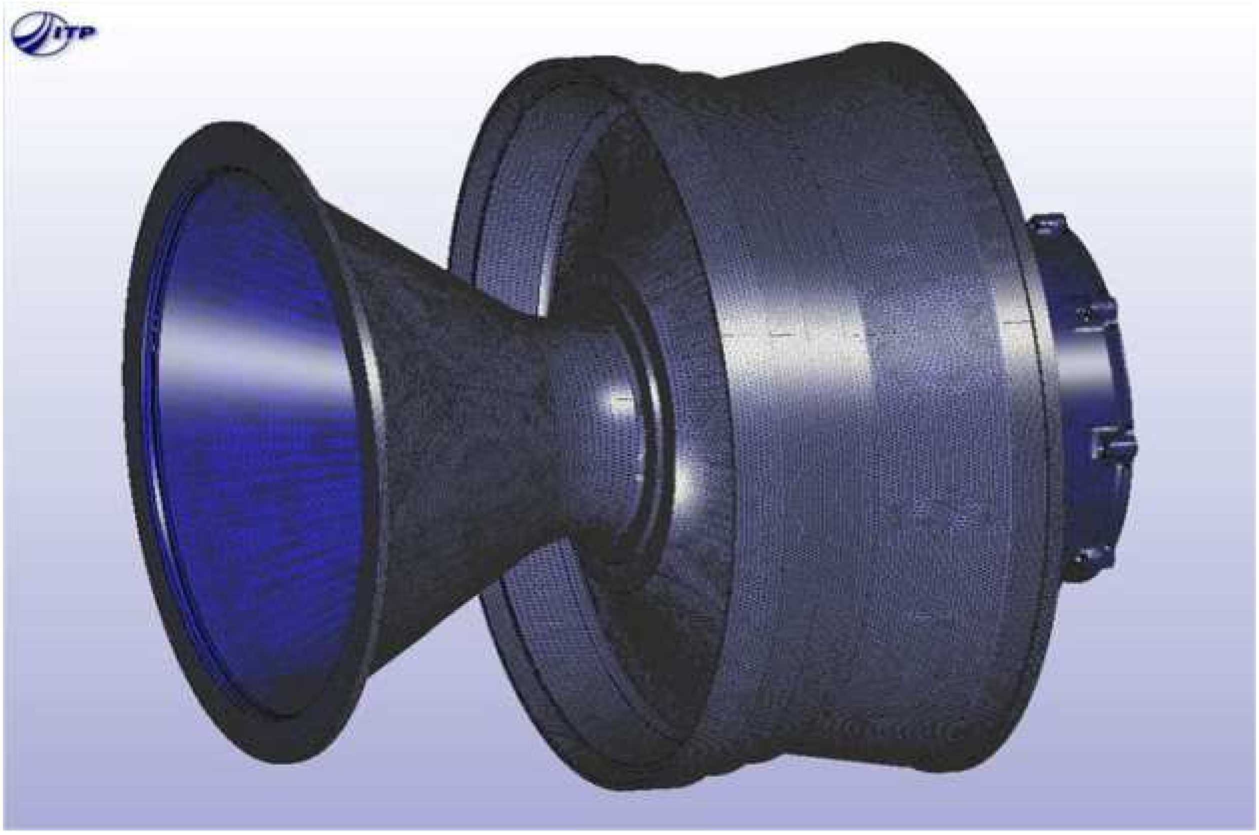
Initially, the 3D model had the same boundary conditions than 2D model has at the moment. The first simulation showed the differences between 2D and 3D model due to the 3D geometry features. This first modelling phase, tried to show the current thermal prediction capacity.

After this first simulation, the next step was the introduction of inputs coming from CFD. The output was a model where there was a good representation of 3D features and also good oil and air distribution, that is, the model showed the current thermal behaviour of the bearing chamber. In order to validate this 3D simulation, the model was checked against steady state thermocouples test data.

An important point of ELUBSYS project, as well for ITP analyses, was the brush seal, so ITP contributes to investigate the effect on bearing chamber thermal behaviour of the use of advanced brush seals. ITP performed thermal runs at 2D and 3D models to assess the impact in temperature since the benefit in terms of SFC is clear because the sealing air reduction.



The numerical (CFD) code developed in Work Package 2 by UNOTT and RRUK for modelling bearing chambers with wall films presence was applied to the MTU bearing chamber housing for code verification. A numerical (CFD) simulation of a real engine tail bearing housing (TBH) was then carried out with the verified code as a case study. Due to size, time consuming and computational time the CFD has run only steady state cases. For the same reason, air baffle was included only for the rotating labyrinth seal configuration. Rotating option was selected since it will be the production configuration.



Conclusions:

- The new oil distribution prediction shows important differences when compared with the current oil distribution assumption. The CFD oil distribution shows that the majority of the oil is concentrated at certain regions, whereas the current model assumption assumes a uniform oil distribution. This information is even more relevant for transient analysis; the thermal response will be different with the new CFD prediction, which is quite relevant from the component stress perspective. The CFD model also covers the air baffle area. In the same manner as in the bearing hub area, the air distribution from CFD is different from the current assumption. It is not relevant for bearing hub cavity since it is insulated by a thermal blanket but it has a notorious impact in components that are linked to the bearing hub. Again, the transient thermal response will be different with consequent stress potential impact.
- Model based on CFD output is more accurate than the one performed based on previous experience.
- Temperature field based on CFD shows temperature differences on areas where there is no instrumentation → mechanical behaviour could be different.
- 3D model based on CFD captures a circumferential behaviour similar to the one of the standard model. No improvement has been achieved in this field.
- Additional engine test (heavy instrumented) is necessary to validate this new set of boundary conditions based on CFD. The transient simulation becomes relevant due to the new oil distribution prediction.
- The new metal temperature field due to brush seal is higher than the current temperature field. The benefit in SFC is clear, but as in the previous cases, stress assessment is required to evaluate the real impact → higher temperature is a driver for new stress distribution and it also must be taken into account in the material selection process.

