Individual Projects available:

1) Data-driven machine learning with Gaussian Processes to eliminate thermoacoustic instability
(University of Cambridge)
2) Supervised learning algorithms for distributed parameter models of thermoacoustic oscillations
(AMINES)
3) Combustion Data Science and Analytics.
(GE Deutschland)
4)Deep Learning approach to enable combustion/acoustic coupling
(ANSYS)
5) Characterization and modelling of acoustically absorbing liners.
(Technische Universität München)
6) Numerical study of thermo-acoustic instabilities in spray flames.
(CERFACS)
7) LES of compressible turbulent flow through combustor liner and dilution holes
(University of Twente)
8) Physics-based machine learning in thermoacoustics, from lab to engine
(University of Cambridge)
9) Characterization and modelling of acoustically absorbing liners.
(Technische Universität München)
10) LES of Acoustically forced spray flames, developing open source code SU2 with liquid fuel combustion.
(University of Twente)
11) Determination of acoustic response of kerosene spray flames at atmospheric pressure and preheated air supply. (
Karlsruhe Insitute of Technology)
12) Characterization of acoustically (un)forced kerosene spray flames at elevated pressure and preheated air.
(University of Twente)
13) Determination of combustion dynamics sub-models: machine learning based on scale resolving simulations.
(GE Deutschland)
14) LES of spray combustion using machine learning enhanced spray models.
(SAFRAN Tech)
15) Numerical study of thermo-acoustic instabilities in a helicopter engine combustor
(Safran Helicopter Engines)

- ***<u>Fellow's individual projects</u>***

Table 3.1 d Individual Research Projects

Fellow in WP	Host inst.	PhD enrol.	Start date	Duration	Deliverable
ESR1 in WP1	**UCAM**	**Y**	**M6**	**36M**	**1.1**
Project Title and Work Package(s) to which it is related: **Input of WP2-4. Output to WP5.** Data-driven machine learning with Gaussian Processes to eliminate thermoacoustic instability					

Objectives: **(I)** Construct a data-based model of the laboratory-scale thermoacoustic rig from many thousand datapoints.**(II)** Use fully probabilistic Bayesian inference to faithfully capture and represent modelling uncertainties **(III)** Project this onto the physics-based model to identify whether any degrees of freedom are missing. **(IV)** Seamlessly combine the physics-based model with the data-driven model over the spectrum of experimental conditions. **(V)** Use the data-driven model to stabilize or destabilize the thermoacoustic system at will, by defining a reward function and using Gaussian Processes **(VI)** Repeat this process on data from the full annular rig at Cambridge, industrial rigs, and on data from full engine tests.

Results: **(I)** Verified method for data-driven machine learning in a laboratory environment. **(II)** Full passive control of a thermoacoustic rig based on Gaussian Processes. **(III)** Scale-up to a large laboratory rig and to full engines

Secondment(s): **(I)** SHE, Dr Richard, M18, Apply data-based model to industrial gas turbine **(II)** ARMINES, Prof Di Meglio, M30, Benchmark model based on Gaussian Processes against AMINES distributed parameter model

Fellow in WP	Host inst.	PhD enrol.	Start date	Duration	Deliverable
ESR2 in WP1	AMINES	Y	M6	36M	1.2

Project Title and Work Package(s) to which it is related: **Input of WP2-4. Output to WP5.**
Supervised learning algorithms for distributed parameter models of thermoacoustic oscillations

Objectives: **(I)** Deriving observability conditions for the parameters of a distributed parameter model of the thermoacoustic oscillations. **(II)** Derive model-based estimation methods and adaptive observers relying on transient pressure data **(III)** Validate the proposed approach on experimental data from UT and KIT.

Results: **(I)** Set of experiments enabling identification of unmeasured parameters **(II)** Validated Algorithms ensuring the convergence of estimations to the true value of model parameters from experimental measurements of UT and KIT.

