**START PAGE**

MARIE Skłodowska-CURIE ACTIONS

**Doctoral Networks (DN)**

**Call:** **HORIZON-MSCA-2024-DN-01-01**

PART B

“HyNOISE”

**Hydrogen combustioN nOise Investigation for Safe and Efficient energy systems**

**This proposal is to be evaluated as:**

**[DN]**

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|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Consortium**  **Member** | **Legal Entity Short Name** | **Academic** | **Non-academic** | **Awards Doctoral Degrees** | **Country** | **Dept./**  **Division /**  **Laboratory** | **Scientist-in-Charge** | **Role of associated Partner or link to beneficiary** |
| Beneficiaries |  |  |  |  |  |  |  |  |
| INSTITUT NATIONAL POLYTECHNIQUE DE TOULOUSE | INPT | X |  | X | France | IMFT Laboratory | Prof. Thierry SCHULLER |  |
| CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE | CNRS | X | X |  | France | EM2C Laboratory | Dr. Antoine RENAUD |  |
| CENTRE EUROPEEN DE RECHERCHE ET DE FORMATION AVANCEE EN CALCUL SCIENTIFIQUE | CERFACS |  | X |  | France | CFD Division | Dr. Laurent GICQUEL |  |
| POLITECHNIKA CZESTOCHOWSKA | CUT | X |  | X | Poland | Department of Thermal Machinery | Prof. Artur TYLISZCZAK |  |
| NORGES TEKNISK-NATURVITENSKAPELIGE UNIVERSITET | NTNU | X |  | X | Norway | Department of Energy and Process Engineering | Prof. James DAWSON |  |
| TECHNISCHE UNIVERSITÄT BERLIN | TUB | X |  | X | Germany | Fluid Dynamics | Prof. C. O. PASCHEREIT |  |
| CENTRO DE INVESTIGACIONES ENERGÉTICAS, MEDIOAMBIENTALES Y TECNOLÓGICAS | CIEMAT | X |  |  | Spain | Department of Energy | Dr. Carmen JIMENEZ |  |
| POLITECNICO DI BARI | POLIBA | X |  | X | Italy | Department of  mechanics, mathematics and management | Prof. Davide LAERA | Coordinator |
| THE CHANCELLOR MASTERS AND SCHOLARS OF THE UNIVERSITY OF CAMBRIDGE | UCAM | X |  | X | United Kingdom | Department of Mech. Eng. | Prof. Matthew JUNIPER |  |
| TECHNISCHE UNIVERSITEIT DELFT | TU Delft | X |  | X | The Netherlands | Aerospace Engineering Department | Dr. Francesca DE DOMENICO |  |
| UNIVERSITEIT TWENTE | UT | X |  | X | The Netherlands | Thermal Fluid Engineering | Dr. Lionel HIRSCHBERG |  |
| TECHNISCHE UNIVERSITÄT MÜNCHEN | TUM | X |  | X | Germany | School of Engineering and Design | Prof. Wolfgang POLIFKE |  |
| Associated Partners |  |  |  |  |  |  |  |  |
| TECHNISCHE UNIVERSITAET GRAZ | TU Graz | X |  | X | Austria | Institute of Thermal Turbomachinery and Machine Dynamics | Prof. Jakob WOISETSCHLÄGER | Hosting secondments/Training, mentoring DC |
| UNIVERSITE DE SHERBROOKE | UdeS | X |  | X | Canada | Department of Mechanical Engineering | Prof. Stephane MOREAU | Hosting secondments/training, mentoring DC |
| ROLLS-ROYCE DEUTSCHLAND LTD & CO KG | RRD |  | X |  | Germany | N/A | Dr. Claus LAHIRI | Hosting secondments/training, providing tools/data, mentoring DC |
| SAFRAN AIRCRAFT ENGINES | SAE |  | X |  | France | N/A | Dr. Yoann MERY | Hosting secondments/training, mentoring, mentoring DC |
| ANSALDO ENERGIA SPA | AE |  | X |  | Italy | N/A | Dr. Giovanni CAMPA | Hosting secondments/training, mentoring DC |
| UNIVERSIDAD CARLOS III DE MADRID | UC3M | X |  | X | Spain | Thermal and Fluids Engineering | Prof. Mario SANCHEZ SANZ | Training and award Doctoral Degree, Hosting Secondments |
| UNIVERSITÉ PARIS-SACLAY | UPSaclay | X |  | X | France | N/A | Sylvie Pommier | Award Doctoral Degree |

**Data for non-academic beneficiaries:**

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Name** | **Location of research premises**  **(city / country)** | **Type of R&D activities** | **No. of full-time employees** | **No. of employees in R&D** | **Web site** | **Annual turnover**  **(in Euro)** | **Enterprise status (Yes/No)** | **SME status (Yes/No)** |
| **CERFACS** | **Toulouse/France** | **Computational Fluid Dynamics (CFD)** | **124** | **108** | **https://cerfacs.fr** | **7845925** | **YES** | **NO** |