Guidelines:

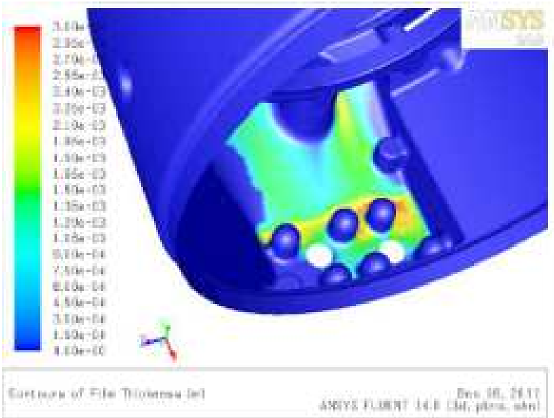
Thermal and mechanical assessment of the bearing chamber structure should be based on the oil distribution in its inside. This assessment should be done in the early phase of the design so that selection of seal types is done in a way that benefits (like SFC improvement) and disadvantages (like thermomechanical problems) are balanced.

E. Real Engine TBH (KIT) Bearing Housing Simulation Results (RRUK, UNOTT)

Work Package 1 (WP1) is specifically aimed at investigating the impact of advanced seal technology on bearing chamber thermal behaviour. Here are presented results from two case studies which apply new modelling techniques developed in WP2. The first test case is an experimental rig model produced by Nottingham UTC for validation. The second test case, is a real engine Tail Bearing Housing (TBH) model produced by RRUK.

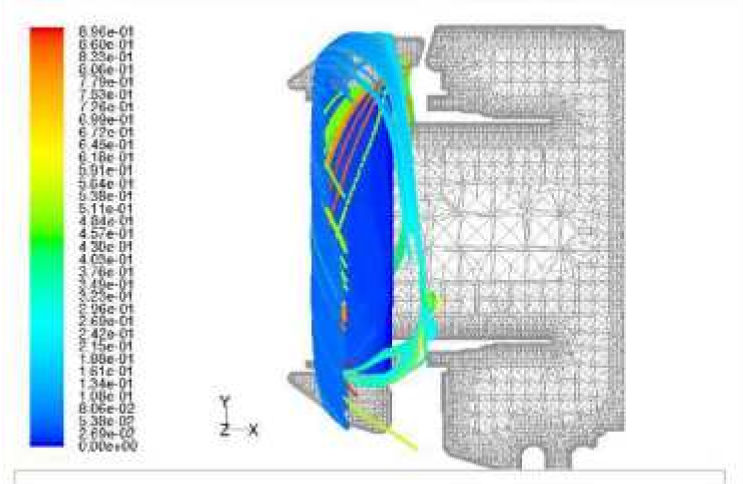
The smaller-section KIT bearing chamber model has been used to investigate the influence of sealing air flow on the chamber air flow structure in the absence of oil. Comparison with experimental data has shown that although good agreement was obtained for a sealing dominated flow field, the level of agreement reduces as the sealing air flow is reduced. It should be noted that discrepancies also seem to exist between experiments measuring air only chamber flows and air-oil flows which leaves uncertainty about the true nature of the flow field in the rotationally-driven flow regime. The reliability of the CFD air model has therefore not been confirmed for this flow regime and further investigation is required.

Both case studies have exhibited a gravity dominated oil flow behaviour on the chamber outer wall. The models suggest that the influence of air shear, even at high shaft speeds, is not sufficient to establish a continuous circumferential wall film in the chambers considered. The air shear does influence the axial distribution of oil in the chamber and varying the air seal flow could lead to significant changes in the axial oil flow distribution. This is one consideration one should remember as tighter seals, such as brush seals, are introduced in this type of chamber. Whilst leading to medium to low shear on the outer walls, some of the flow structures computed in the work have also led to the prediction of high azimuthal shear components which have been found to drive the oil along an annular path on the bearing side wall, in particular in windage dominated situations.



Contour Plots of film thickness

Modelling of the oil flow from the bearing has proved difficult and there remains a large uncertainty in both case studies, not least because it is unclear in which form the oil might be leaving the bearing but also because of the uncertainty in the driving air flow structures in the simple KIT chamber. Future research in the area of oil shedding from bearings is required to build on the CFD modelling capability presented in this report.



Droplets Trajectories in front chamber

WP2 Experimental investigation of scavenge and vent ports (RRD, RR-UK, SN, TM, ULB, INSA, KIT, UNOTT, IPB)

In WP2, experiments on scavenge and vent port performance have been conducted on a generic rig at KIT for several geometries and boundary conditions such as air and oil flows. To investigate different geometries, the rig allows quick change of outlet ports via inserts providing high flexibility. Good access for measurement equipment allows detailed measurements of air and oil flows, film thickness, and pressures in the ports and adjacent pipe work. The database obtained from the experiments has been used for comparison with the CFD predictions.

The experiments increased the knowledge about the two-phase flows in aero-engine bearing chambers. They also generated an extensive set of data, which is valuable for an improved understanding and for a validation of improved CFD methods.

The effect of several offtake designs and of the bearing chamber dimensions on the scavenge efficiency and on the film thickness distribution was determined. Furthermore, design proposals could be provided in order to increase the scavenge efficiency.

During the experiments, two distinct flow regimes could be detected in a bearing chamber. Although it is not yet clear which flow regime is desirable, the experiments showed how a certain regime can be generated. The regime change depends on bearing chamber size, rotational speed and offtake design. Furthermore, the pressure loss in scavenge pipes was studied and found to be within known correlations.

In general, the investigations that were performed within the project Elubsys increased the fundamental understanding of the relevant parameters of the bearing chamber flows.

Modelling of bearing chambers

Physical models for CFD predictions such as Volume of Fluids (VOF) and wall film models and a more advanced approach called Smoothed Particles Hydrodynamics (SPH) have been applied to simulate the complex two-phase flow to account for the high proportion of oil (up to 80% by volume). Transient flow phenomena and heat transfer have been considered.

A wall film model was developed and implemented into a CFD code. The equations describing the film flow were derived by depth-integration of the continuity, momentum (Navier-Stokes) and energy equations.

First, the film model was successfully tested as a separate module designed to solve film flows in cylindrical geometries, i.e. rimming flow situations. This served as test ground for the CFD model but also to determine a suitable formulation and solution strategy.