Secondment(s): **(I)** GEDE, Dr Lynass, M18, Apply distributed parameter models to aircraft engine combustors **(II)** UCAM, Prof Rasmussen, M30, Training on machine learning algorithms for distributed parameter models

Fellow in WP	Host int.	PhD enrol.	Start date	Duration	Deliverable
ESR3 in WP1	GEDE	Y	M6	36M	1.3

Project Title and Work Package(s) to which it is related: **Input from WP2-4. Output to WP5.**
Combustion Data Science and Analytics.

Objectives: **(I)** Fusing the physics understanding of combustion dynamics, the data collected at test and in the field with a machine learning approach to construct a better model system that will be accurate over the lifetime of the asset. This will allow for better prediction of failure, increase fuel efficiency and lower noise and emissions. **(II)** Explore the cross-domain whitespaces at the intersection between engineering and scientific fields with the aim to identify and validate ways to fuse these fields to provide innovative applications. **(III)** Reconcile various machine learning methods with data clustering and other analysis methods for use in combustion systems. Identify quasi-physical phenomena at the boundary between domains best identified using a hybrid method.

Results: **(I)** Identification, evaluation and validation of methods applicable for experimental data and physical combustion model fusion. **(II)** Application and industrialization of the aforementioned methods on a cloud analytics platform. **(III)** Discovery of novel methods for use in industrial analytics applications

Secondment(s): **(I)** ANSYS, Dr Rochette, M18, Training on Ansys ROM technology **(II)** ARMINES, Prof Di Meglio, M33, Implement machine learning algorithms in GEDE tools

Fellow in WP	Host inst.	PhD enrol.	Start date	Duration	Deliverable
ESR4 in WP1	ANSYS	Y	M6	36M	1.4

Project Title and Work Package(s) to which it is related: **Input from WP2-4. Output to WP5.**
Deep Learning approach to enable combustion/acoustic coupling

Objectives: **(I)** Develop deep learning techniques (ROM) for unsteady global pollutant level characterisation on a non-premixed gas-gas jet configuration **(II)** Develop deep learning techniques (ROM) for unsteady full field characterisation on a non-premixed gas-gas jet configuration **(III)** Develop deep learning techniques (ROM) for unsteady full field characterisation on a non-premixed gas-gas jet configuration submitted to controlled pressure excitation **(IV)** Apply the previously developed techniques to a multiple injection combustion chamber.

Results: **(I)** Reduced Order Model applications running in real time and providing the same results as a full 3D unsteady simulation.

Secondment(s): **(I)** ST, Dr Cazalens, M18, Application of ROMs to aircraft engines **(II)** UCAM, Prof Juniper, M30, Comparison of model based and deep learning approaches

Fellow in WP	Host inst.	PhD enrol.	Start date	Duration	Deliverable

ESR5 in WP2	TUM	Y	M3	36M	2.1
Project Title and Work Package(s) to which it is related: **Output to WP1.** LES of spray combustion for low order modelling of dynamics: Uncertainty Quantification.					
Objectives: (I) Carrying out combustion LES including a liquid spray model in the presence of acoustics to determine the flame transfer function (FTF) of a spray flame. (II) Use system identification (SI) to quantify the uncertainty (UQ) of the FTF with respect to simulation parameters, e.g. length of time series and number of modelled liquid spray droplets. (iii) Investigate the response of spray parameters, e.g. droplet number and size, evaporation rate, to flow perturbations by determining the corresponding impulse and transfer functions.					
Results: (I) Flame impulse response and transfer functions for liquid fuel combustion. (II) Quantification of the uncertainty of the obtained FTF related to system identification (SI). (III) Analysis of the contribution of various physical processes to the overall flame response in terms of impulse and frequency response functions.					
Secondment(s): (I) CERFACS, Dr. Cuenot, in M18, learn LES of spray combustion with CERFACS's AVPB software. **(II)** GEDE, Dr. Kostrzewa, in M30, apply UQ method to industrial application					

