FIRST Project Participants

A2 Photonic Sensors (A2PS)

ARTTIC (ARTTIC)

Centre Europeen de Recherche et de Formation Avancee en Calcul Scientifique (CERFACS)

Centre National de la Recherche Scientifique (CNRS-CORIA / CNRS-LEGI)

EnginSoft (EST)

GE AVIO (Avio Aero)

German Aerospace Center (DLR)

Imperial College of Science, Technology and Medicine (IMPERIAL)

Karlsruher Institut fuer Technologie (KIT)

Loughborough University (LU)

MTU Aero Engines AG (MTU)

Office National d'Etudes et de Recherches Aerospatiales (ONERA)

Rolls-Royce Deutschland (RRD)

Rolls-Royce PLC (RRUK)

SCITEK Consultants (SCITEK)

SNECMA (SN)

TURBOMECA (TM)

Universita Degli Studi Di Bergamo (UNIBG)

Universita Degli Studi Di Firenze (UNIFI)

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FIRST

Fuel Injector Research for Sustainable Transport

FIRST Project Summary of Achievements: Advancements in Spray & Soot Research

Introduction

The FIRST project (Fuel Injector Research for Sustainable Transport) was a collaborative project that ran for 48 months from December 2010 to 2014. Its 7.2M euros budget was partly funded by the European Union 7th Framework Programme and the 20 industrial and academic project partners.

Aviation's environmental impact must be reduced to allow sustainable growth to benefit European industry and society. This is captured in ACARE's 2020 goals of reducing CO2 by 50%, NOx by 80% and in SRA1/2 proposed reductions in soot and the development of alternative fuels.

Consequently, the aims of the FIRST project were to deliver key enabling technologies for combustion emissions reduction by developing improved design tools and techniques for modelling and controlling fuel sprays and predicting soot emissions. CFD simulations have for many years relied upon over-simplistic definitions of the fuel spray for model boundary conditions. By understanding and controlling the complex physics of fuel atomisation and the subsequent mixing the emissions predictions can be directly improved leading to more competitive aero combustor designs.

The FIRST project has delivered a step change in the detail and accuracy of the fuel spray boundary conditions and the propagation to downstream conditions. This has been achieved through the implementation of advanced experimental diagnostic measurements, the development of novel physics based modelling techniques and the derivation of sophisticated correlations.

FIRST has also delivered improved CFD soot models, thereby, enabling the reduction of soot in aero-engine combustors. These calculations require the improved fuel spray boundary conditions provided within the project and also need the higher fidelity physical and chemical models describing the soot production and consumption processes provided from FIRST.

The potential use of future alternative aero fuels will be enhanced by the FIRST project as it has provided information for performing predictions and measurements of both fuel sprays and soot across a number of different alternative fuel types.

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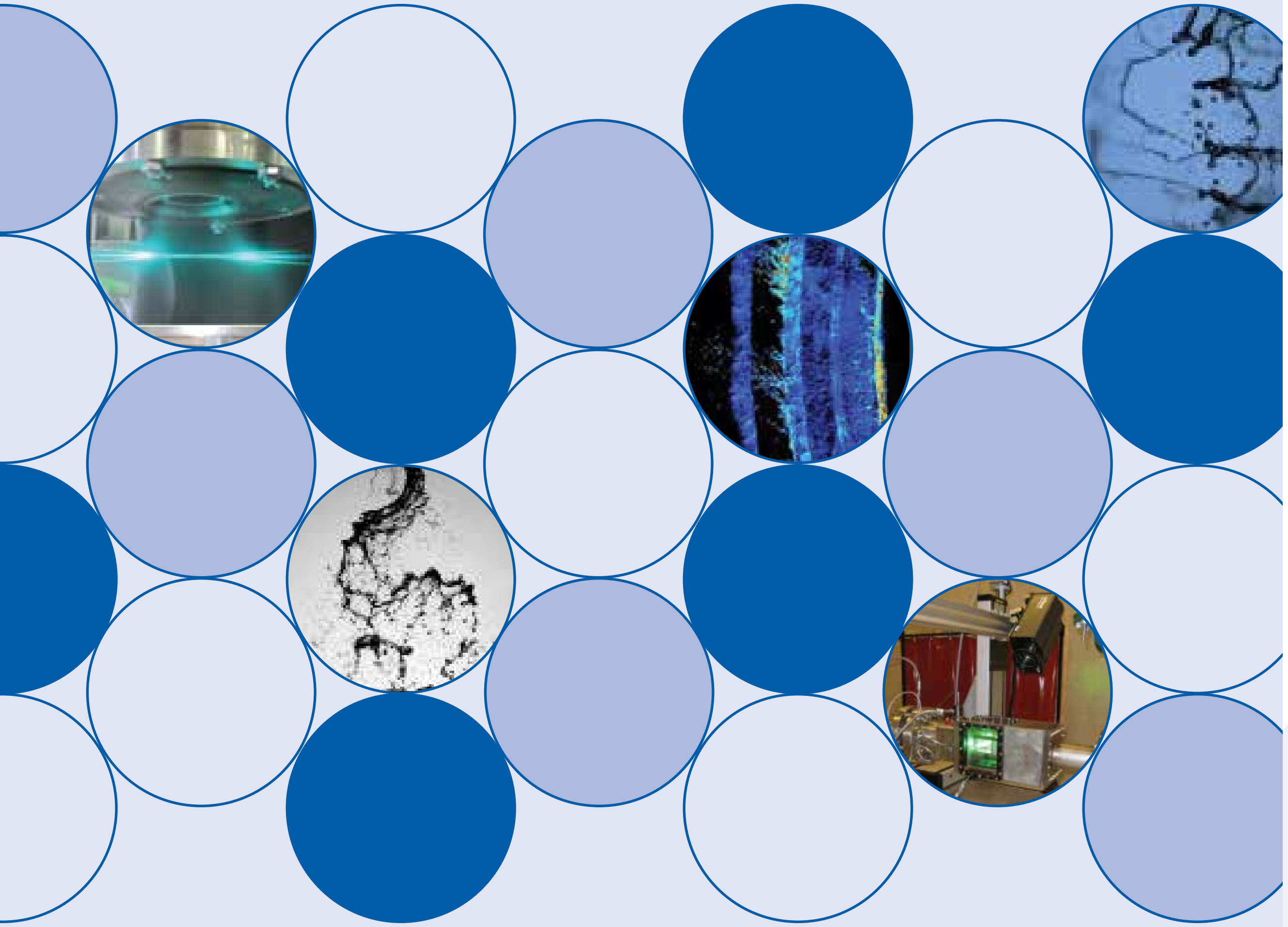
Glossary

AMR	Adaptive mesh refinement
CARS	Coherent Anti-Stokes Raman Scattering
CFD	Computational Fluid Dynamics
CPU	Central Processing Unit
DFT	Density Functional Theory
DNS	Direct Numerical Simulation
EE/EL	Eularian/Lagrangian
FGM	Flamelet Generated Manifold
GSMD	Global Sauter Mean Diameter
ILIDS	Interferometric Laser Imaging Droplet Sizing
KS	Kinematic Simulation
LES	Large Eddy Simulation
LIF	Laser-Induced Fluorescence
LII	Laser-Induced Incandescence
nPB	n-Propyl Benzene
OC	Optical Connectivity
OH	Hydroxyl Radical
PAH	Poly-cyclic Aromatic Hydrocarbon
PDA	Phase Doppler Anenometer
PDF	Probability Density Function
PFR	Plug-Flow Reactor
PSD(s)	Particle Size Distribution
PSR/JSR	Perfectly Stirred Reactor / Jet-Stirred Reactor
RANS	Reynolds Average Navier Stokes
RDF	Radial Distribution Function
SMD	Sauter Mean Diameter
SPH	Smoothed Particle Hydrodynamics or Spherical Particle Hydrodynamics
ULN	Ultra Low Nox
VOF	Volume of Fluid
WSR	Well-Stirred Reactor



Sprays:

Experimental Measurements

Fundamental mechanisms of assisted atomisation and spray characteristics (CNRS-LEGI)

1. State of the Art before the FIRST project

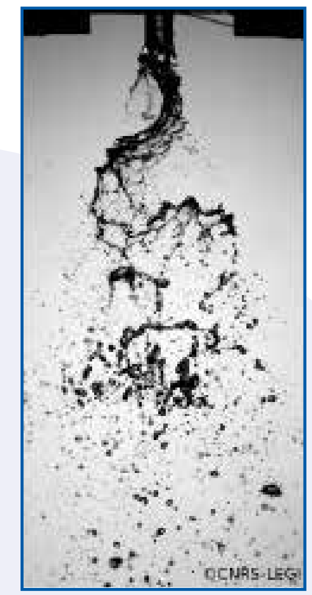
Assisted atomisation is widely exploited for fuel injection in aero-engines, but the involved complex break-up phenomena are only partly understood. Prior to the FIRST project, some data and a few phenomenological models were available to evaluate the size of drops formed by stripping. Much less was known on the large-scale instabilities of jets.

2. Research & Development Activities Performed

Extensive finely controlled experiments were performed to identify the influence of flow conditions and of injection geometrical parameters on spray characteristics. Dedicated measuring techniques were developed together with stability and/or phenomenological analysis. These activities also benefited from advances in phase detection probes and in direct simulations as developed by partners of the FIRST project.

3. Advancement of Capability due to the FIRST project

Beside the production of a data base over a wide range of flow conditions and more than 10 injector geometries, our understanding of atomisation process has been significantly improved. In particular, quantitative agreements between stability theory and experiments have been obtained for the first time on the interfacial instabilities leading to the stripping of drops off the liquid film. The size of drops due to stripping remains strongly controlled by internal injector design, with a diameter evolving from a few (at high gas velocities representative of take-off) up to 20 (at low gas velocity representative of cruise regime) times the gas vorticity thickness at injection. For large scale instability, new data were gathered on flapping frequency, size distributions, fluxes and their evolution with control parameters: the corresponding drops happen to be typically ten times larger than those due to stripping. Moreover, hidden parameters acting on the axial instability that open the way to new atomisation control strategies were also unveiled. These advances provide useful guidelines for optimal injector design and the data bases are helpful to test DNS or to feed numerical codes.



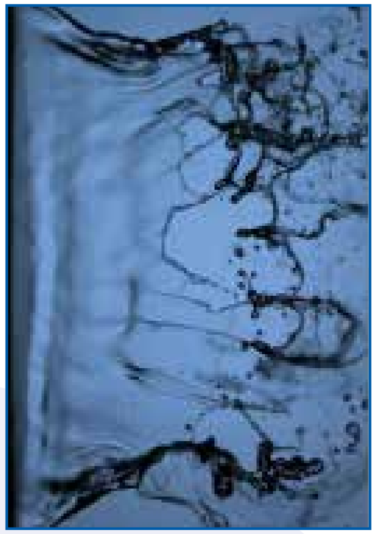
4. Additional information

Application: Fuel injection in aero-engines
Research area: Fundamental mechanisms controlling assisted atomisation
Technology readiness level: 3
Owner of IPR: CNRS – LEGI
FIRST Task: T3.1.1
Main author and contact: Alain Cartellier, CNRS

Planar liquid sheet atomisation (ONERA)

1. State of the Art before the FIRST project

Before the start of the FIRST project there was a lack of information about the influence of air thickness and air ambient pressure on a liquid sheet behaviour and atomization.



2. Research & Development Activities Performed

ONERA conducted an experiment on liquid sheet atomization with variable air flow around a liquid sheet and investigated this under pressure.

Different measurement techniques were used to characterise the liquid sheet atomization. The use of optical techniques based on visualisation and image analysis coupled with conventional techniques of fluid mechanics, hot wire or Pitot allowed information obtained to be merged from the gas phase and the liquid phase to improve knowledge on this phenomena.

3. Advancement of Capability due to the FIRST project

The most important results were obtained on the influence of the surrounding air, specifically its thickness and the characteristics of the resulting boundary layer. As expected the role of the boundary layer is of primary importance on the liquid sheet behaviour. Differences in the flapping frequencies and on the breakup length linked to the type of air boundary layer, laminar or turbulent, at the beginning of the liquid sheet were shown. The wall shear stress seemed to be an important parameter but not the only one.

To examine the pressure influence on atomization study it is necessary to work in a confined environment. In these conditions, the droplet size measurements are difficult and the systems currently used are not able to give primary droplets sizes due to their non spherical shape. The pressure effect on final drop size is visible and it improves the atomization process, but it is difficult to determine where the effect is greater, on primary or on secondary atomization due to the lack of information on primary breakup.

4. Additional information

Application: Fuel injection
Research area: Liquid film atomization
Technology readiness level: 3
Owner of IPR: ONERA
FIRST Task: T3.1.1
Main author and contact: Pierre Berthoumieu, ONERA

Fiber optic sensor for sprays: improvements and performance (A2PS)

1. State of the Art before the FIRST project

The technology of fiber optic probe for bubbly flow spray characterisation (liquid concentration, bubble/drop size and velocity) was initially developed in the 90s by an academic lab then transferred in 2007 to the company A2 Photonic Sensors for improvement, industrialisation and commercialisation. Commonly used in bubbly flows, this sensor was also used in sprays, but was limited to the analysis of droplets no smaller than 15 μm and drop velocities no higher than 25 m/s, and was therefore not fully responding to the requirements of turbomachinery and aeronautic engine injector studies.

2. Research & Development Activities Performed

A2PS has improved its spray analysis fiber optic sensor by optimising the sensing element, improving the data analysis algorithm and implementing it with easy-to-use software. In addition, a large part of the activities were dedicated to testing and qualifying the sensor performance in terms of small drop size detection capabilities and maximum velocity reachable, as well as testing the sensor in spray conditions representative of real engine injector study case.

3. Advancement of Capability due to the FIRST project

Improvement of the optical probe technique led to a measurement system fully functional in unidirectional sprays with droplet sizes down to 10 μm and velocity up to 60 m/s. The capability to measure precise flow rate and flux was demonstrated even with a very high droplet number per volume (very dense spray). In addition, a comparison with a PDA system showed good results agreement and more importantly, a clear advantage to the optical probe system due to its user-friendliness with its very short installation time and very easy set-up and use. As a result, A2PS are convinced that the optical probe technique will become an essential instrument for spray analysis in addition to already existing techniques.

4. Additional information

Application: Fuel injector and nozzle of aero combustors
Research area: Spray and atomization measurements: drop size & velocity, flux
Technology readiness level: 7 or 8
Owner of IPR: A2PS
FIRST Task: T3.1.1 & T3.1.3
Patent: none
Main author and contact: Stéphane Gluck, A2PS

Sprays: Experimental Measurements

Combined Break-Up Length and Droplet Size and Velocity Distribution Measurements (IMPERIAL)

1. State of the Art before the FIRST project

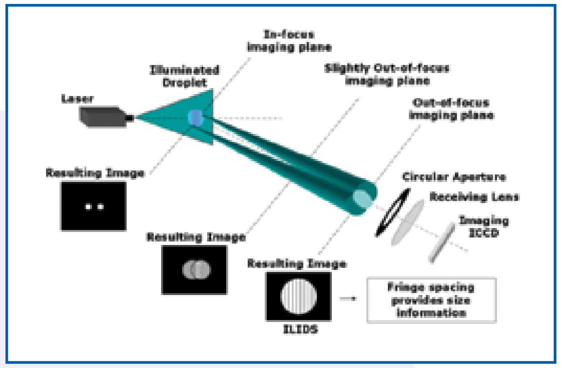
Prior to FIRST, ILIDS for the simultaneous measurement of droplet size and velocity had only been performed on automotive fuel injectors. While the OC technique for determining the break-up length had never been applied to pre-filming atomizers.