Second, the model was implemented into the CFD code. A number of integration and numerical aspects had to be solved. The implemented model is clearly capable and on target but the numerical solution becomes more difficult as the shaft speed, and therefore air shear applied, is low, in particular in light of the relative volume of oil on which gravity is acting. Additional (force) terms become important, as does an efficient numerical procedure.

Finally, the code was applied to the rig chamber to test the model on a representative bearing chamber geometry. Predicted film thicknesses for different operating conditions compare reasonably with experimental observations. The code was successfully applied on an engine representative bearing housing.

A number of issues remain with the model. Prediction of bearing chambers has been found more difficult than anticipated due to the long simulation times, a combination of the transient procedure required to date, sensitivity to the mesh as well as the nature of the flow and the boundary and initial conditions.

Numerical investigations were also performed to evaluate the CFD Volume of Fluid method for the numerical modelling of an aero engine bearing chamber. For this purpose, a numerical model of the simplified bearing chamber test rig was set-up. The model construction included the modelling of two scavenge off-take geometries to investigate the influence of geometry variation.

To evaluate the method, test cases at two different shaft speeds were simulated. Model modifications, such as the description of wall adhesion and different corrections for shear driven liquid wall films, were also applied to investigate their influence on the oil distribution within the bearing chamber. Previous experiments at the simplified bearing chamber test rig provided the validation data for the numerical results of this investigation.

Promising results could be gained with the simulation of the test cases. All test cases yielded scavenge efficiencies near the experimentally determined data. Especially the influence of the geometry variation of the scavenge off-take was reflected properly. The quality of the calculated oil distribution and the film height at the chamber wall is significantly affected by the mesh resolution at the interface. The experimentally determined tendencies of the oil film distribution were calculated approximately right with the Volume of Fluid method, especially at higher shaft speeds.

Heat transfer validation has been established on academic cases representing an oil jet impinging on a flat surface.

In addition, the Smoothed Particles Hydrodynamics (SPH) approach has been studied. It is regarded as a potential future alternative to known CFD methods as it requires no mesh and is dedicated to liquid atomization. SPH method has been improved towards application in two-phase flows and assessment of computational effort. Initial predictions have been completed to simulate rig test results obtained within this WP. However, more work has to be spent to improve computational speed.

Regarding all modelling approaches, potential next steps include the further assessment and potential improvements of available methods and sub-models, validation of test data in more depth, and increased performance of tools to achieve convergent solutions within acceptable time scales.

<u>Oil flow interruption</u>

Experimental and numerical work on heat generation in bearings under normal operating and no lubrication conditions have been studied. This relates to CS-E680 regulation that dictates the need for aerospace bearings to remain reliable in the absence of lubrication for small periods of time during negative acceleration.

The predictability of thermal behaviour in bearings under no lubrication was improved based on rig test data. A set of design rules and guidelines has been derived for building bearings that are better designed under minimum cooling conditions.

WP3: Externals (TA, MTU,   SN, WSK, ULB, CENAERO)

A. Supply System Components Optimisation :

The ULB/TA objectives were to perform testing campaigns on ULB lubrication test bench. Focus on the influence of the supply circuit. Study the air content in oil and its influence. Identify parameters in the supply system susceptible to influence the oil pump (Gerotor) performance.

Two tests campaigns were performed:

- For the first test campaign, series of pump performance measurements were established for different supply circuits (short, long, flexible, rigid, with different roughness, presence of valves, etc.). In order to survey the air content, a sight glass was installed at the pump inlet with a new CCD camera to observe the gas bubbles population.

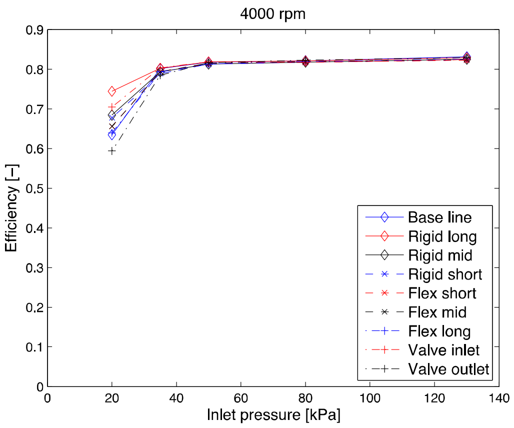
  Two types of working conditions:

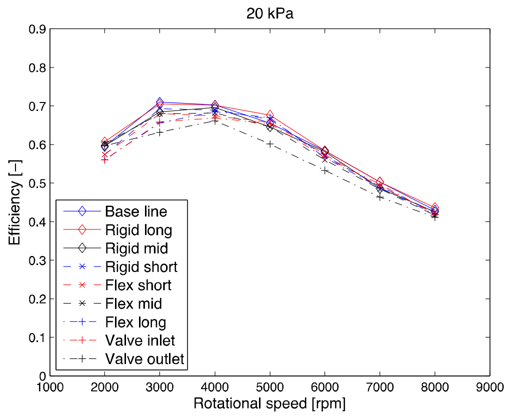
  1. Leak zone: at high inlet pressure or low rotational speed.

     Good efficiency: 80-90%

  2. Cavitation zone: at low inlet pressure and high rotational speed

     Rapid decrease in efficiency: 60% or less. Influence of the supply circuit in cavitation zone.