Fellow in WP	Host inst.	PhD enorl.	Start date	Duration	Deliverable
ESR6 in WP2	**CERFACS**	**Y**	**M3**	**36**	**2.2**
Project Title and Work Package(s) to which it is related: **Output to WP1** Numerical study of thermo-acoustic instabilities in spray flames.					
Objectives: (I) Perform LES of spray flames with a focus on the role of fuel droplets on the flame response to acoustic waves. **(II)** Study the interaction with the atomization process, which may introduce another characteristic time in the system loop. **(III)** Adapt and apply the AVSP chain of tools to spray flames : analyze the role of fuel droplets on the flame response, build FTF using specific data processing tools.					
Results: (I) LES of pulsated spray flames **(II)** Knowledge on the interaction between spray and acoustics. (III) Numerical tools to predict the Flame Transfer Function for a liquid fuel spray flame and the effect of the atomization.					
Secondment(s): (I) ST, Dr Calazens, M18, Case study of aero GT engine combustor **(II)** TUM, Prof Polifke, M30, Acoustic liner modelling and boundary conditions					

Fellow in WP	Host inst.	PhD enrol.	Start date	Duration	Deliverable
ESR7 in WP2	**UT**	**Y**	**M3**	**36M**	**2.3**
Project Title and Work Package(s) to which it is related. **Output to WP1.** LES of compressible turbulent flow through combustor liner and dilution holes					
Objectives: (I) Extend the high order Discontinuous Galerkin method, (SU2 code), such that it is able to simulate the flows through combustor liner and dilution holes. Specific items to look at are time accurate local time stepping and the addition of some LES subgrid scale models. **(II)** Apply this method to LES of compressible turbulent flows, for the acoustic prediction of the flow through a liner dilution hole. **(III)** Compare the acoustic performance of the different LES subgrid scale models for the above mentioned flows.					
Results: (i) High fidelity simulations of compressible LES to predict the acoustics. It is expected that the high order Discontinuous Galerkin discretization is able to provide these predictions with increased efficiency compared to current state of the art discretizations due to its superior quality of the numerical solutions.					
Secondment(s): (I) RR, Dr Zedda, M21, Simulation of turbulent flows in an aero GT engine (II) Stanford University, Prof Alonso, M33, Optimization of the code, appl of the LES DG solver to Stanford problems					

Fellow in WP	Host inst.	PhD enrol.	Start date	Duration	Deliverable
ESR8 in WP3	**UCAM**	**Y**	**M3**	**M36**	**3.1**
Project Title and Work Package(s) to which it is related: **Output to WP1** Physics-based machine learning in thermoacoustics, from lab to engine					
Objectives: (I) Add measurement instruments and automated actuators to a laboratory thermoacoustics rig such that many thousand measurements can be obtained while several parameters are changed automatically during each test. **(II)** Starting with a simple rig and a simple physical model, use Bayesian analysis to estimate the model parameters and to assess the adequacy of the model. **(III)** Increase the complexity of the rig and physical model and, with the previous results as a prior, use Bayesian analysis to estimate the new model parameters and assess the adequacy of the model. **(IV)** Using predictions from the model, stabilize or destabilize the thermoacoustic system at will, by changing the actuators or the system's geometry. **(V)** Repeat this process on the full annular rig at Cambridge and then to a sector rig and full annular rig in industry.					

Results: (I) Verified method for physics-based machine learning in a laboratory environment. **(II)** Full passive control of a thermoacoustic system based on gradient-based optimization of a reliable model. **(III)** Scale-up to a laboratory-scale full annular rig and to industrial rigs.

Secondment(s): (I) RR, Dr. Zedda, M21, Apply physics-based machine learning to thermoacoustics in industrial application **(II)** TUM, Prof Polifke, M33, Thermoacoustic modelling

Fellow in WP	Host inst.	PhD enrol.	Start date	Duration	Deliverable
ESR9 in WP3	TUM	Y	M3	36M	3.2

Project Title and Work Package(s) to which it is related: ***Output to WP1***
Characterization and modelling of acoustically absorbing liners.