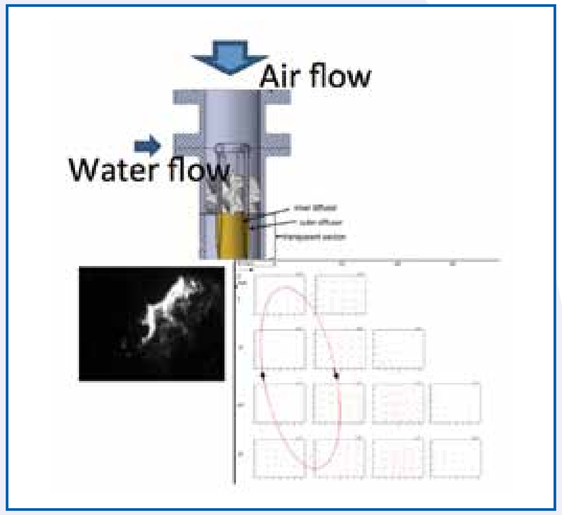
2. Research & Development Activities Performed

IC was the first to apply the ILIDS and OC techniques on a prefilming airblast atomiser, typically found in aero-engine combustion systems and pioneered the concurrent application of both techniques. Instrumentation and data processing algorithms were developed for the simultaneous collection of measurements and their interpretation. The spray characteristics of two prefilming atomizers (designed at IC and ONERA) were reported. Experiments were performed for different air and water flow test conditions.

3. Advancement of Capability due to the FIRST project

ILIDS measurements were reported for different axial and radial positions away from the nozzle exit and axis respectively. The increase in SMD of droplets towards the spray edge for both atomizers was explained on the basis of larger centrifugal force acting on the bigger size droplets due to the swirling flow. The average droplet velocity plots in case of the model atomizer showed the presence of an induced vortical flow structure causing flow reversal near nozzle axis, which arose due to the swirling motion of the air. Away from the nozzle axis, the droplet velocity was downward and increased till the droplets lost momentum near the edge of the spray. Apart from the basic velocity statistics, the spatial droplet-droplet velocity correlations (Rdd) and RDF are presented for different droplet size classes. Measurements of Rdd quantified the strength of the intra-phase coupling of the droplet flow field in both the axial and radial directions. The RDF for the different droplet size classes indicated that the larger droplets (45-60 μm) showed greater tendency to form instantaneous droplet clusters in the sprays. The average cluster dimension decreased towards the spray edge. The break-up length of the liquid sheet was measured by the LIF technique, and the measurements were reported for different Reynolds number of water flow for the same air flow rate. Finally, the statistics including the fluctuations of droplet concentration and its correlation with the droplet velocity, which are vital for understanding the droplet cluster formation, were measured.





4. Additional information

Application: Fuel injector for aero combustors
Research area: Combined Break-Up Length and Droplet Size and Velocity Measurements
Technology readiness level: 3
Owner of IPR: Imperial College London
FIRST Task: T3.2.2
Main author and contact: Yannis Hardalupas, Imperial College

FIRST Project Summary of Achievements: Advancements in Spray & Soot Research

Experimental investigation of the onset of film breakup in an annular prefilmer (KIT)

1. State of the Art before the FIRST project

Prior to FIRST, experimental investigations of the onset of film breakup in an annular prefilmer were difficult to perform. The reasons were the poor homogeneity in the circumferential direction of the liquid film flowing through the annular prefilmer for small liquid mass flow rates and incorrect arrangements of laser sheet and camera position.

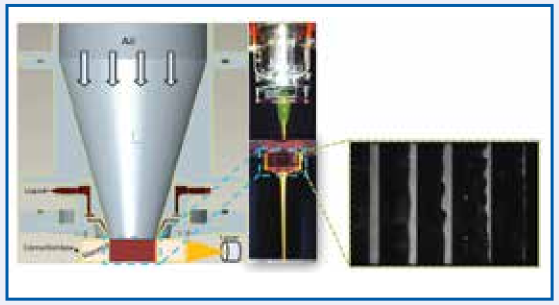
2. Research & Development Activities Performed

The Engler-Bunte-Institute (EBI) of KIT has designed a model research nozzle which generates homogeneous laminar film flow without any support of air flow and developed a measurement technique to determine the film thickness and detect the onset of the film breakup. One of the crucial points in detecting the film thickness was the position of the camera capturing the film at the illuminated surface with a light source.

The simulation and experimental investigation performed for different positions of the camera have proved that different positions of the camera gave different results for a predefined film thickness at the same boundary conditions. These investigations lead to the fixing of an arrangement of laser sheet and camera position which detects a predefined film flow precisely. Based on this validated arrangement, investigations of film breakup were performed with two main results. The first one concerns the Momentum Ratio (MR) between air and liquid flow. In contrast to existing research on film breakup we found that MR is not sufficient to characterise the beginning of primary atomization. The second one deals with the comparison of swirling and not swirling air flow. For the same air pressure drop the swirling flow generates a thinner liquid film thickness.

3. Advancement of Capability due to the FIRST project

During the FIRST Project a model research nozzle which produces a homogeneous laminar liquid film flow was designed and a measurement technique to capture the liquid film thickness was developed. The generated experimental data can be used in order to validate software programs calculating film flows. Furthermore, the experimental facility can be used for future research work in order to extend the experimental data base.



4. Additional information

Application: Fuel injector of aero combustors
Research area: Experimental study on primary breakup
Technology readiness level: 3
Owner of IPR: KIT
FIRST Task: T3.2.3.1
Main author and contact: Mulubrhan Gebretsadik, KIT

Sprays: Experimental Measurements

Effect of linear geometrical scaling and aerodynamic boundary conditions of a double swirl airblast atomizer on GSMD (KIT)

1. State of the Art before the FIRST project

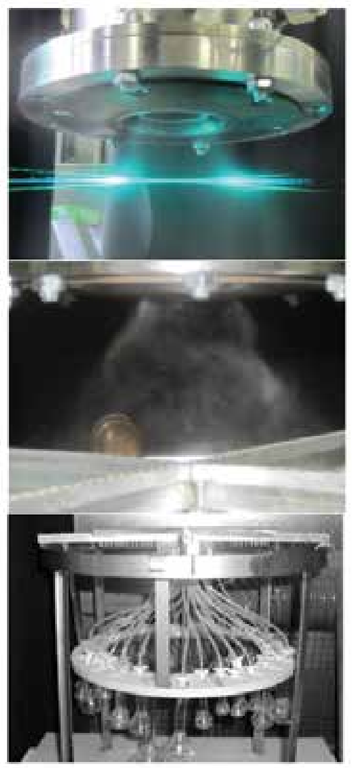
The evaluation of the GSMD for the whole spray is very difficult because it requires the radial SMD and liquid mass flow distribution. Therefore, the existing data base on GSMD for different performance conditions is very limited. Based on this limited experimental data base the developed correlations predict the GSMD as a function of the Weber number (We = $(\rho u2 \cdot D)/\rho$).

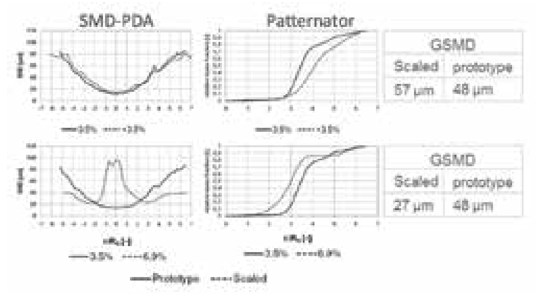
2. Research & Development Activities Performed

The Engler-Bunte-Institute (EBI) of Karlsruhe Institute of technology (KIT) has developed a method to evaluate the GSMD of a spray produced by double swirl airblast atomizer by a combination of two measurement techniques. The radial distribution of the liquid mass flow is captured by a patternator, whilst the radial distribution of the SMD is evaluated from PDA data. A prototype and a scaled version of the prototype injector with a linear geometric scaling factor of two were investigated at different boundary conditions to determine the effect of different parameters explicitly on GSMD.

3. Advancement of Capability due to the FIRST project

The combined experimental investigation of patternator and PDA within the FIRST project has enabled the evaluation of the GSMD for the whole spray produced by a specific boundary condition in double swirl airblast atomizer. This helps to compare effects of different parameters on the spray. The combined measurement technique reveals that the impacts of the variables in the We-Number in predicting the GSMD are different. The air velocity, which is calculated from the pressure drop, has much higher impact on the GSMD than the characteristic length at constant air to fuel ratio (AFR), surface tension and density.





4. Additional information

Application: Fuel injector of aero combustors
Research area: Experimental study on spray
Technology readiness level: 3
Owner of IPR: KIT
FIRST Task: T3.2.3.2
Main Author and Contact: Mulubrhan Gebretsadik, KIT

Characterisation of the Pre-filming Inlet Velocity Field (LU)

1. State of the Art before the FIRST project

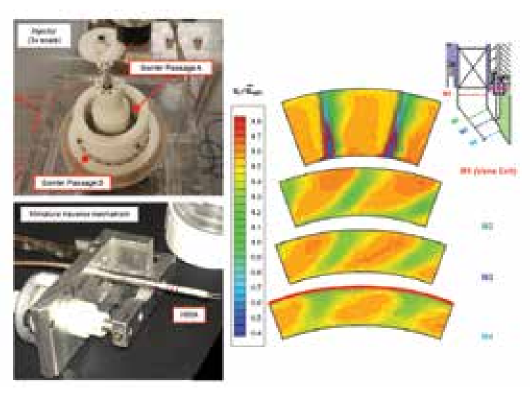
Modern fuel injectors often incorporate a pre-filmer surface onto which liquid fuel is introduced. Both computational and experimental studies were done which examine the development of the liquid film and its subsequent break-up. However, these studies have invariably utilised simplified geometries which may not capture the significant aerodynamic flow features present within a representative injector geometry. Such aerodynamic features were thought to be prominent in the development of the two phase flow field and therefore should be resolved.

2. Research & Development Activities Performed

A large scale representative fuel injector geometry was designed and manufactured. This facilitated detailed 2-D aerodynamic measurements at multiple planes within the pre-filming passage. Mean and fluctuating measurements were acquired, with and without fuel present, capturing the development of the aerodynamic flowfield within the pre-filming passage.

3. Advancement of Capability due to the FIRST project

An aerodynamically representative data set was generated which captures key flow features along the pre-filmer passage. These include the influence of fuel blockage, vane wake stretching and migration, resultant variations in mean velocity and turbulence adjacent to the pre-filmer and total pressure loss development. The data provides inlet boundary conditions for numerical (CFD) predictions relating to fuel injector flows. As the data charts the flowfield development along the pre-filming passage, it also provide a means of validating the numerical predictions.



4. Additional information

Application: Fuel injector of aero combustors
Research area: Internal Velocity Field Characterisation
Technology readiness level: 2
Owner of IPR: Rolls-Royce
FIRST Task: T3.3.2
Main author and contact: Ashley Barker, Loughborough University

Time-Resolved Measurements of Fuel Film Thickness on Representative Fuel Injector Geometries (LU)

1. State of the Art before the FIRST project

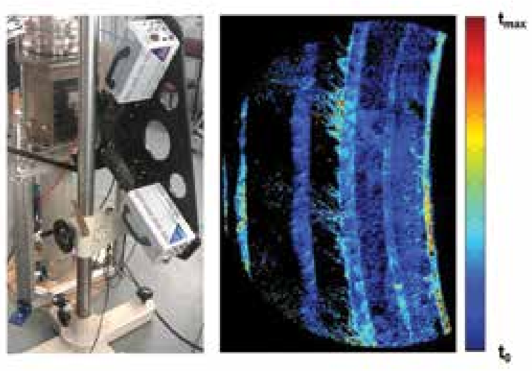
Prior to FIRST, 2-D measurements of fuel film thickness had been made on an engine representative injector at atmospheric conditions. They were obtained using a prototype instrumentation assembly which successfully demonstrated the capability, but was unrefined and did not temporally resolve the dynamics of liquid structures on the pre-filming surface.

2. Research & Development Activities Performed

LU has developed the instrumentation to make it more robust, increase portability and enable time-resolved measurements of fuel film thickness. Parametric studies were completed to better understand the effects of dye concentrations, optical filter choice, laser power/uniformity and substrate surface finish. Software development has facilitated rapid processing of the large quantities of data associated with such a measurement.

3. Advancement of Capability due to the FIRST project

Development of the instrumentation technique within FIRST enabled refinement of the opto-mechanical setup, culminating in a robust portable system capable of high-speed fuel film thickness measurements. The technique has been demonstrated at ambient pressure and at 4 Bar, and such measurements will improve the identification and understanding of significant factors affecting the development of the liquid fuel film and thus the downstream two-phase flow field. As measurements have not previously been available, this data will also facilitate improved methods for predicting such flow fields. Factors have been identified which will facilitate further advancement through acquisition of appropriate hardware, such as improved temporal resolution using higher powered lasers.



4. Additional information

Application: Fuel injector of aero combustors
Research area: Liquid film thickness measurements
Technology readiness level: 2
Owner of IPR: Rolls-Royce
FIRST Task: T3.3.2
Main author and contact: Ashley Barker, Loughborough University

FIRST Project Summary of Achievements: Advancements in Spray & Soot Research

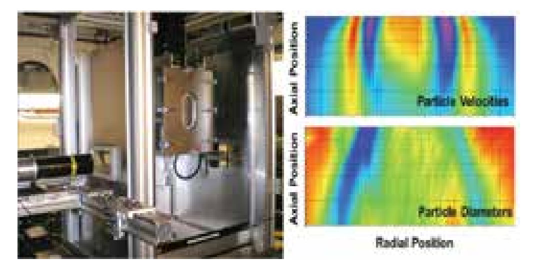
Engine Injector Spray Characterisation (RRUK, SCITEK)

1. State of the Art before the FIRST project

Before the FIRST project there was very little information available to describe the properties of atomisation from Rolls-Royce aero engine rich and lean burn fuel injectors. Lefebvre correlations were typically used to estimate the fuel spray boundary conditions for CFD modelling of these injectors in combustor flows. This coarse method used for numerical modelling made accurate prediction of combustor flow fields, and consequently emissions, difficult. Actual measurements of the fuel particle sizes and velocities were required before further progress could be made in improving modelling techniques.

2. Research & Development Activities Performed

A new test facility was built in the combustion laboratories in Rolls-Royce Derby that was specifically designed to enable PDA measurements of fuel sprays from engine injectors. All PDA and flow visualisation measurements were performed by SCITEK. Test geometries were designed and made that represented a single sector of an engine combustor so that the spray conditions were more closely representative of reality. Lean and rich burn fuel injectors were tested at a range of conditions relevant to their respective engine cycles and detailed measurements of droplet sizes and velocities were made at numerous locations. The work was extended to include sprays from alternative fuels as a comparison to a standard kerosene spray.