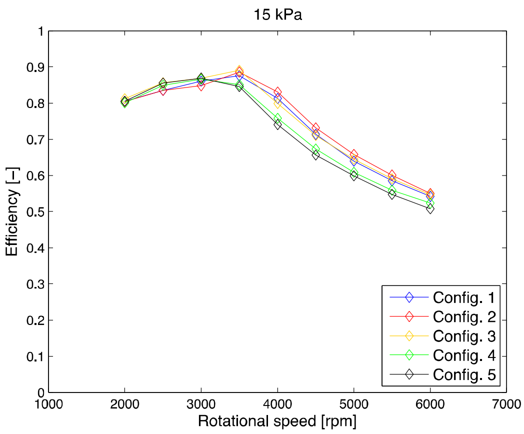


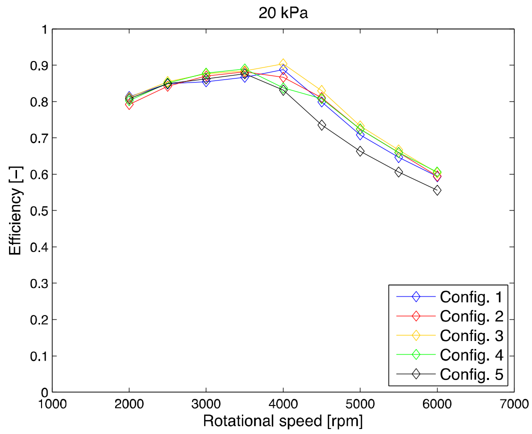


- For the second test campaign, series of pump performance measurements were established for identical working conditions (shaft's speed, inlet pressure, …) for different supply circuits with same geometry and different diameters (using corresponding sight glasses and pump inlets)

  Same trends concerning the leak and cavitation working conditions.

  Influence of the flow velocity in the cavitation zone:



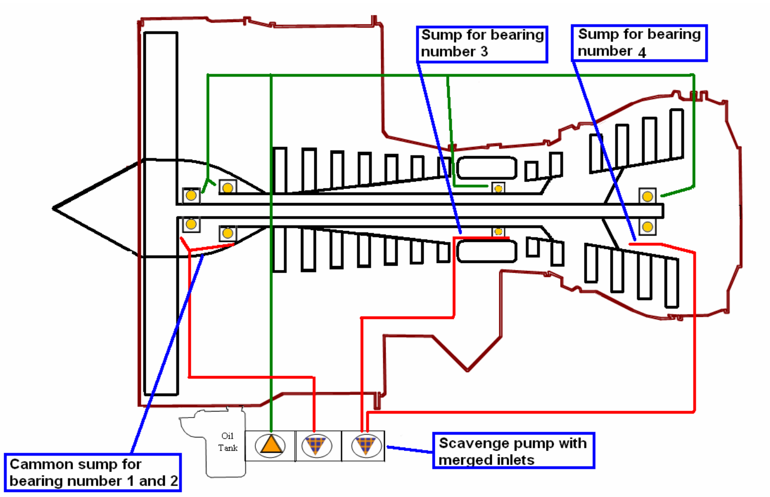


Influence of tank air pressure in the cavitation zone:

- Degassing is influenced by pressure differential between tank and pump inlet. Oil aeration is proportional to the tank pressure (air in contact of the free surface of oil).
- Tank pressure lower than inlet pressure increases pump's performances (tank located higher than the pump).

B. Scavenge System and Vents Components Simplification:

Further to the improvement that are proposed by WP1, the scavenge system was also reviewed and simplified. Heat management (WP2) also drives the modification of the scavenge design and led to new scavenge architectures. Several prototypes were tested under real conditions to demonstrate the feasibility and the advantages of the improved scavenge systems.



New engine architecture (multi-scavenge pump for bearings 3 and 4)

Two new designs were tested, driven by the main goal of mass reduction:

• WSK tested a light and reliable scavenge system that allows evacuation of oil by single pumping element from two separate bearing chambers simultaneously. Main results of this work were:

First design of a gear type pump able to suck oil from two separated inlets.

Suction capacity of this arrangement is demonstrated only in the case of non-pressurized bearing chambers. Any pressurization stops scavenging.

New component allowing engine to run without bearing pressurization is to be found and designed to make the new pump useable.

• MTU tested an ejector pump to replace the set of volumetric pumps.

Main results of this work were:

Large progress in ejector system modeling, including a one dimensional analysis tool for dimensioning the system and a 3D model of internal flows, validated by rig tests results. A first set of performance curves was established.
Although progress still could be done to improve performance, a first optimization has been done on main parameters (for example spray shape and position). Demonstration has been done of the ability of the proposed ejector system design to scavenge a sump to a tank at ambient pressure, even in 60° nose-up attitude.

Some limitation were also discovered, particularly the need for a sufficient sump pressurization to avoid the ejector to being chocked, and the need for a higher discharge pressure in order to cope with tank pressurization or de-aerator inlet resistance.

C. Two Phase Flow Modelling (Cenaero):

During Elubsys, a new approach for the numerical simulation of three-dimensional two phase flows was presented and assessed on several 2D and 3D benchmarks.

The method relies on a strongly coupled discontinuous Galerkin scheme for both the incompressible Navier-Stokes equations and the level set equation, thereby tempting to extending the method, currently used for monophase industrial LES to multiphase flows.

Although promising results have been obtained in terms of accuracy and capture of intricate structures, the method is currently not sufficiently mature for its application to lubrication circuits, as experienced during the first application to the priming of a feed pump. Some difficult issues remain concerning the stability of the interface, which are supposedly generated by the reinitialisation procedure. Therefore more work will need to be done to introduce an approach based on partial differential equations instead of geometric reconstruction, in particular care should be taken not to modify the isosurface corresponding to the interface.

A second issue is the local loss of order of accuracy near the interface. Although it can be traced back to the smoothing procedure, it is not expected that this can be remedied with the available other techniques, such as XFEM, immersed boundary … Unless an effort is done to extend these methods to higher order. However, a significant increase of accuracy is nevertheless obtained with an increase of interpolation order.