Objectives: (I) Measuring and modeling the acoustic impedance of a perforated medium, e.g. acoustically absorbing liner or dilution holes for varying geometries and mean flows. **(II)** Integration of the tested perforated medium in combustion system and measurements of the damping rate of the system with and without the perforated medium. **(III)** Implementation of the model for the tested perforated medium in a non-linear 1D network. **(IV)** Apply impedance in a software solving Linearized Navier-Stokes Equations (LNSE) and benchmark the damping rate from LNSE against experimental and 1-D network findings

Results: (I) Acoustic characterisation of perforated medium, i.e. acoustic impedance, and its relation to geometry and flow parameters. **(II)** Measurement of damping rate of a combustion system with and without perforated medium. **(III)** Benchmark of measured and predicted (1D-network, LNSE) results

Secondment(s): (I) GEDE, Dr Lourier, M18, 3M, Apply LNSE method with liner model to industrial use **(II)** UT, Dr van der Weide, M33, Transfer and exchange experience with acoustic models for perforated medium

Fellow in WP	Host inst.	PhD enrol.	Start date	Duration	Deliverable
ESR10 in WP3	UT	Y	M3	36M	3.3

Project Title and Work Package(s) to which it is related: ***Output to WP1***
LES of compressible turbulent flow through combustor liner and dilution holes.

Objectives: (I) Extend the high order Discontinuous Galerkin method, which is currently being developed in SU2, such that it is capable to carry out an LES simulation. Specific items to look at are time accurate local time stepping and the implementation of the LES subgrid scale models. **(II)** Apply this method to LES of compressible turbulent flows, where the specific goal is the acoustic prediction of the flow through a liner dilution hole. **(III)** Compare the acoustic performance of the different LES subgrid scale models for the above mentioned flow.

Results: (I) High fidelity simulations of compressible LES to predict the acoustics. It is expected that the high order Discontinuous Galerkin discretization is able to carry such predictions with increased efficiency compared to current discretizations due to its superior quality of the numerical solutions.

Secondment(s): (I) KLM, De Jong, M21, Gain experience in aircraft engine operations and its impact on the combustor **(II)** Stanford University, Prof Alonso, M30, Optimization of the code.

Fellow in WP	Host inst.	PhD enrol.	Start date	Duration	Deliverable
ESR11 in WP4	KIT	Y	M3	36M	4.1

Project Title and Work Package(s) to which it is related. Output to WP1
Determination of acoustic response of kerosene spray flames at atmospheric pressure and preheated air supply.

Objectives: (I) Design a device for a forced air excitation in cooperation with the University of Twente, manufacturing of the device at KIT and integration of this air forcing device in the KIT test rig. **(II)** Measurement of the unsteady flow field, the droplet dimension and velocity for various air flow speeds, excitation frequencies and excitation amplitudes. These measurements will be performed for 2 air blast nozzles design. The first one will be a generic design and the second one an application oriented design.

Results: (I) Design of device for forced acoustic excitation of air flows. **(II)** Quantification of the influence of acoustic air modulation on liquid spray characteristics, e.g. droplet dimensions and velocity, and its dependence on the modulation frequency and amplitude.

Secondment(s): (I) Shell, Bauldreay, M21, Gain industrial experience in alternative fuel properties **(II)** TUM, Prof Sattelmayer, M30, Carry out experimental work on acoustic liner characterization

Fellow in WP	Host inst.	PhD enorl.	Start date	Duration	Deliverable
ESR12 in WP4	UT	Y	M3	36	4.2

Project Title and Work Package(s) to which it is related: Output to WP1
Characterization of acoustically (un)forced kerosene spray flames at elevated pressure and preheated air.

Objectives: (I) Perform kerosene spray flame tests in UT rig with KIT double radial swirler nozzle at variable pressure and air inlet temp. **(II)** Determine Flame response at acoustic modulation of air flow at variable pressure and air inlet temperature. **(III)** Flame response diagnostics on basis of measuring acoustics, Heat Release Rate, Laser Induced Fluorescence measured OH*. (IV) Determination of Flame Transfer Function.

Results: (I) Time averaged and RMS fields of OH* at central cross section in combustor. **(II)** Phase triggered time sample averaged OH* fields in air flow forced situation using synchronized pulsed laser. **(III)** Rate of Heat release rate on base of Photo Multiplier data, w/wo acoustic forcing of air flow. **(IV)** Flame Transfer Function for acoustic forcing of air flow as a function of air pressure and air inlet temperature.