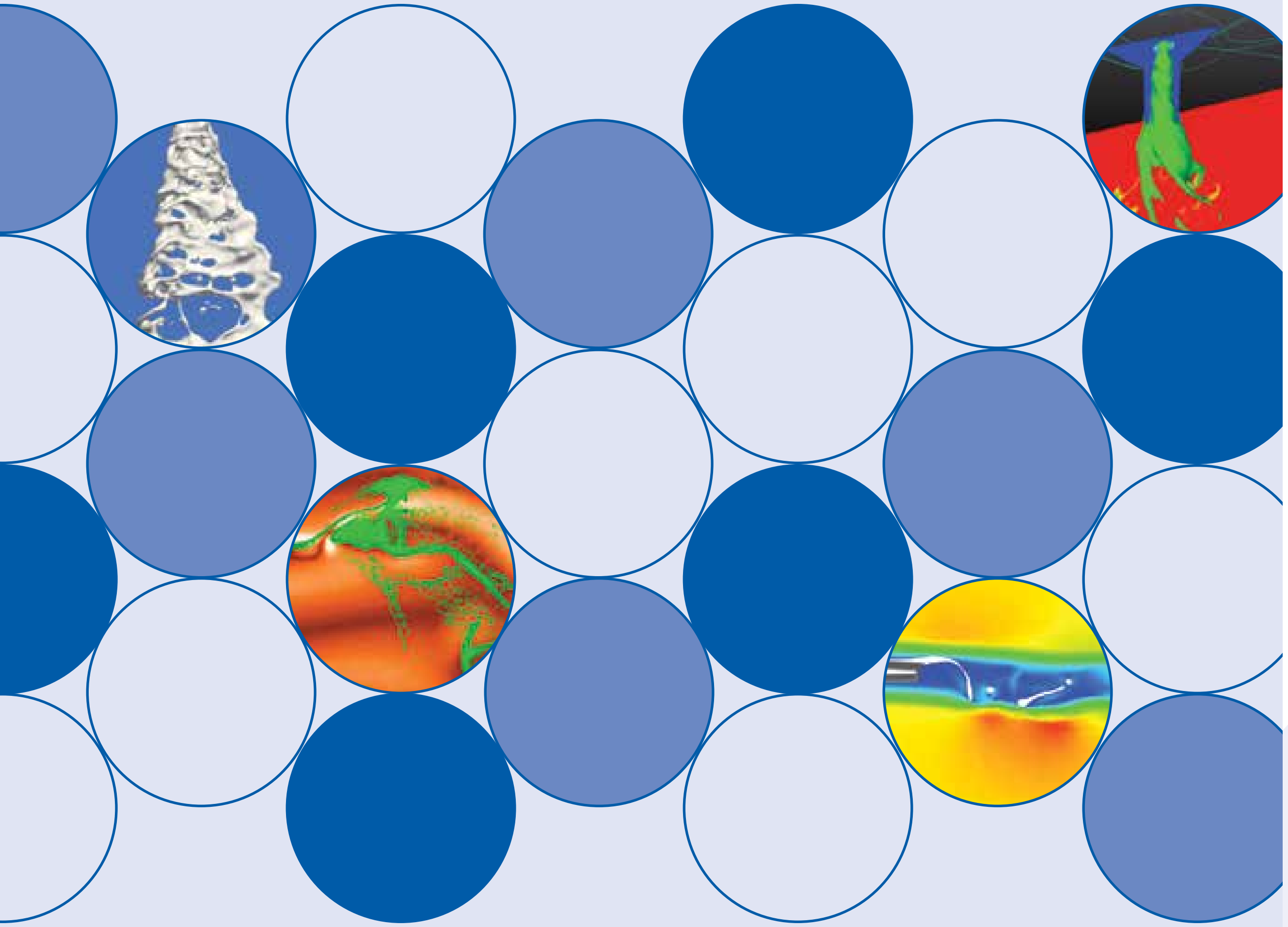
3. Advancement of Capability due to the FIRST project

The measurements of the spray from the fuel injectors have now provided the boundary conditions required for CFD modelling of Rolls-Royce engine combustors and has described the progression of the atomisation process as the flow moves downstream away from the fuel injectors. This is vital information for the improvement of numerical models to predict engine reacting flows. The CFD models can now be validated against the spray measurements for a wide range of geometries and conditions and a step change in modelling accuracy will be the result. Future designs of aero engine combustors and fuel injectors will benefit from the improved modelling accuracy.

4. Additional information

Application: Measurements of engine injector sprays for validating CFD modelling
Research area: Spray measurements from engine injectors
Technology readiness level: 3
Owner of IPR: RRUK
FIRST Task: Task 3.3.3
Main author and contact: Darren Luff, Rolls-Royce UK

Sprays: Experimental Measurements



Sprays:

Numerical Modelling of Academic Configurations

Development and evaluation of numerical methods for the simulation of primary atomization in aeronautical injection systems (CNRS)

1. State of the Art before the FIRST project

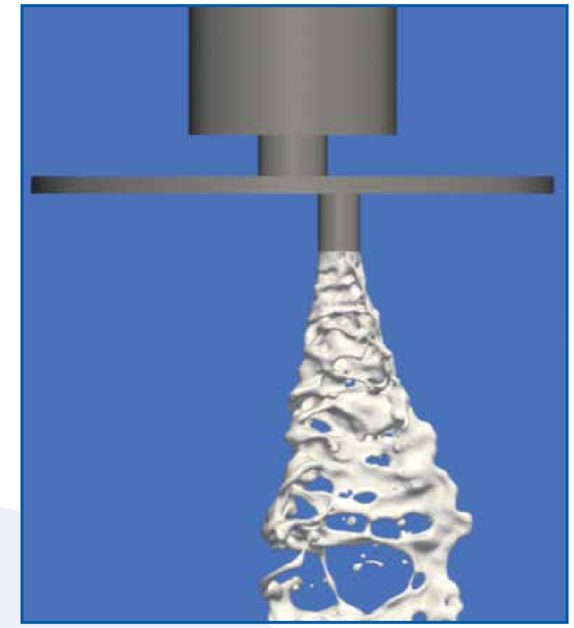
Primary atomization modelling has been an active research topic over the last two decades with the development of various numerical techniques for the tracking of the interface motion (Volume-Of-Fluid, Level Set) and for the capturing of the jump conditions at the interface (Continuous Force, Ghost-Fluid Method). All these techniques have been largely validated for academic two-phase flows and very few attempts have been conducted for realistic geometries such as aeronautical injection systems.

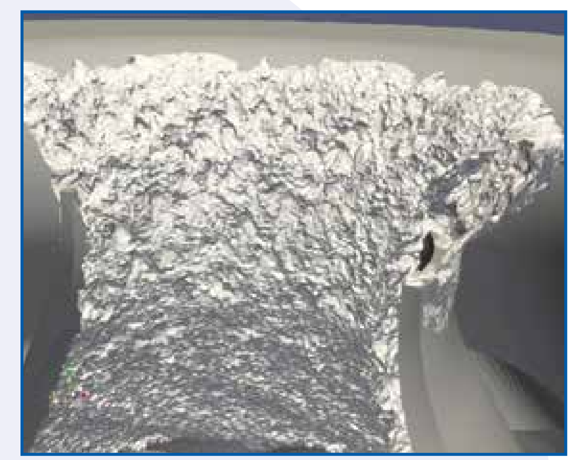
2. Research & Development Activities Performed

In the FIRST project, CORIA researchers have developed and applied numerical methods for primary atomization to realistic injectors. The aim of these simulations was twofold: i) validate the numerical strategy in terms of accuracy and robustness, ii) identify the bottlenecks and the potential improvements. The simulations of the triple injector, of the ONERA liquid sheet with swirl and of the Turbomeca injector, highlighted the need for high mesh resolution at the air/liquid interface. Such resolution may only be obtained through manual or automatic local mesh adaptation.

3. Advancement of Capability due to the FIRST project

During the project, various numerical techniques were developed in order to improve the fidelity of the simulations and enhance their comparison with experiments. Two major new capabilities of the simulation tools are parallel adaptive mesh refinement and segmentation techniques for the calculation of droplet size distribution. All these capabilities have been designed for massively parallel LES with more than 10,000 cores of modern super-computers. These simulations tools are now used by industrial partners in the FIRST project to improve their understanding of primary atomization.





4. Additional information

Application: Liquid fuel injection in aeronautical burners
Research area: Primary atomization modelling
Technology readiness level: 2
Owner of IPR: CORIA - CNRS
FIRST Task: T2.2.2
Main author and contact: Vincent Moureau, CNRS-CORIA

A Multi-Scale Approach For Primary Atomization Modelling (ONERA)

1. State of the Art before the FIRST project

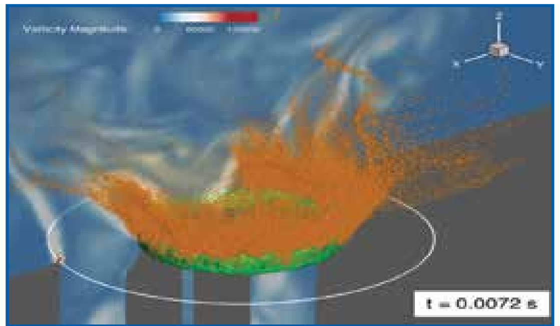
Today most advanced LES simulations of aeronautical combustors are performed with dispersed phase approaches for the fuel. The numerical droplets are directly injected by fixed numerical injectors whose characteristics are obtained by empirical correlations. These correlations demand an a priori knowledge of the injector, defeating the purpose of predictive computations.

2. Research & Development Activities Performed

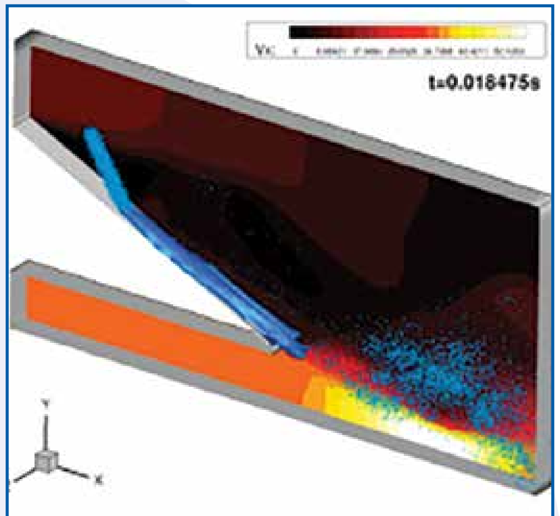
ONERA has developed a new approach for large-scale unsteady simulations of primary atomization. It consists of a coupled multi-fluid solver for the simulation of the liquid core and a dispersed phase approach for the generated cloud of droplets. This approach has been tested on different configurations, such as atomization of a sheared planar liquid sheet, film formation and re-atomization and a realistic circular swirled injector.

3. Advancement of Capability due to the FIRST project

Current industrial numerical simulations of combustion chambers cannot resolve the small-scale mechanisms of primary atomization. Injection of droplets is done by fixed injection points. The ONERA multi-fluid method is able to reproduce the large scale instabilities of primary atomization such as flapping motion and largest ligaments formation. The developed atomization model is able to detect the zone where the droplets are most likely to appear and to act subsequently as an advanced numerical injector, transferring the resolved liquid to an appropriate distribution of numerical droplets. Taking account of the instabilities of the injection, it gives a more accurate initial position and velocity of each particle. The model naturally respects the resolved liquid core and performs the conversion at realistic break-up lengths. The reciprocal model of droplets impact on resolved liquid structures or wall has been developed as well. Implementation of the solvers and the model is straightforward in any unstructured mesh finite volume framework.



Simulation of a sheared planar liquid sheet. Turquoise: resolved liquid core; green: Lagrangian droplets.



Simulation of droplet impact on a wall and subsequent film re-atomization.

4. Additional information

Application: Fuel injector of aero combustors
Research area: LES simulation of combustors injection
Technology readiness level: 2
Owner of IPR: ONERA
FIRST Task: T2.2.4.1
Main Author and Contact: Davide Zuzio, ONERA

Primary break-up modelling using SPH (KIT)

1. State of the Art before the FIRST project

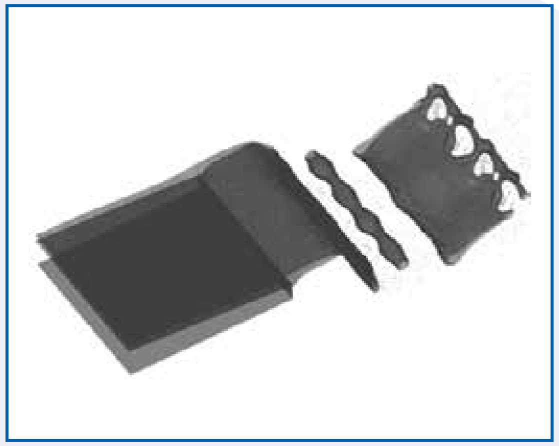
Before FIRST, reliable predictions of the fuel atomisation in aero combustors were not feasible using conventional grid based simulation techniques. By introducing the particle based method SPH, such simulations including multiple fluids can be performed more easily. Prior to FIRST, the method lacked some basic boundary treatment capabilities such as generalised periodic boundaries and suitable inlet/outlet boundary conditions.

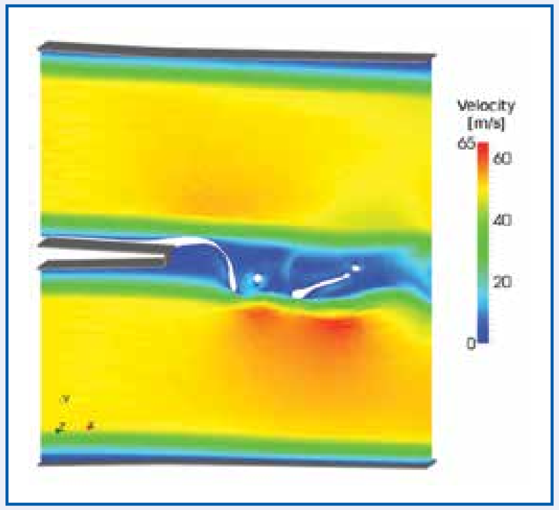
2. Research & Development Activities Performed

KIT has implemented a massively parallel software based on the standard SPH methodology and developed robust inlet/outlet boundary conditions and generic periodic boundaries. Some physical models were adjusted in order to handle fluid pairings with high density and momentum ratios correctly. 2D and 3D simulations of an academic air-blast atomizer were performed and results have been validated by experiments. Additional software has been developed for data reduction and visualisation of the results, even on a standard PC.

3. Advancement of Capability due to the FIRST project

The advancement of the SPH method within FIRST enabled its applicability to the simulation of air assisted atomizers. Detailed simulations, including very fine spatial resolutions and large data sets are possible due to the low memory requirements of the method and the highly parallelized code. The simulation of an academic atomizer at ambient pressure has been performed. The implemented additional post-processing software facilitates and speeds up the analysis of simulation results. The simulations help to understand the complex phenomenon of primary atomization, which in turn is a prerequisite for the development of more environmentally friendly combustion processes.