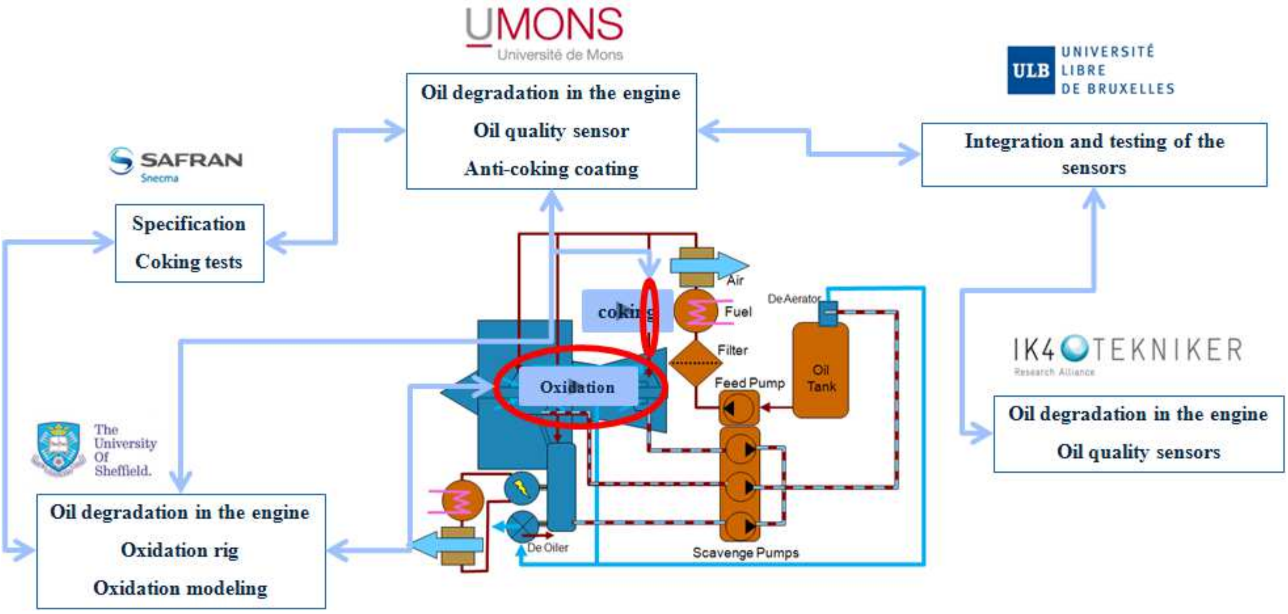
WP4: Oil quality and coking (SN, RRUK, ULB, USFD, TK, UMons)

Oil quality is a key parameter for a good engine functioning. In an engine, as oil is exposed to high temperature, it gets oxidized. As oil is naturally lost (that is the oil consumption of the engine), regular topping-ups have to be done by mechanics. Doing so, oil quality is naturally regenerated, fresh oil taking the place of used oil. After a certain time, oil quality reaches equilibrium, and does not change with time.

Three different approaches have been explored in the project:

- Develop a model taking into account the oxidation kinetics of oil in the engine environment, in order to be able to predict the oil quality in the oil system
- Develop sensors to measure the oil quality in the engine that could warn the engine user that oil is degrading.
- Develop a coating that will prevent coking formation in specific zones, identified as prone to clogging.

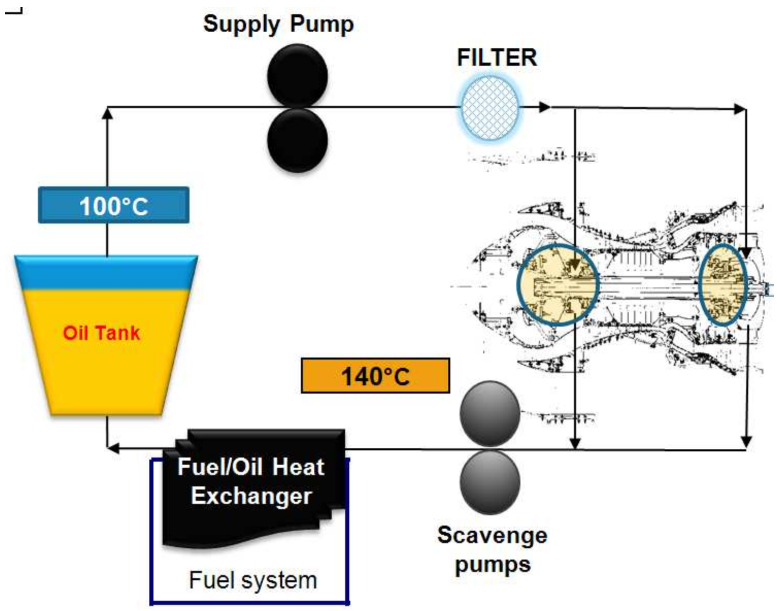
The figure below shows the inter-relations between the different partners, and how they are linked with the different items.



Interactions between partners

Oil degradation Model

The model has been developed by the University of Sheffield. Computer program for the simulation of lubricant ageing is based on the idea of splitting the lubrication system of a typical gas turbine engine into regions that each can be defined by their own temperature and lubricant residence times. By doing this, these regions can be thought as independent reactors where lubricant passes through then in a circular (loop) arrangement. This schematic representation is quite realistic, oil systems for modern aircraft engines being a closed loop, made up of different branches that are the bearing sumps and accessory gear boxes (see figure below)



Schematic of an oil system

Oxidation kinetics depends mainly of temperature and time of exposure. So, knowing the temperature of oil in the complete oil system, the model can easily determine the oxidation rate in the whole system.

The computer code also needs to have the derived reaction rate parameters in a model that is closely related to the Lubricant System Interaction (LSIS) test facility, which in turn has been developed by RRUK as a facility for representative lubricant degradation as occurs in aviation gas turbines.

The LSIS test facility has been used to produce “aged” lubricant samples that have been analyzed by Tekniker in order to extract the species mass fractions throughout the duration of an experiment.

Sensor development and test

In the next generation aircraft engines, engine oil will be stressed at its maximal capabilities, for mainly two reasons:

First, engine will run hotter, due to higher engine speed, thus more heat generation from the bearings to the oil. The oil will be also less cooled, in order to decrease the size of the heat exchangers. The fuel, which is used to cool the oil, will be also less available, as engine efficiency will increase.

Secondly, the oil consumption will decrease, thanks to better sealing of bearing sumps. Less air will be treated by the deoilers, making them more efficient.

As a consequence of these two combined effects, the oil will be more sensitive to accidental overheat, or harsh conditions (very hot countries for example).