Secondment(s): (I) GECH, Dr Schuermans, M21, Spray measurements at elevated pressure and temperature **(II)** KIT, Prof Zarzalis, M12, Experiments of fuel atomization w/wo air flow forcing.

Fellow in WP	Host inst.	PhD enrol.	Start date	Duration	Deliverable
ESR13 in WP5	GEDE	Y	M8	36M	5.1

Project Title and Work Package(s) to which it is related: ***Input from WP1.***
Determination of combustion dynamics sub-models: machine learning based on scale resolving simulations.

Objectives: (I) Use system identification (CFD/SI) applied to perforated medium to gain acoustic transfer matrix or impedance of the configuration tested at TUM/TD. Validate the CFD/SI results against test data. **(II)** Compute flame transfer functions (FTF) with scale resolving simulations for UT test rig. **(III)** Employ machine learning with trainings data set generated in (i) and (ii) to determine and validate FTFs, liner impedances and BTMs automatically.

Results: (I) Validated process to gain acoustic transfer matrix and impedance for TUM perforated medium with CFD/SI. **(II)** Validated trainings data set for flame transfer functions **(III)** Verified and validated process to determine FTFs and liner impedances with machine learning algorithms.

Secondment(s): (I) ANSYS, Dr Rochette, M21, Training on large eddy simulations (LES) enhanced with ROMs (II) GT, Prof Lieuwen, M30, Jet fuel injection and atomization studies

Fellow in WP	Host inst.	PhD enrol.	Start date	Duration	Deliverable
ESR14 in WP5	ST	Y	M8	36M	5.2

Project Title and Work Package(s) to which it is related: ***Input from WP 1 and WP3.***
LES of spray combustion using machine learning enhanced spray models.

Objectives: (I) Low Nox systems are prone to combustion instabilities which could be a strong issue in the development of the engine. On the other hand, these systems operate at high OPR which means that they will undergo pressures varying from ambient to supercritical. It is necessary to develop models suitable for description of srpay/acoustic interactions at all the operative conditions. Machine learning is explored as method to reduce the uncertainty of the spray models.

Expected Results:. Available models for sub- and supercritical fluids do not provide a description of a passage in the critical region. The aim of the present work is to develop, by incorporating diffuse interface, thermodynamic models which allow a continuous description of the fluid, from sub- to super critical regions. Basic configurations will be used for the validation. Finally the flame response of a multipoint injector (SAFRAN geometry) is evaluated, submitted to acoustic pressure excitations, varying from ambient to supercritical conditions.

Secondment(s): (I) FDX, Dr Krüger, M21, Broaden work experience by carrying out spray injection **(II)** CERFACS, Dr Cuenot, M33, Implement the diffuse interface thermodynamic model in AVBP

Fellow in WP	Host inst.	PhD enrol.	Start date	Duration	Deliverable
ESR15 in WP5	SHE	Y	M8	36M	5.3

Project Title and Work Package(s) to which it is related: ***Input from WP1 and WP3.***
Numerical study of thermo-acoustic instabilities in a helicopter engine combustor

Objectives: (I) Study the influence of two-phase combustion modelling (with/without machine learning enhanced models) on flame response to acoustic perturbations. **(II)** Include the spray influence in the Flame Transfer Function model to be exploited in Helmholtz simulations of real combustors. **(III)** Study the interaction between acoustics and multi-perforated liners through highly resolved LES, including acoustic damping and acoustic propagation through the perforations. **(IV)** Adapt/improve multi-perforated liner models (CFD and Helmholtz) accounting for acoustics. **(V)** Apply the different LES and Helmholtz models to full helicopter combustor simulations and study of their impact on combustion stability

Results: (I) Models for spray flames response to acoustic perturbations. **(II)** Models for combustor liner acoustic damping and propagation. **(III)** Impact of new models (liner and spray) on combustion instabilities in a full annular helicopter combustor;

Secondment(s): (I) GEDE, Dr Lynass, M21, learn methods of machine learning for aircraft engine applications **(II)** CERFACS, Dr Cuenot, M33, learn to carry out large eddy simulations (LES) with AVPB software