4. Additional information

Application: Fuel injection in aero combustors
Research area: Liquid fuel atomization modelling
Technology readiness level: 3
Owner of IPR: KIT
FIRST Task: T2.2.4.2
Main author and contact: Samuel Braun, KIT-ITS

Modelling of liquid jet primary break-up in swirl atomisers (UNIBG)

1. State of the Art before the FIRST project

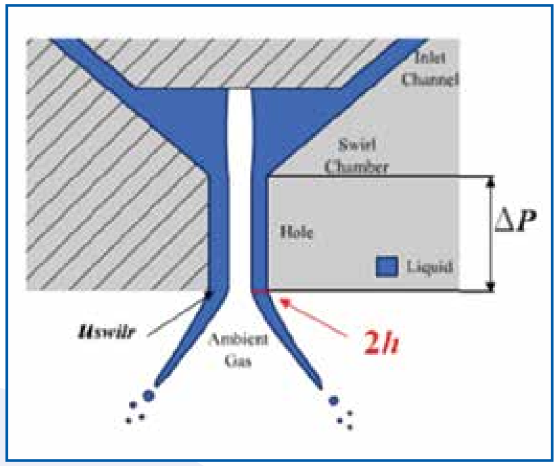
Prior to FIRST the primary break-up models available in the literature for hollow cone sprays did not account for the effect of turbulence on primary atomisation.

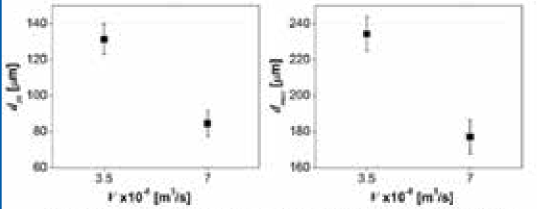
2. Research & Development Activities Performed

A novel formulation of the primary atomisation model has been developed by UNIBG for hollow cone swirling jets, under operating conditions suitable for aeronautic applications and explicitly accounting for turbulence and aerodynamic effects on the liquid break-up. The input conditions of the model have been provided by the simulations performed by UNIBG within the project. The model determines the dominant mechanism responsible for liquid jet break-up and the mean, maximum and drop size distribution of the newly formed spray.

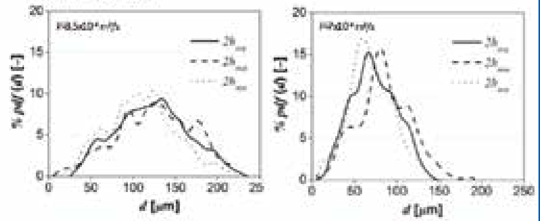
3. Advancement of Capability due to the FIRST project

The atomisation model developed by UNIBG within the framework of the FIRST project for hollow cone sprays is capable of determining the dominant mechanism responsible for primary break-up and the most crucial parameters affecting the process. Under the selected operating conditions, suitable for aero-engine applications, the liquid lamella thickness at the nozzle exit and the fuel injection rate prove to be the most sensitive parameters to the evaluation of the d30 mean diameter of the spray generated after the break-up of the liquid jet. This confirms the crucial influence of internal nozzle flow development on spray formation.





Effect of fuel injection flow rate on drop mean and maximum diameters after primary break-up



PDF distribution of drop diameter after primary break-up, function of the average, min and maximum values of the lamella thickness as predicted by 3D VOF simulations.

4. Additional information

Application: Fuel injector of aero combustors
Research area: Liquid film atomisation
Technology readiness level: 2
Owner of IPR: Università degli studi di Bergamo
FIRST Task: T2.2.6
Main Author and Contact: Gianpietro Cossali, UNIBG

Modelling of spray formation in a ULN injector (UNIBG, AVIO)

1. State of the Art before the FIRST project

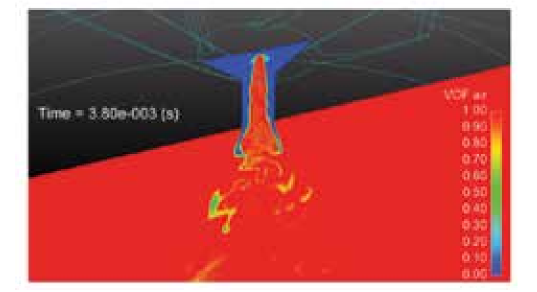
Prior to FIRST the input conditions of the primary atomisation models predicting the jet break-up for aero-engine applications were provided by semi-empirical correlation available in the scientific literature.

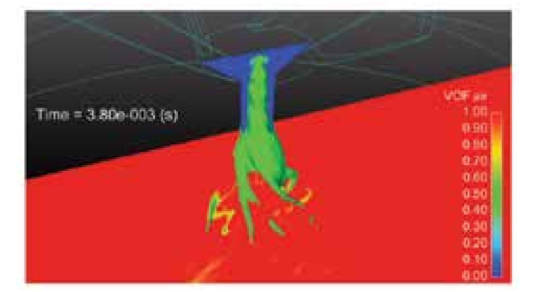
2. Research & Development Activities Performed

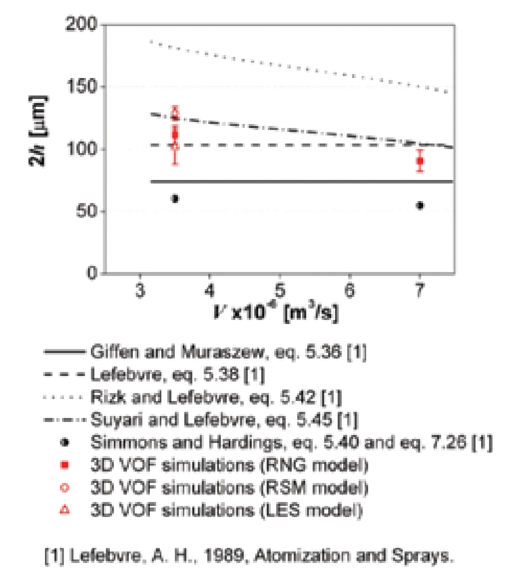
The internal flow and the liquid structure exiting the nozzle have been investigated by UNIBG in a typical pressure swirl atomizer for aero-engine applications under isothermal non reacting environment, using a combination of single and two-phase flow Eulerian models implemented in-house and commercial CFD codes. A numerical methodology has been developed to provide the necessary input conditions for successive atomisation modelling.

3. Advancement of Capability due to the FIRST project

The work performed by UNIBG during the FIRST project has evidenced that the liquid lamella thickness at the nozzle exit results to be the most crucial parameter affecting the successive primary atomisation modelling. The proposed methodology has been refined at a level that the predicted variability due to the numerical method is well below the differences found in the results obtained using well known empirical correlations available in the literature and usually implemented for spray calculations, suggesting that it can be used to improve the performances of primary atomisation models.







4. Additional information

Application: Fuel injection in aero combustors
Research area: Internal nozzle flow simulations
Technology readiness level: 2
Owner of IPR: Università degli studi di Bergamo, GE Avio
FIRST Task: T2.2.5 and T5.1.6
Main author and contact: Gianpietro Cossali, UNIBG

Sprays: Numerical Modelling of Academic Configurations

A Phenomenological Model for Droplet Dispersion and Clustering (IMPERIAL)

1. State of the Art before the FIRST project

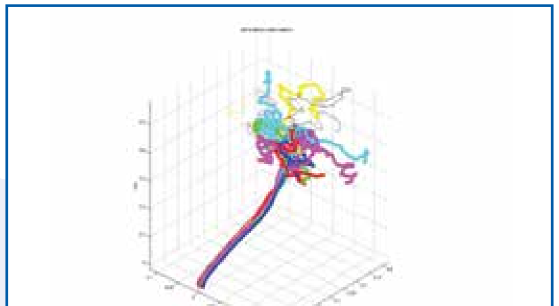
The stimulus for this work is the inability of the currently available RANS modelling tools to predict certain phenomena, experimentally observed, within the dispersed phase. Namely, particle/droplet preferential concentration and droplet trajectories in recirculation zones and regions of flow separation. The consequences of these limitations are that the instantaneous non-uniformity/homogeneity of droplet concentration spatial distributions observed experimentally at high Reynolds number flows cannot be observed in the corresponding modelling efforts.

2. Research & Development Activities Performed

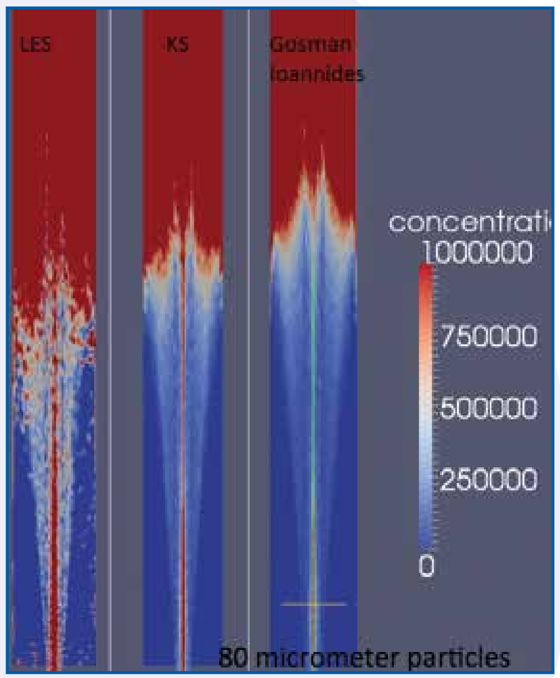
IMPERIAL developed fully coupled incompressible EE/EL solvers for use within the openFOAM modelling package. In addition a phenomenological model for particle dispersion that uses KS was developed to model the smaller scales of the dispersed flow in a RANS framework. The model was tested on an axi-symmetric sudden expansion test case for two distinct particle class sizes and several mass loadings. Results were compared to LES calculations performed and to RANS simulations employing the commonly used dispersion model as well as against experimental data.

3. Advancement of Capability due to the FIRST project

The limitation of current RANS Lagrangian tracking dispersion models may be traced back to the fact that the 'computed' instantaneous flow eddies in Monte-Carlo models are only prescribed from the local values of the turbulent kinetic energy and the local dissipation rate of the flow field from which a fluctuating component of velocity is assigned to the particle. There is no physical flow structure information contained within these 'constructed' eddies. The developed model uses the standard (u)RANS technique for modelling the bulk of the flow field but then employs KS within each 'computationally constructed' eddy in order to introduce a more realistic flow structure for the smaller scales of the flow, which are not computed in a typical RANS calculation. Performance of the developed model is improved over the existing models and, for certain regions of the flow, predictions are very similar to the LES results but is still limited by the RANS framework it was designed for. The developed model is not restricted to the aero-combustor sector but is equally suited for use in a wide range of fields from biological modelling to environmental flows.

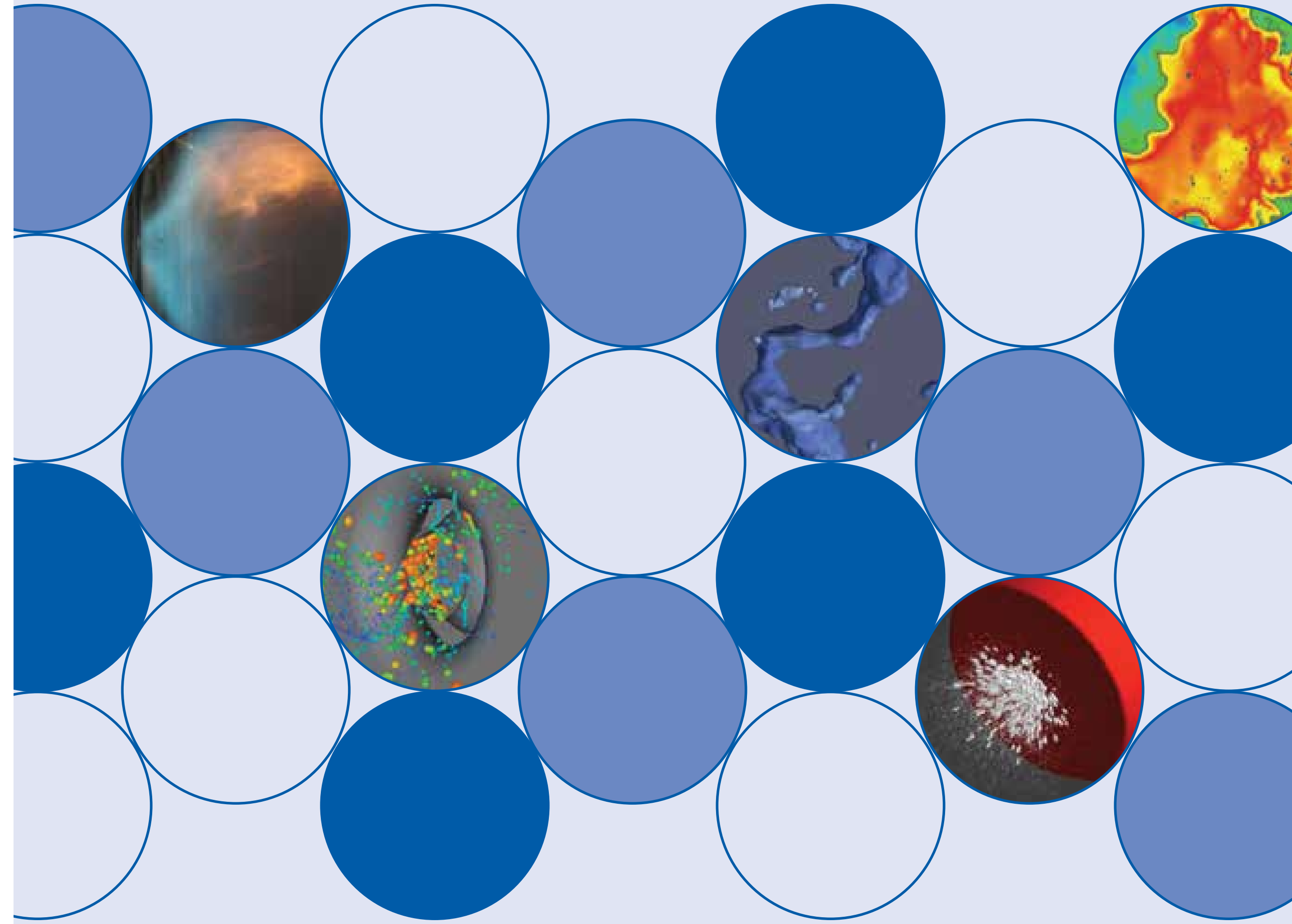


Dispersion of a cluster of fluid particles in KS flow field



4. Additional information

Application: Fuel injector for aero combustors
Research area: Spray Modelling
Technology readiness level: 2
Owner of IPR: Imperial College London
FIRST Task: T2.2.3 & T4.2.2
Main Author and Contact: Koulis Resvanis, IMPERIAL College



Sprays:

Numerical Modelling of Ideal and Real Injectors

Secondary breakup CFD models (EST, UNIFI, AVIO)

1. State of the Art before the FIRST project

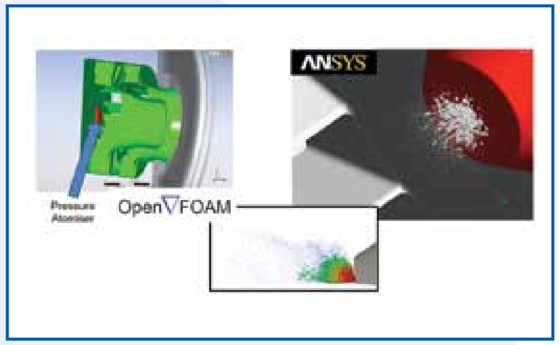
Before FIRST, recent developed secondary atomization models were not available in the OpenFOAM suite and the commercial code Ansys CFX had not been verified in the aerospace sector as a tool to study the breakup process. All available models had only been tested in the automotive field.