In order to control the oil quality, and prevent sudden oil degradation that could lead to engine malfunction, three sensors have been developed, based on oil physical and chemical changes during oxidation:

- Anti-oxidant additive content
- Acidity
- Presence of particles
- Oils are protected from oxidation thanks to anti-oxidant additives. These additives act in a sacrificial transformation, which means that they capture oxygen atoms before they oxidize the oil. Doing so, they block the oxidation reaction at the initiation stage. There, the remaining concentration of anti-oxidant in the oil gives the level of quality of this one. This is the principle of the VIS-NIR sensor developed by Tekniker. The sensor has an optical system to split up the light into different wavelengths after the light goes through an oil sample. These wavelengths are gathered in the detector which transforms the light signal into an electrical signal to obtain transmittance spectra. The selected measurement range was 400-1100 nm, so it covers the visible range (400-780 nm) and the short wave near infrared (780-1100 nm). The spectra obtained with this sensor have been correlated with the anti-oxidant additive content.
- One of oxidation by-product of ester based oil is organic acids. The more acid in the oil (measured through the Total Acid Number), the more degraded the oil. The second sensor, developed by UMONS, is based on the quartz crystal microbalance technique. It is a high sensitive device (0.1-0.2 $\mu g/cm^2$) which is able to capture the changes in the properties (density, viscosity, presence of particles, etc) of a liquid and to characterize them by a single parameter, the change in frequency of the crystal resonator. The higher mass on the sensor, the higher frequency shift can be measured. Thus, to enhance this frequency shift and make it stable in time, the surface of the sensor has to be functionalized to improve its affinity toward the molecules of the oil with the consequence to increase the number of the molecules in contact with the substrate. This is a key point. This coating is made from a protocol which combined a TiO_2 sol-gel (glue layer) and a molecular imprinted polymer technique that produces TiO_2 nanoparticles. The role of this molecule is therefore to modify the surface of the nanoparticules by imprinting a shape that fit to the aged oil molecules. The acid used for this is a capric acid, which is similar to the acid molecules formed during oil oxidation. The prints

made on the nanoparticle surface are the spots where the "aged" oil molecules will be trapped, thus changing the frequency of the QCM resonator.

- The third change in used oil that we thought useful to measure is the presence of particles.

These particles can be produced by a severe oxidation process of the oil, giving carbon rich particles. Metallic particles can also be produced by wear phenomena between two metallic parts, if the degraded oil is no more able to create a smooth film between these two parts, following viscosity change for example.

The OPD sensor developed by Tekniker is a prototype whose functions are the detection and the quantification of metallic and non-metallic particles in the lubricating oil taking into account their size. The sensor is able to distinguish between particles and bubbles, which are frequent in oil system, due to churning. .The sensor takes the picture of the lubricating oil distinguishing bubbles from particles and identifying the size of the particles suspended into the oil. The sensor gives a result report where is showed a picture of the oil with the particle detected in red and the number of particles ≥ 4μm, ≥ 6μm and 14μm per ml of sample. The number of particles detected is codified taking into account the ISO 4406. This figure associated to this ISO specification could be easily compared to a criterion, which would tell whether the oil has the required cleanliness, or if it is getting degraded.

The three sensors have been tested under real oil conditions in a lubrication test bench available at the "Université Libre de Bruxelles" (ULB/ATM department).

In a first time, robustness of the sensors has been assessed, that is to say resistance to representative conditions, oil temperature, pressure and flow. All sensors are quite robust.

Some oil leakage has been observed with OPD sensor.

The VIS-NIR sensor revealed to be sensitive to oil temperature, showing that a compensation algorithm was necessary.

QCM has shown good results in a derivation configuration, but was sensitive to pressure in the "on-line" configuration.

This showed us that the integration of one sensor has to take into account its capability to withstand oil conditions. In an oil system, many conditions in terms of oil pressure, temperature and flow can be found, and this variety of conditions opens a lot of possibilities to implement different sensors, with different level of resistance to engine conditions.

As far as Technological Readiness Level (TRL) is concerned, we can say that the basic principles have been shown to be relevant for oil quality analysis.

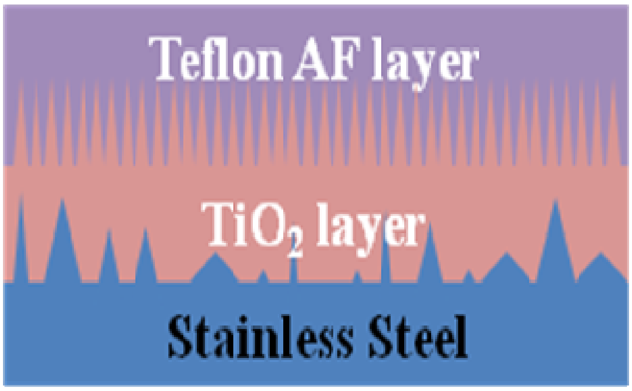
If we refer for example to classical TRL scales, we can estimate that we have reached the TRL2, and that the three sensors are currently being evaluated under TRL 3 and 4 conditions.

Anti-coking coating

Coking is the ultimate stage of degradation of engine oil. It combines both oxidation and molecule cracking, leading to hard deposits formed of carbon. Coking specially takes place in very hot places (near the turbine parts), and under low oil flow conditions. These conditions are met particularly in oil tubes (supply or scavenge) and vent tubes connected to the rear sumps of the engine, and more precisely after engine shut-down, as heat soaks back from hot part to oil tubes.

The original idea is to make the surface of the tubes oleophobic: oil droplets that would normally stay stuck to the internal surface of the tubes can slip away from the hot zone by simple gravity, leaving a clean surface.

The oleophobic function is ensured by a Teflon layer type, while an intermediate TiO_2 layer to enhance the mechanical anchoring of the Teflon AF layer to the metallic substrate (figure below):

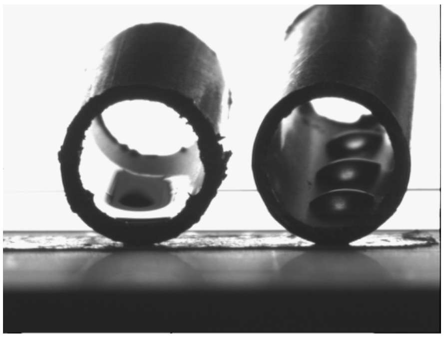


This coating can resist to temperatures up to 250°C, in the range of the engine temperatures near the turbine rear frame.