2. Research & Development Activities Performed

In order to test the accuracy and reliability of selected secondary breakup and droplets coalescence/ interaction models in Ansys CFX, different operating conditions were investigated. The cases considered were characterised by different values of pressure and temperature for the chamber and different flow rates. In the FIRST project, UNIBG performed numerical simulations of the injector using the VOF method in order to provide a text file with droplets position, velocity and diameter as a function of time after primary breakup for each case. These files were used as droplets boundary conditions for calculations in the project. Global and local criteria have been used to evaluate the process. The behaviour of the models is very similar in the global criteria and some differences are only visible in the local distribution of diameters. Selected secondary breakup models have been implemented in the OpenFOAM suite. To test the accuracy and reliability of the implemented models, a selected case was investigated with different breakup models and the results compared with Ansys CFX. The behaviour of the models is similar in normal penetration and spray angle. Some differences are visible in axial penetration.

3. Advancement of Capability due to the FIRST project

The FIRST project has enabled investigation of secondary breakup models in different operating conditions for a real injector developed by GE Avio using the commercial code Ansys CFX. The results indicate that the available models are almost equivalent in the evaluation of the global characteristics of the spray (penetrations and angle), but differ enough in the local diameter distribution. In addition, the FIRST project has enabled the implementation and exploitation in OpenFOAM of recently developed secondary breakup models.



4. Additional information

Application: Secondary atomization using commercial and open source CFD codes
Research area: CFD analysis of injection zone
Technology readiness level: 2
Owner of IPR: EnginSoft, Università degli Studi di Firenze, GE Avio
FIRST Task: T4.1.1
Main Author and Contact: Michele Andreoli, EnginSoft

Numerical methods to compute dense spray inside the injector (CERFACS)

1. State of the Art before the FIRST project

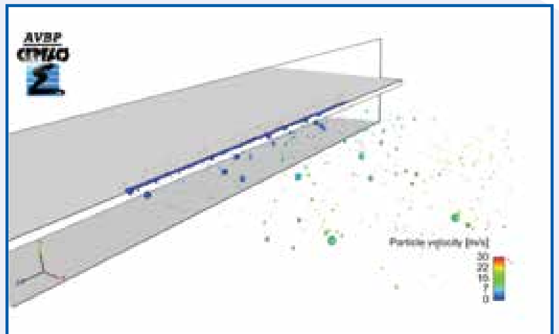
Fuel injection models such as FIMUR developed by CERFACS only describe the spray issued from a pilot injector. However in many real engines, the spray generated by the central nozzle impacts the walls of the diffuser, forming a liquid film that re-atomizes downstream at the tip of the diffuser to create a secondary spray that has very different features. The objective was to develop a model for Spray-Wall Interaction (SWI), capable of describing the film forming, flowing and atomization.

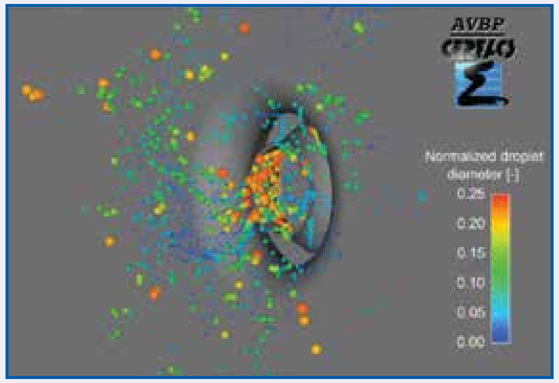
2. Research & Development Activities Performed

A phenomenological model was developed based on the knowledge available in the literature. It describes the droplet impact, film flow and film atomization and was parameterised by the known two-phase flow characteristics and geometrical features. The implementation in the numerical code AVBP, using the Lagrangian framework, was validated against experimental results obtained in the KIAI project by KIT, before being applied to a real Turbomeca injector. The impact on the subsequent two-phase flow and flame in the combustion chamber was observed and analysed.

3. Advancement of Capability due to the FIRST project

This work allowed significant improvements of the representation of the complex physics of liquid injection in the code AVBP. The code has been equipped with a model for SWI and liquid film, that may now be used in other contexts than injection (SWI and liquid films may also exist inside the combustion chamber).





4. Additional information

Application: Spray-Wall interaction and liquid films
Research area: Two-phase flow modelling
Technology readiness level: 2
Owner of IPR: CERFACS
FIRST Task: T4.1.3
Main author and contact: Geoffroy Chaussonnet, CERFACS

Sprays: Numerical Modelling of Ideal and Real Injectors

Assisted atomisation process: advanced simulations and comparison with experiments (UPMC, CNRS, ONERA)

1. State of the Art before the FIRST project

Prior to the FIRST project, DNS of complex interfacial phenomena were already under development. Yet, they remained ineffective and numerically unstable for flow conditions encountered in aero-engines, namely high density (> 1000) and velocity (≥ 10 in favour of the gas).

2. Research & Development Activities Performed

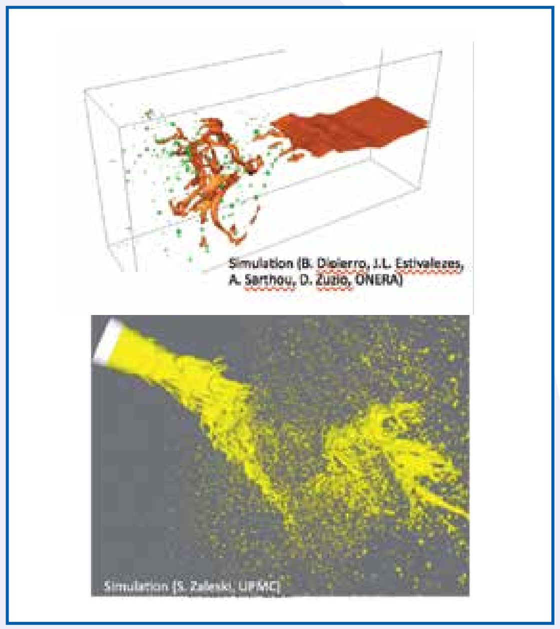
Detailed analysis of code limitation have led to the development and the implementation of new resolution schemes for DNS based on VOF and/or Level-Set methods. The spatio-temporal resolution as well as numerical performances of these codes were significantly improved, allowing to simulate laboratory experimental conditions. The combined investigation of atomisation processes by way of controlled experiments, simulations and theoretical analyses was also undertaken to test the ability of these codes, to accurately represent the elementary physical processes and to evaluate their reliability.

Simulation (A. Berlemont, T. Ménard, G. Vaudor, CNRS-CORIA)

Experiment (A. Cartellier, A. Delon, J.P. Matas, CNRS-LEGI)

3. Advancement of Capability due to the FIRST project

DNS of assisted atomisation phenomena that were out of reach at the start of the project, are now available for flow conditions relevant for turbo-reactors. The codes developed are thus at the cutting edge. The combination of such advanced simulations and of experiments has led to a new understanding of the interfacial instabilities arising in assisted atomisation. In addition, quantitative agreements between experiments and simulations have been obtained on a number of physical quantities. In particular, preliminary comparisons between predicted and observed size distributions is quite encouraging. A further significant decrease of computation times that remain enormous - at the limit of today's computers – is required to fully ascertain the reliability of such tools in terms of drops size and flux.



4. Additional information

Application: Prediction of spray characteristics in aero-engines
Research area: Fundamental mechanisms controlling assisted atomisation and their simulation
Technology readiness level: 3
Owner of IPR: UPMC, CNRS-CORIA, CNRS-LEGI, ONERA
FIRST Task: T4.1.4
Main Author and Contact: Alain Cartellier, CNRS

FIRST Project Summary of Achievements: Advancements in Spray & Soot Research

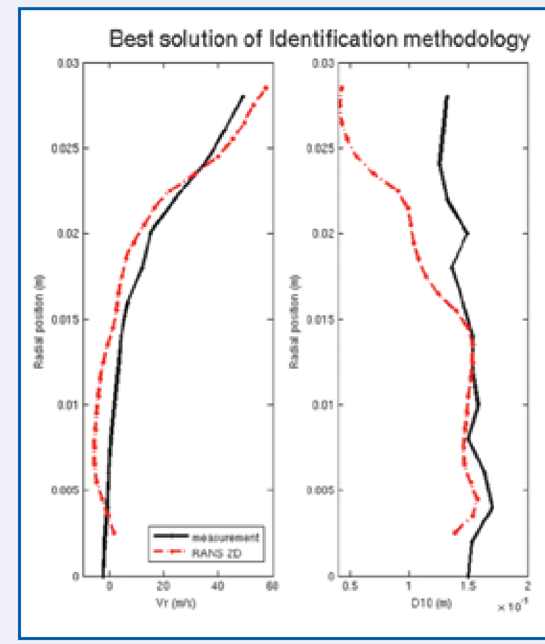
Identification of Spray Boundary Conditions from Measurements (ONERA)

1. State of the Art before the FIRST project

Two phase flow computations require the specification of the boundary conditions for the liquid phase. When they are not known but measurements not too far from the injection points are available, an approach based on the inverse problems can be implemented. The fuel injection model developed by CERFACS (FIMUR) provides the size and velocity distributions of the droplets at injection for a pressure-swirl atomizer. The purpose was to develop a methodology of identification for any type of atomizer.

2. Research & Development Activities Performed

Spray boundary conditions are a solution of an inverse problem which involves the minimisation of the distance between computed and measured distributions of size and velocity of the droplets at measurement section. This optimisation problem is solved as a results of a surrogate modelling approach and a genetic algorithm. Because of the high cost of two phase flow computations, the choice was made to use 2D-axisymmetrical computations with the ONERA code CEDRE. In order to validate the process, the boundary conditions obtained were then applied to 3D LES (code AVBP, CERFACS) and 3D RANS (code N3SNatur, SNECMA) computations.



3. Advancement of Capability due to the FIRST project

A methodology for boundary condition identification is now available as a result of the FIRST project. Moreover, the measurements necessary for its validation are issued from the project and have benefited from the setup improvements, by allowing the measurement section to be moved closer to the injection point. Although the TLC SNECMA injector chosen for the experimentation did not appear to have an axisymmetric behaviour, the application on this injector has shown that a valuable expertise can be obtained with this methodology.

4. Additional information

Application: Boundary conditions of liquid phase for two phase flow computations
Research area: Two-phase flow injection modelling
Technology readiness level: 2
Owner of IPR: ONERA
FIRST Task: T4.2.1
Main author and contact: Patricia Klotz, ONERA

Sprays: Numerical Modelling of Ideal and Real Injectors

Exploitation film model (SNECMA)

1. State of the Art before the FIRST project

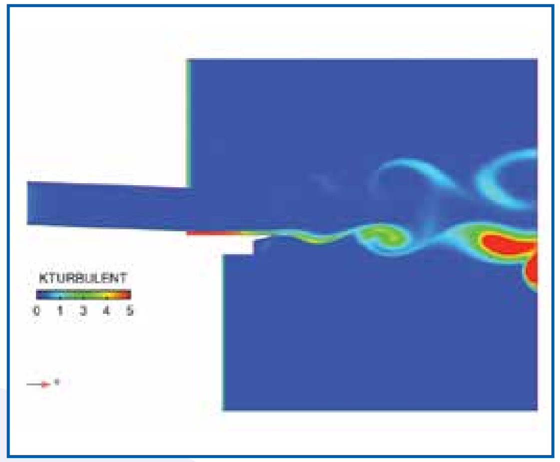
The numerical simulation of an aeronautical combustor requires a number of assumptions or simplifications. The formation of a film over the wall surrounding the injector which will then be atomized by the shear flow is in general not taken into account. To deal with the interaction of the droplet with the wall, a simple elastic or non elastic rebound is implemented in the solver. Numerically, the droplet never forms a film at the wall. By adopting this approach, an interesting physical behaviour that can modify the fuel distribution inside the combustor is lost. A film model accounting for those mechanisms was available in the Snecma in-house RANS solver but hadn't been validated.

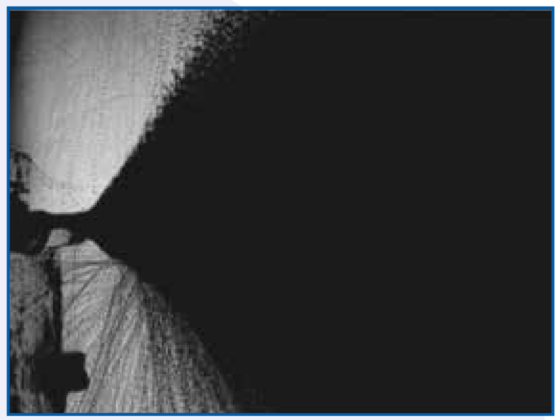
2. Research & Development Activities Performed

In close collaboration with CNRS-LEGI, a planar film experiment was defined in order to provide data to validate the film model available in the Snecma in-house RANS solver and in particular the formation of droplets at the end of the injector wall (geometrical discontinuity). The liquid used in this experiment was water. Two operating conditions were agreed and LEGI provided the mean droplet characteristics at several radial and axial locations. Several calculations were made using the Snecma in-house film model to validate it against the available data.

3. Advancement of Capability due to the FIRST project

The Snecma in-house film model has been validated. The formation of a fuel film by the fuel droplets impacting the injector wall and the subsequent droplet formation at the wall end can now be included in combustor simulations. Nevertheless, this kind of RANS modelling is just one intermediate step in the path to the final use of more sophisticated and physics based models (Cerfacs and Coria work) to account for film and atomisation processes in computations.





4. Additional information

Application: Boundary conditions of liquid phase for two phase flow computations
Research area: Two-phase flow injection modelling
Technology readiness level: 2
Owner of IPR: SNECMA
FIRST Task: T5.1.2
Main Author and Contact: Juan Carlos Larroya Huguet, SNECMA

Exploitation of phenomenological models (SNECMA)

1. State of the Art before the FIRST project

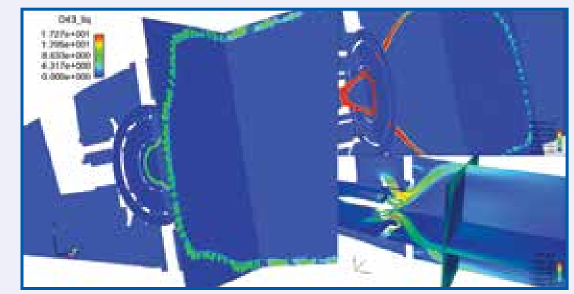
The simulation of two phase flow inside a combustor required the specification of the boundary conditions for the liquid phase. An experience based approach was available at Snecma to define these boundary conditions. Experimental characterisation of the injector was used to specify a pertinent ensemble of droplet classes as well as their initial velocities and injection locations close to the injector exit.

2. Research & Development Activities Performed

Snecma provided a TLC injector system to ONERA, who conducted the experimental characterisation of the spray. This information was used to feed an ONERA numerical tool devised to obtain a new and better set of boundary conditions for the liquid phase as output. Unfortunately, the experimental data has shown an unexplained asymmetric behaviour and the exploitation of this data by the ONERA tool was compromised. Partial data from TLC project on this injector was used to overcome this difficulty. ONERA provided a new set of boundary conditions for the liquid phase to Snecma and a back-to-back calculation was made in order to evaluate the result of applying the new methodology versus the old one.

3. Advancement of Capability due to the FIRST project

A new methodology for liquid phase boundary conditions identification is available as a result of the FIRST project. This methodology will be used to automate the generation of boundary conditions for the liquid phase and to improve the reliability of the combustor simulations. This kind of approach is just one intermediate step in the path to the final use of more sophisticated and physics based models (CERFACS and CNRS-CORIA work) to account for the liquid phase in simulations.



4. Additional information

Application: Boundary conditions of liquid phase for two phase flow computations
Research area: Two-phase flow injection modelling
Technology readiness level: 2
Owner of IPR: SNECMA
FIRST Task: T5.1.3.1
Main author and contact: Juan Carlos Larroya Huguet, SNECMA

Exploitation of phenomenological models (Turbomeca)

1. State of the Art before the FIRST project

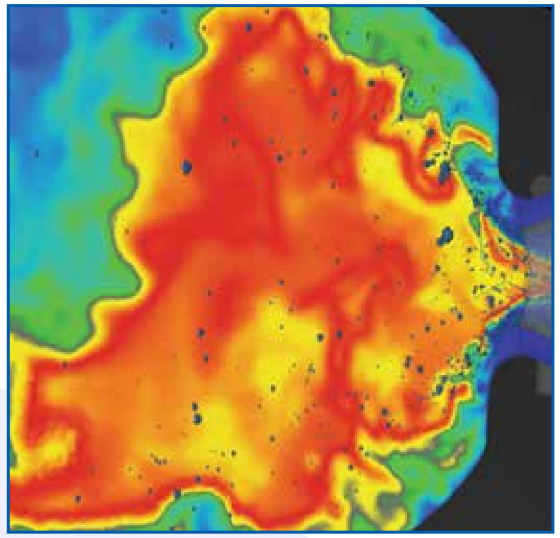
The specification of liquid injection properties can be of paramount importance when simulating a combustion chamber for reaction zone localization, pollutant formation, ignition or extinction processes. To specify such characteristics, Turbomeca employs the extrapolation of experimental measurements (velocity, droplets distributions) to reach realistic operating conditions.

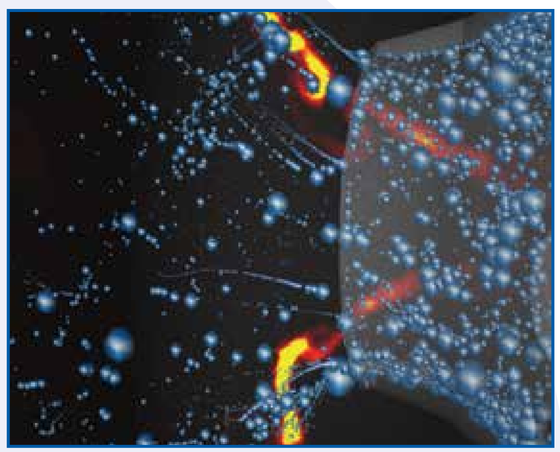
2. Research & Development Activities Performed

In the FIRST project, CERFACS developed liquid film and atomization models suited for the simulation of the dense-spray region inside an aeronautic combustion chamber equipped with airblast atomizers with film-wall interaction. CERFACS and Turbomeca performed reactive LES of a combustion chamber at two operating conditions, using different approaches to model the liquid boundary conditions.

3. Advancement of Capability due to the FIRST project

A new methodology for liquid phase boundary condition identification is available and requires no constraining parameters extrapolated from experimental data. This enables Turbomeca to confidently perform reactive two-phase LES at various operating conditions for a reasonable CPU cost. This kind of approach bridges the gap between very costly primary atomization simulations and cheap experimental correlations, which are not properly validated for a wide arrange of injection technologies and operating conditions.





4. Additional information

Application: Boundary conditions of liquid phase for two phase flow computations
Research area: Two-phase flow injection modelling
Technology readiness level: 2
Owner of IPR: Turbomeca
FIRST Task: T5.1.3.2
Main Author and Contact: Jean Lamouroux, Turbomeca

FIRST Project Summary of Achievements: Advancements in Spray & Soot Research

Validation of the VOF approach in regards to primary atomization in a model injector (MTU)

1. State of the Art before the FIRST project

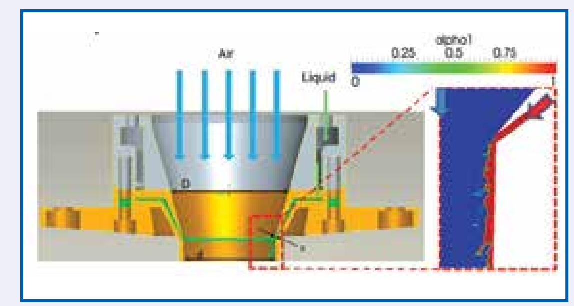
The volume of fluid (VOF) approach is a well known numerical method to simulate two-phase-flows. However, mainly due to the lack of detailed validation data, the applicability of VOF to predict the primary atomization in annular aero engine injectors could not be verified so far.

2. Research & Development Activities Performed

In cooperation with the Engler-Bunte-Institut (EBI) of the University of Karlsruhe, MTU performed a detailed comparison of numerical results with the experimental data base of a generic model injector. The analysis covered the comparison of the average film thickness as well as the local film thickness distribution. Through a comprehensive sensitivity study over a wide range of operation conditions, the occurrence of primary atomization inside the model injector was correlated to a minimum of momentum ratio of the liquid to gaseous flow.

3. Advancement of Capability due to the FIRST project

Using the validated numerical model, the parameter studies performed delivered a more detailed insight into the primary atomization occurring inside the model injector. The analysis of fuel mixed into the gaseous flow before leaving the injector nozzle and entering the combustion chamber indicates that the primary atomization influences the fuel distribution inside the reaction zone significantly. The simplification of ignoring the primary atomization inside the nozzles widely used in current modelling approaches may lead to incorrect fuel distribution predictions during design phases of combustion systems. The comprehensive sensitivity study revealed that the characterisation of the two phase interaction cannot be based only on the momentum ratio.



4. Additional information

Application: Fuel injector of aero combustors
Research area: Numerical investigation of primary atomization zone in fuel injectors
Technology readiness level: 2
Owner of IPR: MTU Aero Engines AG
FIRST Task: 5.1.4
Main author and contact: Marco Konle, MTU Aero Engines AG

Sprays: Numerical Modelling of Ideal and Real Injectors

Thin film model for prefilming airblast atomizers (UNIFI, AVIO)

1. State of the Art before the FIRST project

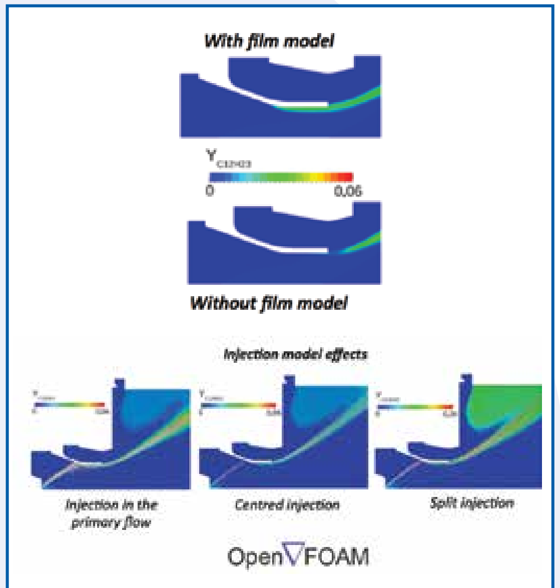
Before FIRST, computational techniques for liquid fuelled combustors based on Lagrangian tracking were not fully capable of dealing with liquid film development along the injector prefilming surface. This lack influenced both prefilming atomizer injection characterisation and parcel/wall interaction between prefilming surface and droplets coming from secondary injection (e.g. pressure atomizer functioning as pilot injector). For the former, modelling correlations were generally employed using a priori estimates of liquid film and gas flow field development, while for the latter, simple rebound models were often implemented neglecting the influence of liquid film development on droplet splashing.

2. Research & Development Activities Performed

A simplified model for the liquid film development along the prefilming atomizer surface coupled with a newly implemented steady-state Lagrangian tracking solver able to perform reactive simulations has been developed in the OpenFOAM suite. The model is based on the thin film approximation solving film conservation equations (film thickness, momentum and energy) with the Eulerian approach on a 2D mesh extruded normally from the wall. Coupling with the gas phase is achieved on the film/gas interface maintaining equal interface velocity and shear stress on both sides. Coupling with the Lagrangian tracking includes implementation of a splashing model (for droplet hitting the wet surface) and of injection models to account for the primary break-up. These injection models are based on available correlations which are solved with updated film and gas properties at each iteration to provide the required feedback from the film solver. Among the others, some of the implemented models are based on newly developed correlations developed in KIAI EU program by KIT for planar prefilming airblast atomizers.

3. Advancement of Capability due to the FIRST project

The FIRST project has enabled the investigation of the effects of the liquid film developing on the prefilming airblast on the global combustor performance by means of fast and robust CFD analysis suitable for industrial applications. A pre-filming injector geometry with an additional pressure swirler pilot injection (provided by GE Avio) was considered in a tubular configuration simplified to obtain axisymmetric computations. Results indicate that fuel evolution is deeply impacted in the injector region by liquid film formation, especially when droplets from the pilot injector impinge on the film. Furthermore the OpenFOAM toolbox is now upgraded to provide reliable simulations of other prefilming airblast atomizers or of the same injector in other configurations.



4. Additional information

Application: Thin film model for prefilming airblast atomizers
Research area: CFD analysis of injection zone
Technology readiness level: 2
Owner of IPR: Università degli Studi di Firenze, GE Avio
FIRST Task: T5.1.5
Main Author and Contact: Antonio Andreini, UNIFI

FIRST Project Summary of Achievements: Advancements in Spray & Soot Research

Expert system for liquid breakup (EST, AVIO)

1. State of the Art before the FIRST project

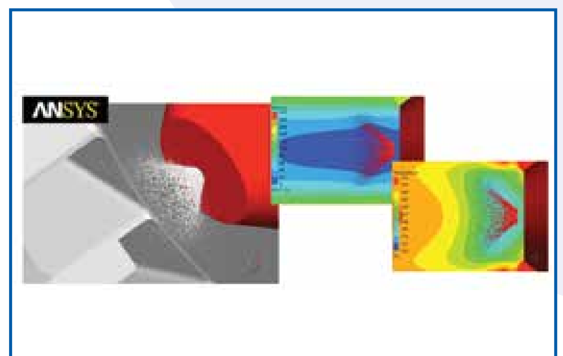
Before FIRST, the diameter distribution for sprays after the breakup process was computed by empirical expression.

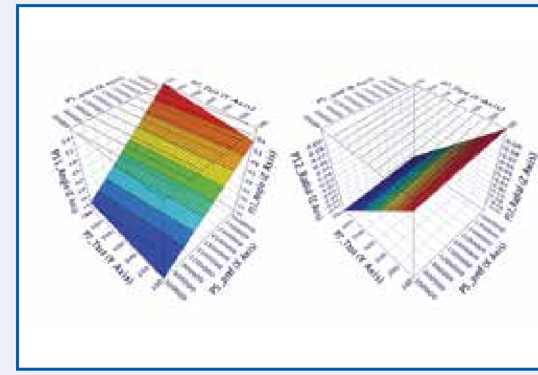
2. Research & Development Activities Performed

An expert system for the atomization scenario has been developed in order to characterise the breakup process in any physical scenario. Different operating conditions were considered and numerical simulations, including primary and secondary atomization have been computed using Ansys® CFX. The Design of Experiments (DoE) methodology was used to identify which input variables most affected the output variables. Starting from these results, response surfaces have been generated using the commercial code modeFrontier®.

3. Advancement of Capability due to the FIRST project

The FIRST project has enabled the prediction of diameter distribution for sprays after the breakup process in any scenario starting from the knowledge of the physical boundary condition. The accuracy of this method depends on the initial number of configurations used in the DoE, but can be considered more consistent with the physics compared to the empirical correlations used until now.





4. Additional information

Application: Response surface of breakup process
Research area: CFD analysis of injection zone
Technology readiness level: 2
Owner of IPR: EnginSoft, GE Avio
FIRST Task: T5.1.6
Main author and contact: Michele Andreoli, EnginSoft

Sprays: Numerical Modelling of Ideal and Real Injectors

Exploitation of spray models (IMPERIAL, RRUK, RRD)

1. State of the Art before the FIRST project

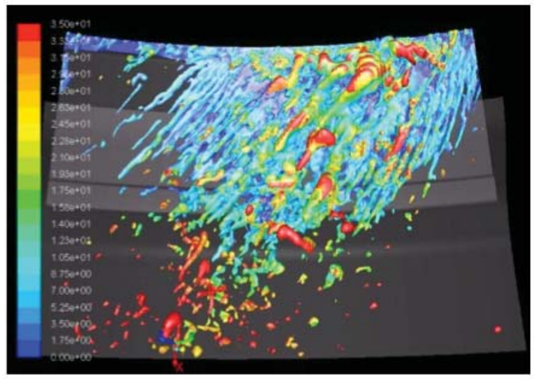
While CFD is widely used to simulate reacting flows in aero-engine combustors, spray boundary conditions have always been affected by significant uncertainty, which in turn can have a dramatic impact on a range of critical combustor performance parameters. In CFD simulations, spray is usually injected at a rather arbitrarily defined location downstream of the injector and particles tracked based on Lagrangian methods. Correlations derived in the past on geometries and conditions not necessarily representative of today's designs and pressure conditions have been used to define spray boundary conditions with mixed success. Limited understanding of the impact injector geometry has on spray quality has made injector design a highly empirical process with long development times, potentially leading to suboptimal solutions.