The difficult part is to coat the inside of a tube which is 30 cm long, with an internal diameter of 6 mm. A procedure using a liquid route has been developed as an alternative to the spray coating on a flat surface;

This process revealed to be efficient, as checked by wetability measurements.

The picture below shows that the wettability of the inner side of the tube was reduced (5 cm in length tube samples).



On the left side, there is no anti-coking coating; an oil droplet forms a thin film. On the right side, the tube is coated with the Teflon AF, some droplets can be clearly seen.

Two tests lubricant degradation tests were carried out on the hot wall nozzle of the LSIS rig at the University of Sheffield. The first test was designed as a baseline test with a bare 316 stainless steel surface. The second test was a repeat of the first test with an anti coking surface preparation on the lubricant wetted surface. This preparation was carried out by the University of Mons. The tests were completed on the plain and coated nozzles. Each nozzle was exposed to the same thermal conditions for approximately 150hours. The flow rate through the nozzle appears to drop during the test, causing the wall temperatures to rise above their initial values under a constant heat flux. No deposit was observed for the coated tube.

WP5: Scientific Coordination and Benefit Evaluation (SN, TA)

The Progress Meetings (PMs) of the Elubsys project serve in organising the work of the Task 5.1 of WP5 towards its objectives. The PMs in Bordeaux, Limassol and Lyon really helped in the discussions and the coordination work for the numerical simulation tools and their experimental validation. This scientific coordination also led to the assembly and write-up of the deliverable D6.4 on the simulation tools roadmap for GTE lubrication systems.

The PMs were also essential in the organisation of the Final Technical Workshop of mid October 2012 in Biarritz. This Final Technical Workshop has been organised together with the NATO Research and Technology Organisation (NATO RTO) with 16 technical papers in total plus 4 keynote presentations. Outside of this event, a total of 8 conference papers have also been published by various partners of the Elubsys consortium at different occasions. In addition, two special sessions on GTE Lubrication Systems have also been organised through the Elubsys consortium at the ASME IGTI in San Antonio of June 2013.

The Elubsys project really achieved the creation of a group of specialists involved in GTE lubrication systems. A large part of this group has in fact worked together for the set-up of the SP2 in the FP7 Level 2 E-Break project that started in October 2012.

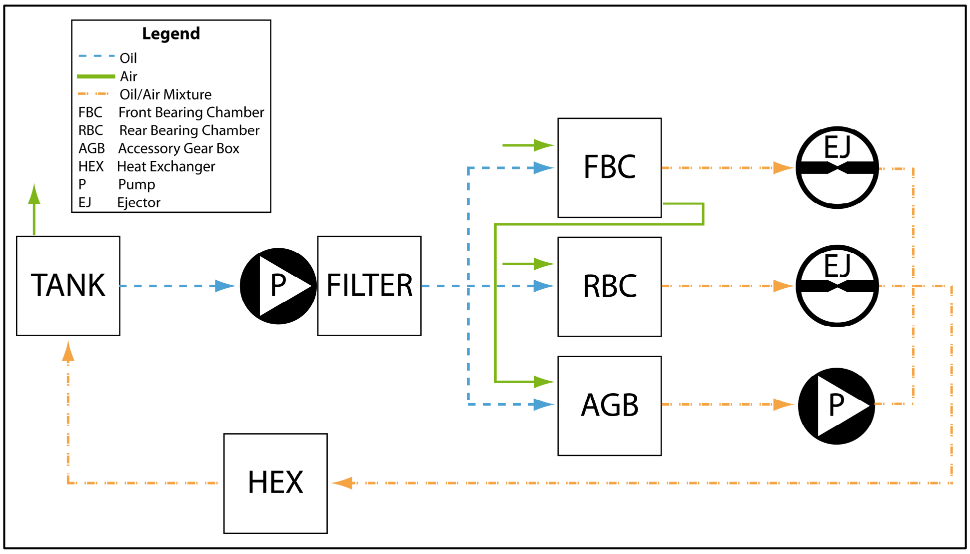
The numerical simulation of the complete lubrication system as a 0D model of an aircraft gas turbine has been realized in Task 5.2. The initial architecture of a typical modern lubrication system has been analyzed and described and modifications/upgrades with some new technology features coming from the Elubsys work have been introduced. The first modification consisted in replacing the initial labyrinth seals by more efficient brush seals. The results obtained showed that the reduction of the air flow leaking through the seals is significant (a reduction between 70% and 80% of the original air flow). This modification led the way to another modification of the architecture of the system, which consists in closing the vents that conduct the air flow from the bearing chambers to the atmosphere. This new configuration implied several other changes. First, the scavenge pumps, located at the exit of the bearing chambers, are replaced by ejectors (the ones developed in Elubsys by MTU). Second, the pipes of the scavenge part of the circuit have been redesigned because the flow of the mixture of oil and air going through them generated not acceptable pressure drops and air flow speeds. Third, the tank is not pressurized by the bearing chambers anymore but is now at atmospheric pressure and pressurizes them.

After comparing the results obtained with the simulations performed in EcosimPro in this Task 5.2 and the ones obtained by the partners on their different test benches, it can be concluded that brush seals are really useful and that the 0D modeling developed in Task 5.2 is efficient. Brush seals allow a reduction from 60% to 80% of the airflow to the scavenge lines (table below). It is interesting to note that a reduction of 60% of the airflow to the scavenge lines corresponds to a reduction of 0.46% of the TSFC.

	Air flow through the front bearing chamber Brush seals / labyrinth seals (ratio)	**Air flow through the rear bearing chamber Brush seals / Labyrinth seals (ratio)**
Pre-flight	11%	16%
Take-Off	28%	32%
Cruise	22%	27%
Approach	15%	18%

Comparison between the air flow that goes through the front and the rear bearing chambers while using labyrinth or brush seals

Different interesting conclusions have also been given about the many advantages to use a ventless oil system configuration. The figure below presents this new configuration.



Closed-vent configuration of a modern lubrication system and introduction of two ejectors to replace scavenge pumps

The 0D model of a complete modern GTE lubrication system has been finalised and fully developed in Ecosimpro in Task 5.1 and a few validations have been done based on the Elubsys developments and results from the other WPs. The D5.1 was delivered rather at the beginning of the 2nd reporting period, i.e. at T0+20, the D5.2 at T0+25 at the beginning of July 2011 and the D5.3 just before the end of the project, i.e. in mid November 2012.