2. Research & Development Activities Performed

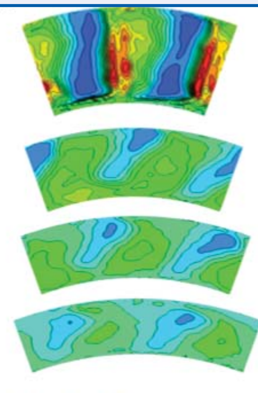
Detailed steady and unsteady simulations of an industrial lean burn fuel injector were carried out as part of FIRST, based on well resolved validation data provided by Loughborough University. The capability of single-phase LES methods to predict time-averaged and unsteady components for both the lean burn injector and a more conventional injector was assessed. Detailed simulation of the fuel passages enabled characterisation of the non-uniformity of fuel feed to the prefilmer of the lean burn injector. Furthermore, two-phase VOF simulations of an academic test case as well as the two injectors' film and primary break up were conducted. Eventually, an advanced dispersion model developed by Imperial College and based on the KS concept was implemented into the in-house code PRECISE and tested.

3. Advancement of Capability due to the FIRST project

The work done in FIRST has enabled to characterise the internal aerodynamics of a typical lean burn injector and validate the approach. In particular, an understanding has been obtained about the relative merits of LES over RANS within the injector design process. Moreover, a simple approach to simulating the fuel passages has proven beneficial to the definition of spray boundary conditions. While more research work will clearly be needed to make the two-phase flow methods for prediction of primary break up more accurate and computationally affordable, VOF has been proven to provide useful information about spatial and temporal distribution of fuel film on prefilming surfaces.



VoF LES of fuel film



LES of fuel injector air passages

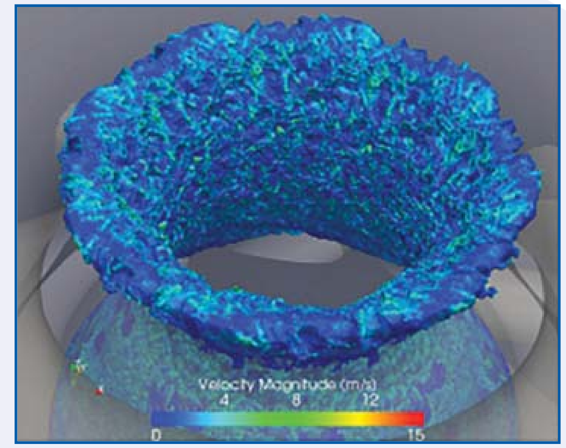
4. Additional information

Application: Emissions, temperature and flow field predictions in aero engine combustors
Research area: Spray modelling
Technology readiness level: 2
Owner of IPR: Imperial College, Rolls-Royce plc and Rolls-Royce Deutschland
FIRST Task: T5.1.7, T5.1.1
Main Author and Contact: Marco Zedda, Rolls-Royce UK

Exploration and Exploitation of fundamental models (Turbomeca)

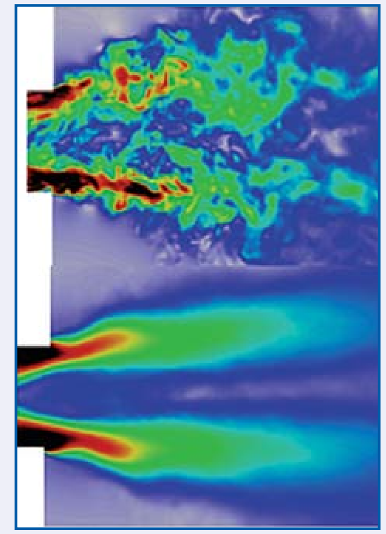
1. State of the Art before the FIRST project

A wide range of methodologies on primary atomization modelling exist and numerous validations of these techniques are performed on academic configurations. However, due to the high CPU cost and to the complexity of primary atomization simulation, CFD computations of real industrial injectors are solely focused on aerodynamics at Turbomeca. The computations are used in the early stages of design, and correlations and experimental analyses are used in conjunction to develop the injectors.



2. Research & Development Activities Performed

In the FIRST project, CNRS-CORIA researchers developed numerical methods for primary atomization adapted to large and complex geometries. Turbomeca assessed the feasibility of the simulation of one of its aerodynamic atomizer injectors where film-wall interactions are present by performing aerodynamic computations of the configuration. Turbomeca provided CORIA with one geometry and the associated experimental data for the primary atomization simulation using homogeneous mesh refinement methods. The simulations showed that the prediction of atomization using this approach was not compatible with industrial needs in terms of CPU costs, and highlighted the need for the development of heterogeneous mesh refinement methodologies.

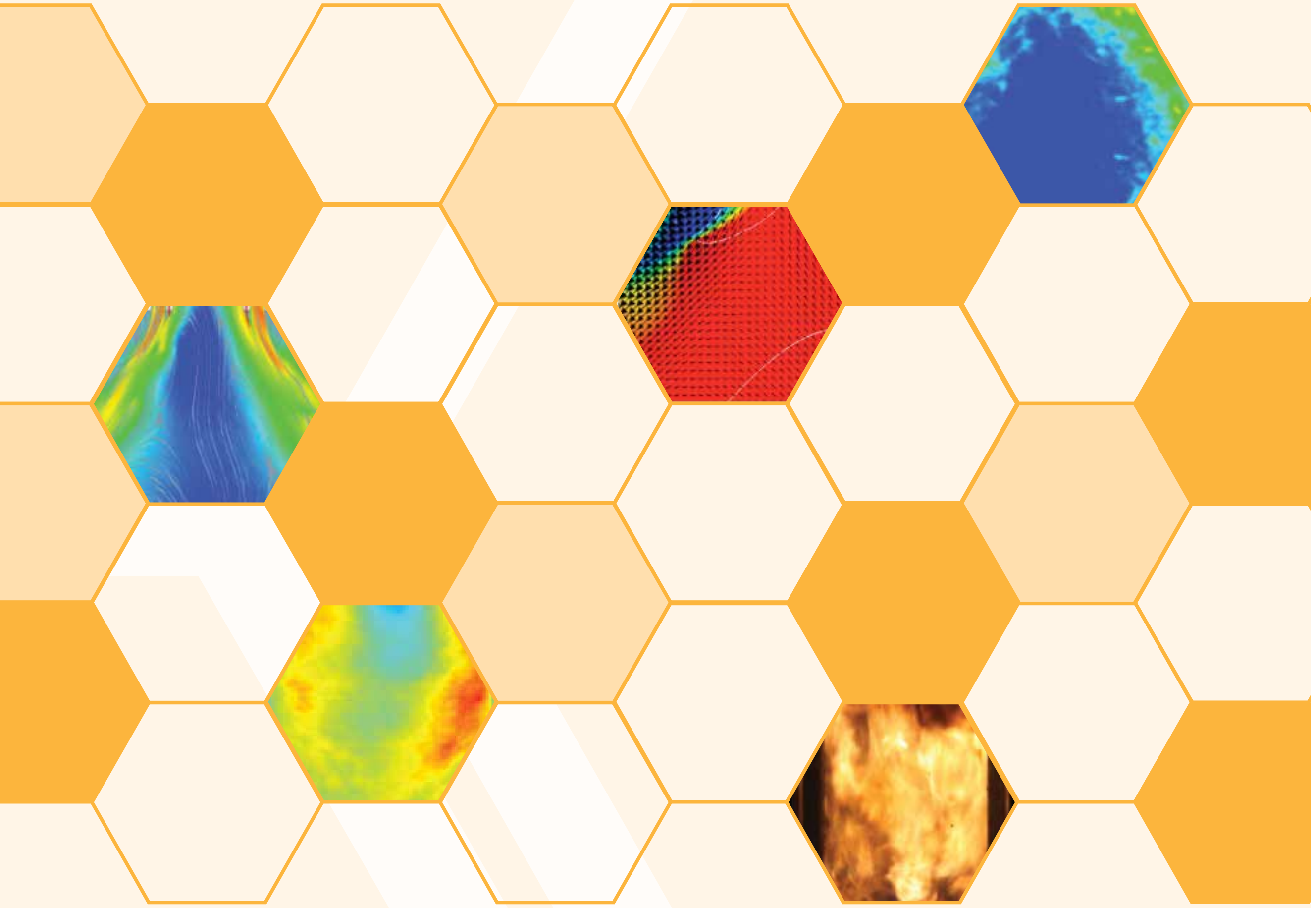


3. Advancement of Capability due to the FIRST project

In the project, Turbomeca obtained knowledge and tools to simulate the atomization process for pressure atomizers. For air-assisted atomizers, CORIA developed heterogeneous mesh refinement and partitioning techniques, adapted to industrial geometries and CPU capacities. The Safran group is continuing to work on primary atomization with CORIA with the start of a PhD thesis in 2014.

4. Additional information

Application: Primary atomization computations of industrial injectors
Research area: Primary atomization modelling
Technology readiness level: 2
Owner of IPR: SAFRAN - Turbomeca
FIRST Task: T5.1.8
Main Author and Contact: Jean Lamouroux, Turbomeca



Soot:

Experimental and Numerical Investigation of Soot Production

Advanced modelling for complex combustion systems including PAH and soot BINs (DLR)

1. State of the Art before the FIRST project

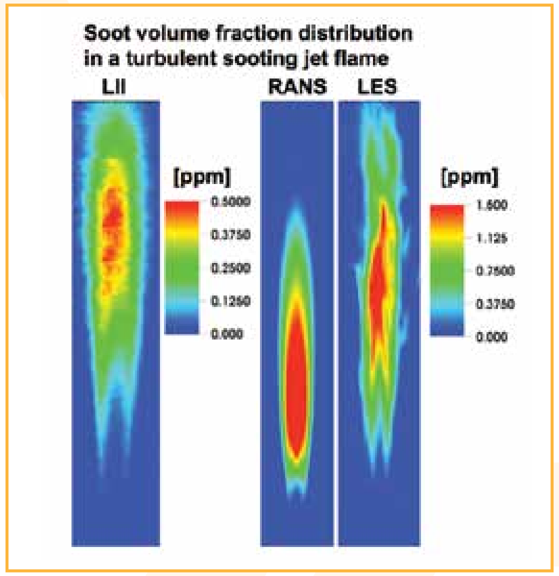
Before FIRST, the DLR soot model had been validated successfully for a wide range of different validation experiments (different fuels; laminar and turbulent; non-premixed, partially-premixed and premixed; atmospheric and high pressure conditions) with one set of model constants. However, the reversibility of surface chemistry was not considered in the soot model, yielding too fast soot formation compared to measurements. Turbulence was described by RANS turbulence models.

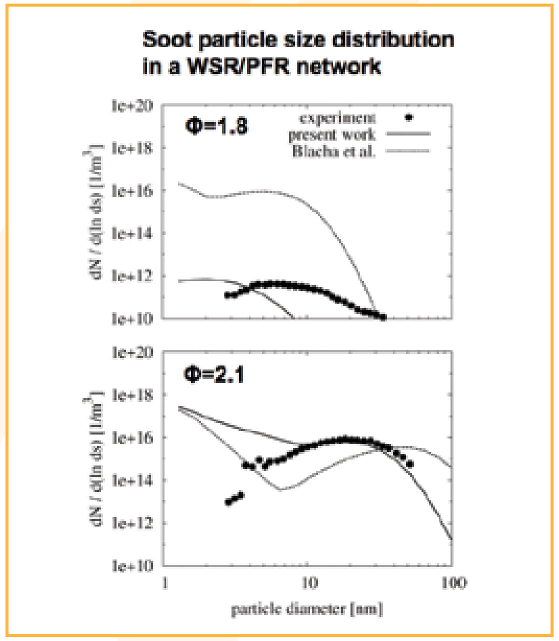
2. Research & Development Activities Performed

Within FIRST, the DLR soot model was coupled to LES turbulence models and LES simulations of a turbulent sooting jet flame were performed. Furthermore, a sectional soot precursor model which includes radical branches of PAH and reversible PAH surface chemistry has been developed and implemented in the DLR THETA code.

3. Advancement of Capability due to the FIRST project

The prediction of soot volume fractions in turbulent flames has been significantly improved by the coupling of the soot model with LES. The implementation of reversible soot precursor surface chemistry yielded a delayed soot formation and a better agreement on the validation of data. The sensitivity of the soot model to the equivalence ratio was improved, especially at equivalence ratios close to the sooting limit.





4. Additional information

Application: Soot model development for turbulent pressurized combustion
Research area: Soot modelling
Technology readiness level: 2
Owner of IPR: DLR-ST
FIRST Task: T2.1.1
Main Author and Contact: Christian Eberle, DLR-ST

Improved Soot Nucleation and Oxidation Mechanisms and Links to Surrogate Fuel Chemistry (IMPERIAL)

1. State of the Art before the FIRST project

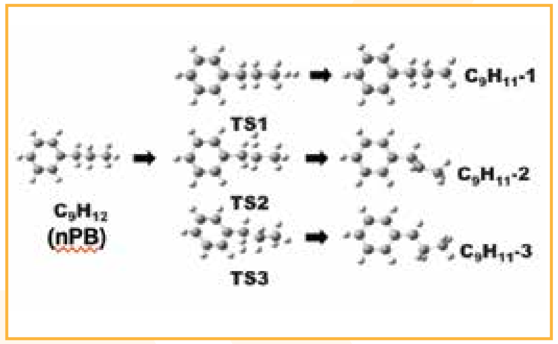
The formation and oxidation of aromatics is crucial in the context of links to surrogate fuel models used in combustor design calculations with nPB selected as a representative molecule in EU and US surrogate blends in order to modulate the sooting propensity. Prior to FIRST, the link between the chemistry of surrogate fuels and soot relied upon the application of reaction class, based estimation techniques with soot emissions typically computed using moment based or empirical methods, that do not provide PSDs.

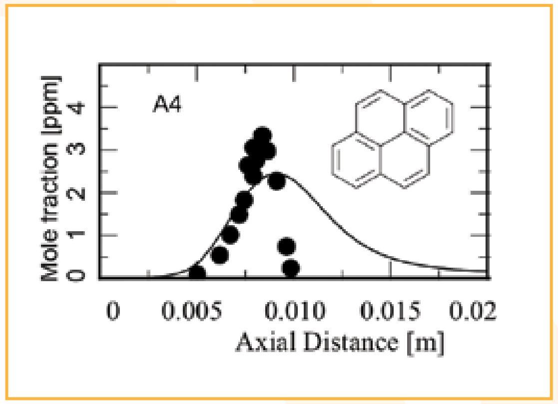
2. Research & Development Activities Performed

Ab initio methods at the G4, G4MP2 and G3B3 level were used to determine thermodynamic properties of 92 PAHs with up to 16 carbon atoms involved in soot nucleation and oxidation sequences. The recommended aromatic nPB component selected in the CFD4C programme (award: GRD1-1999-10325) was further studied through accurate ab initio methods with results obtained for six side-chain hydrogen abstraction reactions at the "gold standard" CCSD(T)/jun-cc-pVTZ//M06-2X/6-311++G(3df,3dp) level (bottom right image). More economical state of the art DFT methods were also evaluated. Test cases for laminar premixed flames, laminar diffusion flames and PSR/JSR geometries were computed and an evaluation of the PAH, soot formation and oxidation mechanisms performed in the context of computations coupled to sectional models capable of calculating full PSDs.

3. Advancement of Capability due to the FIRST project

The resulting chemical mechanism has been used to improve predictions of soot PSDs and particulate levels in premixed and diffusion flame environments through the further development of a mass and particle number density conserving sectional approach that links directly to the detailed PAH and soot inception chemistry. The ability of the devised approach to reproduce PAH concentrations up to pyrene (A4), used to define the smallest soot section via a dimerization, has been assessed using comparisons with laminar flame data (top right image). The prospects for simplifications of soot nucleation sequences has been evaluated along with the accuracy of computationally efficient DFT methods for larger molecules and recommendations made as to a suitable balance between accuracy and complexity.





4. Additional information

Application: Prediction of soot emissions from aero combustors
Research area: Surrogate fuels and link to soot particle size distributions
Technology readiness level: 2
Owner of IPR: Rolls-Royce
FIRST Task: T2.1.2
Main Author and Contact: Peter Lindstedt, IMPERIAL College

FIRST Project Summary of Achievements: Advancements in Spray & Soot Research

Characterisation of a Lean Burn Module Air Blast Pilot Injector with Laser Techniques (DLR)

1. State of the Art before the FIRST project

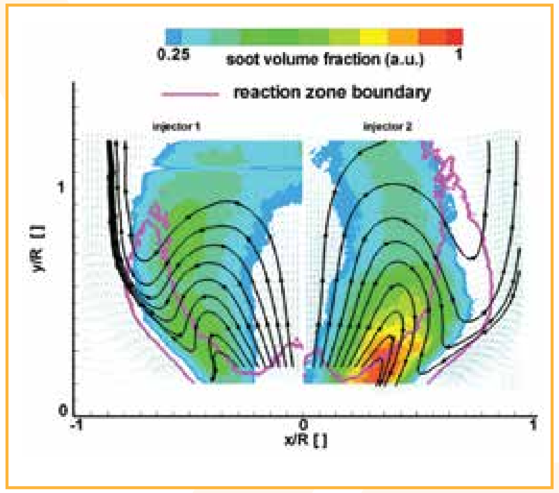
Pilot modules in staged lean burn fuel injectors exhibit a propensity to form soot at the upper power end of their operational envelope. Data on global smoke numbers at combustor exit and parametric dependence existed, but no detailed information on soot formation and its coupling to flow field and reaction zones inside the combustor were available. In particular, no validation data for CFD modelling of soot formation existed.

2. Research & Development Activities Performed

Data on velocities, soot volume fractions, reaction zone and fuel distributions, along with rig operation data, were obtained from a single sector combustor with optical access, equipped with a Rolls-Royce lean burn injector, by various optical methods under realistic operation conditions. The measurements allowed identification of soot forming regions inside the combustor and illustrated their dependence on flow field structures (through modified injector aerodynamics), equivalence ratio, temperature and pressure. These tests helped to obtain a qualitative understanding of the soot formation mechanisms. The data was provided to project partners for CFD validation.

3. Advancement of Capability due to the FIRST project

For the development of a virtual injector numerical tool, or more specifically soot formation predictive techniques, extensive databases with qualitative and quantitative measurements are necessary. For soot measurements, the LII technique was tested and applied under realistic operating conditions at idle and part load. Along with additional data on velocity field and reaction regions, these measurements form a database to validate the soot formation and transport models developed in FIRST.



4. Additional information

Application: Validation data for an industrial fuel injector; optical study of soot formation
Research area: Soot formation in lean burn injectors
Technology readiness level: 4
Owner of IPR: DLR
FIRST Task: T3.3.1
Main Author and Contact: Ulrich Meier, DLR

FIRST Project Summary of Achievements: Advancements in Spray & Soot Research

Validation data from sooting, turbulent flames (DLR)

1. State of the Art before the FIRST project

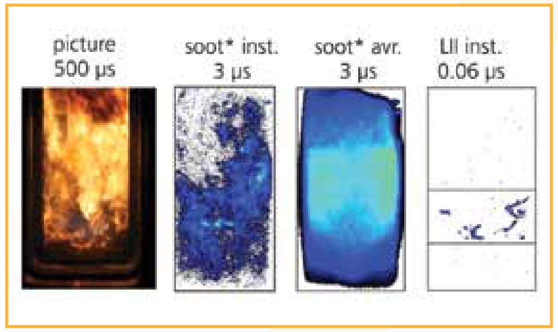
In literature no high quality validation data set is available at increased burner complexity. Soot model validation is mostly done using laminar flames or turbulent atmospheric jet flames. The only existing data set at increased pressure involving turbulence/swirl and oxidation air was good at that time but limited to soot concentration and few temperature measurement points for one single out of the set of flames (data set recorded during EU project Soot in Aeronautics, SiA).

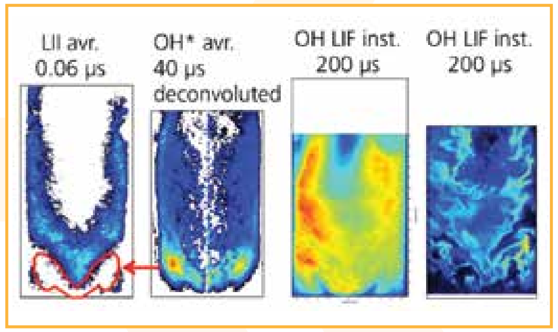
2. Research & Development Activities Performed

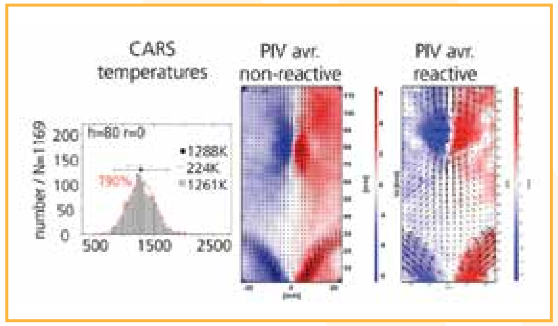
In addition to SiA, an optimised model combustor was developed with even better suiting simulation needs. A large suite of different optical and laser-based diagnostics was applied to this burner operating at increased pressure which resulted in a comprehensive data set. This data set includes soot concentration maps, a fine grid of CARS temperatures and statistics, OH distributions and velocity fields. In addition some instantaneous correlations were measured such as OH/soot and PAH/soot to show feasibility. Few flames were characterised in full detail, for others trends are available with a lesser degree of detail. The very sensitive influence of secondary air injection past the primary combustion zone provides an excellent test case for soot model validation, the comprehensive set of quantities being important to check different sub-models of CFD codes, i.e. cold flow, turbulent mixing, gas phase kinetics, and soot chemistry.

3. Advancement of Capability due to the FIRST project

A data set of unprecedented quality has already been used by CFD partners in the project and the scientific community was very interested (dissemination activities: publications, conferences) and requested access. The data was proposed as target flame in this year's International Sooting Flame Workshop ISF2. A combination of soot concentration with flow fields, temperatures and OH distributions was highly appreciated. New knowledge will be created by the comparison of model results with experiments. For this purpose, the use of correlated application of different diagnostics were made. This was not the main focus of the project and might be a task for future.







4. Additional information

Application: Soot formation and oxidation in pressurized turbulent flames
Research area: Understanding soot formation by detailed experimental data
Technology readiness level: 3
Owner of IPR: DLR-ST
FIRST Task: T3.4.1
Main Author and Contact: Klaus Peter Geigle, DLR

Validation of advanced soot modelling for complex combustion systems (DLR)

1. State of the Art before the FIRST project

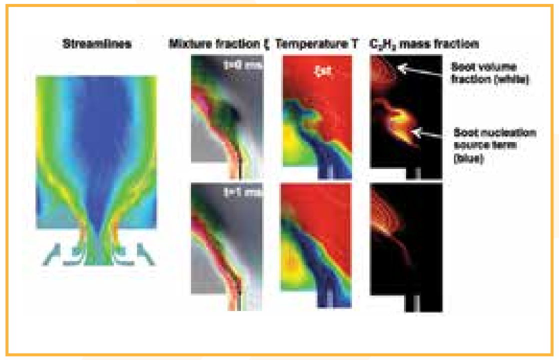
For complex combustion systems such as aero-engine combustors, quantitative validation of soot models was limited due to the lack of detailed experimental data. So far detailed validation data for sooting combustion was restricted to academic test cases like laminar flames or turbulent jet flames. Test cases which provide well defined boundary conditions and comprehensive validation data on one hand and feature technically relevant conditions as confined swirling flow and operation at elevated pressure on the other, were not available until recently.

2. Research & Development Activities Performed

This gap was closed by the measurements performed in the FIRST project, yielding a detailed characterisation of an aero-engine model combustor. Optical access to the combustion chamber via four quartz windows permitted the use of non-intrusive laser measurement techniques. This new data set provides an unprecedented opportunity to validate soot models at technically relevant conditions. Within FIRST, URANS and LES simulations of the model combustor using finite-rate chemistry and a two-equation soot model were performed successfully. Good agreement against experimental data was obtained and potential for further model development was deduced.

3. Advancement of Capability due to the FIRST project

The capability of the DLR soot model to predict soot distributions in complex combustion configurations has been demonstrated. It was shown by time-resolved data analysis that soot formation is highly unsteady and might be influenced by coherent flow field structures such as precessing vortex cores. Thus, time-resolved simulations are important for accurate soot predictions.



4. Additional information

Application: Soot model validation for complex combustion systems
Research area: Soot model validation for complex combustion systems
Technology readiness level: 2
Owner of IPR: DLR-ST
FIRST Task: T4.1.2
Main Author and Contact: Christian Eberle, DLR-ST

Soot: Experimental and Numerical Investigation of Soot Production

Cost-effective numerical simulation of soot formation (ONERA)

1. State of the Art before the FIRST project

Before the FIRST project soot modelling was either:

- very crude and with very low predictive accuracy when applied to technical scale devices;
- or complex and very expensive when applied to academic or semi-technical scale configurations, as most of the time it was used with simple turbulence modelling (RANS) to save CPU.

2. Research & Development Activities Performed

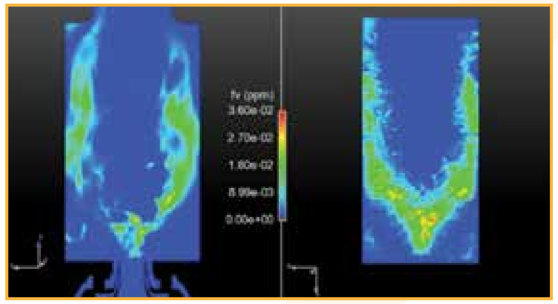
ONERA developed two complementary approaches in order to obtain a level of accuracy that significantly improved compared to the usual simple models, while keeping to an acceptable cost.

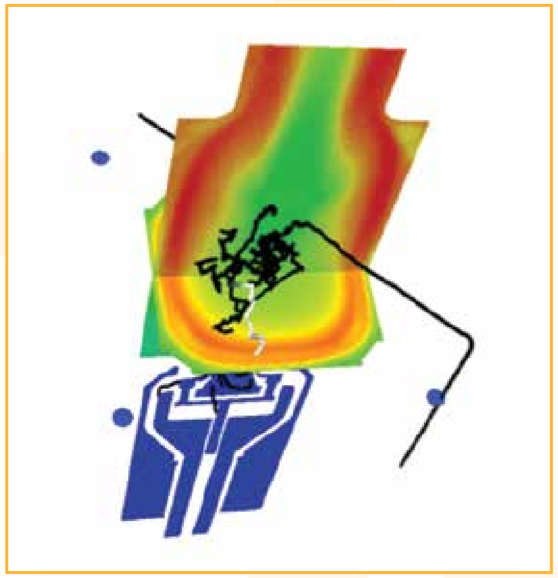
These new models are designed to be used in conjunction with LES and are applied to technical scale burners:

- 1st approach: The Soot model based on tabulated chemistry. This model is based on gaseous precursors like C_2H_2 instead of on total fuel as in simple models. Since all the chemical kinetics complexity is embedded in a pre-processed table, the CFD computation cost is significantly reduced compared to the "standard" approach, in which all the species are transported. Extracting species concentrations from the table gives the possibility of using rather accurate soot models;
- 2nd approach: The Hybrid EE/EL model with time-reversed trajectories. Soot characteristics are computed in post-processing with high accuracy only at points where information is required, which leads to low computation time despite the use of complex chemistry.

3. Advancement of Capability due to the FIRST project

These models were applied to the DLR burner. They successfully reproduced both topology of the soot field and magnitude of the soot mass-fraction. In the picture to the right, soot volume fractions computed with the tabulation-based soot model is reproduced on the left side of the image and compared with the experimental field obtained by LII, in the right side of the image. On the bottom image, trajectories of fluid particles are plotted, in order to illustrate the principle of the EE/EL method. The part of the trajectories where soot is produced is in white in the bottom picture.





4. Additional information

Application: Aero combustors
Research area: Soot modelling
Technology readiness level: 2
Owner of IPR: ONERA
FIRST Task: T4.1.5
Main Author and Contact: Nicolas Bertier, ONERA

Exploitation of soot models (RRD, RRUK, DLR)

1. State of the Art before the FIRST project

Prior to the FIRST project, rather simplified soot models were available within the Rolls-Royce in-house combustion CFD code. The reliability and predicting capability of these models were shown to be limited. Furthermore, the applied reaction mechanism for flamelet type combustion models like the FGM method, were based on reaction mechanism developed within the EU FP6 project CFD4C, and were not the state of the art anymore. Well documented and comprehensive databases were missing to validate the soot models.

2. Research & Development Activities Performed

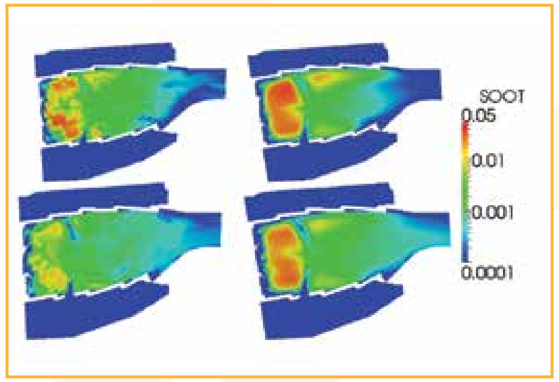
DLR-VT developed a soot model, which is based on detailed chemistry and includes all the required physics of soot production and oxidation processes. This detailed soot model was implemented into the Rolls-Royce in-house combustion CFD code PRECISE-UNS.

Furthermore, state of the art detailed chemistry models were developed by Imperial College London which describe the gas phase combustion process. This detailed chemistry model is used within the FGM combustion model used for combustor CFD applications.

DLR-VT generated a comprehensive validation data base of a generic combustor to validate the soot models.

3. Advancement of Capability due to the FIRST project

The development and implementation of these reaction mechanisms and soot models provides a framework to perform soot predictions based on state of the art detailed kinetic models. Although further development and validation for aero gas turbine combustors is required, the developments performed within FIRST is a step towards a more accurate and reliable soot predicting capability.



4. Additional information

Application: Soot prediction in aero engines
Research area: Soot modelling, detailed chemistry models
Technology readiness level: 5
Owner of IPR: DLR-VT, Imperial College, Rolls-Royce plc and Rolls-Royce Deutschland
FIRST Task: T5.2.1, T5.2.2
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Soot: Experimental and Numerical Investigation of Soot Production

FIRST Project Participants Directory

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FIRST Project Summary of Achievements: Advancements in Spray & Soot Research

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