Potential impact

The worldwide civil aeronautics industry continues to grow, and demand for air transport from passengers and for freight shows no sign of slowing down. 40% of the worldwide aeronautics industry sales are within the EU, and the industry contributes annually some 8 Billion € to the European economy. It is a high technology, high added value industry that provides some 380,000 highly qualified jobs throughout the Member States.

The world aircraft engine market is characterised by strong competition between Europe, the US, and increasingly the Far East. To be competitive, engine manufacturers need to respond to the needs of their customers (i.e. the aircraft manufacturers) who are under pressure to improve cost efficiency, whilst having to ensure highest levels of security and convenience to airline passengers.

Fuel consumption represents approximately one third of the Direct Operating Costs (DOC) of an airline for a narrow bodied aircraft. Current forecasts for rising fuel prices will further increase the pressure on aircraft manufacturers to find ways of reducing SFC.

Aircraft engine maintenance also represents an important cost for airline companies, accounting for 15% of the DOC and 14% of the engine possession cost. A significant part of the maintenance costs is linked to expensive shop visits after an In Flight Shut Down (IFSD).

For these reasons, improvements and innovations in several areas of the architecture of lubrication systems can play an important role in reducing aircraft operating costs through reduced SFC, increased reliability and higher maintainability:

- It is estimated that the secondary air losses from the engine used to pressurize the bearing chambers (bleed air) could be reduced by 60% when using new seal technologies resulting in a gain of around 0.46% of SFC.

- The thermal energy generated in the housings of a conventional turbofan is around 1% of the propulsive engine power. The deletion of parasitic effects, like churning, through improved thermal efficiency could decrease the heat generation in the housings of up to 30% and thereby the SFC by further 0.3%.
- The simplification of the bearings housings (reduction or deletion of vent tubes) combined with a reduction in the number and size of the pumping equipment required for scavenging oil from them could lead to a reduction of mass of 18kg per engine, representing a further gain of 0.05% for the SFC.
- It is anticipated that improved designs in lubrication systems can reduce the oil consumption required to lubricate engines by 60%. This reduction in oil consumption means that oil tank sizes could be reduced by 30% (-6kg).
- The use of new high performance seals would also reduce the debris originating from the air pressurisation which constitutes the main source of pollution for the lubrication systems. The filters used in the lubrication systems could then be reduced in number and size (-2kg per engine).

Overall, innovations in the architecture of lubrication systems could increase the efficiency of the engine and yield a reduction in the SFC. Lower SFC translates into less amount of fuel needed by the aircraft to fly to a given destination. The accumulation of lower SFC and lower fuel weight in the aircraft's tanks can yield a reduction in fuel burn (fuel consumption).

Further than the SFC reduction, the introduction of the new and simplified lubrication system architectures would decrease DOC thanks to improved reliability and maintainability.

Globally, new architectures and equipment for lubrication systems such as those proposed by ELUBSYS could achieve a benefit to DOC, 0SFC savings and maintenance reductions.

The results of WP1 has improved the knowledge on brush seals and their impact on bearing chambers. The underlying aims for this WP was to determine the suitability of brush seals as a replacement for labyrinth seals in bearing chambers, measure the reduction in deflected compressor air they can achieve and also to evaluate whether they can lead to the elimination of the vent pipes in bearing chambers. Testing on the brush seals showed a reduction of air consumption between 75% to 95%.

The results of WP2 will allow both, a more detailed understanding of flow and heat transfer phenomena and two-phase flow prediction capability. Correlations have been developed based on test results and CFD predictions to support the engine design process. The derived design guidelines for chamber ports will support the engine design process to account for advanced technologies such as contra-rotating shafts for improved turbine performance, less fuel burn and green house gases.

The methods developed in this WP will improve the prediction of oil content in bearing chamber outlet pipes. This will enable the design of innovative bearing chambers that deliver acceptable performance whether they are un-vented and use with tight seals (carbon or brush) or whether they are conventionally vented.

RRD: The project results are mainly of technical nature, i.e. improving knowledge on lubrication systems of gas turbines, with focus on bearing chamber housings. Socio-economic impact is mainly related to training of students and research assistants at Universities.

The results of WP3 showed design rules that if followed will improve supply pump efficiencies and reliability. Work performed on the multi-inlet and ejector scavenge pump will lead to future research work.

The results of WP4 improved knowledge in oil ageing and monitoring which will reduce oil replacement rates and maintenance cost.

The ELUBSYS innovations and results have to be further exploited in order to lead to new designs for lubrication systems that will:

- Enable future engine architectures with higher cooling demands (Power Gearboxes, More Electrical Engines).
- Reduce the DOC related to fuel burn and engine maintenance: fewer expensive non-programmed visits to maintenance shops; increase in average number of engine availability hours thanks to longer time on-wing and extended component life.
- Reduce emissions of oil and fuel.

- Ensure the safety of the passengers by maintaining the reliability figures to the highest level from the EIS (Entry In Service) of mature technologies and architectures.
- Reach the ambitious target of mass and cost reduction of the externals compared to previous generation engines.

It will produce significant technological advances in the area of lubrication for aircraft engines which will fully support the needs of future engine generations (e.g. geared turbofan engines with a highly loaded core, higher by-pass and high speed LPT and LPC). These advances will also increase the competitiveness of Europe's aviation industry and airlines because of the improved technologies and savings on operating costs that they will enable. Last but not least, the project will enable Europe to sustain the lead in providing innovative technologies that will benefit air travellers worldwide in terms of more reliable and safer aircraft engines and cheaper air travel (because of reduced fuel consumption and lower maintenance cost).

All Elubsys achievements were presented at the NATO Specialists' Meeting in Biarritz, France (16-17 October 2012) and at the Elubsys end of project Workshop in Spa-Francorchamps Belgium (15 November 2012) where a dedicated session for the construction of a future project to pursue the work was held between Elubsys partners.

Address of the project public website

www.elubsys.eu