# Excellence #@REL-EVA-RE@#

## Quality and pertinence of the project’s research and innovation objectives

### Introduction, objectives and overview of the research programme

Our energy and transport infrastructures, marked by a heavy reliance on fossil fuels, must drastically change. Currently, over 90% of the world's energy demand is generated from these finite and polluting resources[[1]](#footnote-2). Projections indicate an over 25% increase in energy demand by 2040. At the current rate of growth of the renewable energies (and nuclear power) technologies, fossil fuels are still expected to contribute to roughly 90% of the world’s power demand[[2]](#footnote-3). For what concerns aviation, the International Energy Agency (IRA) has recently reported that this sector stands out as one of the swiftly expanding contributors to greenhouse gas emissions, predicting 2.1 gigatons of carbon dioxide (CO2) emissions per year by 2050[[3]](#footnote-4). From 2020 and beyond, the EU has set major policy goals and targets for all European countries to reduce their carbon emissions by 55% by 2030 and to reach net 0 by 2050. A main challenge lies in the fact that, due to their lower energy density compared to conventional fuels, batteries currently lack the capacity to quickly replace fossil fuels. This limitation is particularly pronounced in heavy-duty operations requiring substantial power, such as the take-off of large aircrafts for long-distance flights. Addressing this climate change challenge, therefore, requires alternative solutions for the decarbonization of combustion systems to be used both in the energy and transport sectors. In this context, hydrogen-based technologies are foreseen as promising methods to reduce CO2 emissions. Hydrogen (H2) combustion is particularly noteworthy for both aviation and power generation, serving as an alternative to current fuels for powering gas turbines: H2 combustion produces no CO2 nor UHC pollutants, and its broad flammability range supports the stabilization of extremely lean flames, resulting in an effective reduction of NOx[[4]](#footnote-5). **However, H2 combustion poses several challenges in terms of storage, combustion performance and safety.** Indeed, although gas turbines can be designed to operate with different fuels (natural gas, syngas, biogas, etc.), fuel substitutions may lead to the onset of unwanted phenomena, such as instability, flashback, auto-ignition, which limit stable operation[[5]](#footnote-6). One key issue, which has not been explored yet and may hinder the development of the new generations of burners, is the **noise produced by hydrogen flames**. In combustion science, coupling mechanisms between acoustic waves and flames are for many reasons linked with **environmental but also with critical operability and safety** issues. Combustion noise is a significant component of overall engine noise. Recent goals in noise reduction, particularly in the aviation sector, have brought increased attention to understanding core noise sources and defining mitigation strategies[[6]](#footnote-7),[[7]](#footnote-8). Engines operating with turbulent flames usually give rise to high levels of noise radiation, due both to direct and indirect combustion-noise sources[[8]](#footnote-9). In open systems, **direct combustion noise** is associated with acoustic radiation due to unsteady volumetric expansion in flames. When operated in a real system, the **coupling with acoustic waves** adds additional complexity, as flame dynamics are very sensitive to acoustic waves and can lead to **thermoacoustic instabilities,** withlarge self-sustained pressure oscillations, affecting performances and lifetime of combustors and gas turbines[[9]](#footnote-10). Violent events such as **(auto)ignition events** or coherent structures resulting from **hydrodynamic flow instabilities** also alter this spectrum and add other tonal components to the radiated direct noise[[10]](#footnote-11). Indirect noise sources include both **entropy noise**, i.e., inhomogeneities of gas temperature, density[[11]](#footnote-12) or composition[[12]](#footnote-13), and vorticity noise[[13]](#footnote-14). When accelerated by cross section area restrictions, these non-uniformities generate additional sound waves which are radiated into the external environment or emitted back into the combustion chamber, leading to the production of new entropy patches and vortices. Under unfavourable circumstances, this results in a feedback loop which promotes self-sustained pressure pulsations impacting the noise spectra characteristics12. These noise sources have mainly been studied for standard hydrocarbon fuels, including kerosene and natural gas (NG) for the aeronautical and power sector, respectively. Hydrogen flames, which are characterized by fast ignition, high burning velocities and fast diffusive transport (sub-unity Lewis number) promoting thermo-diffusive instabilities[[14]](#footnote-15), feature shorter flame shapes and smaller flame structures, leading to a strong modification in the acoustic energy radiated. Noise is expected to play an important role in the triggering of flow instabilities, together with the appearance of new types of acoustically coupled combustion instabilities that were so far not observed for systems powered by traditional fuels. Furthermore, H2 preferential diffusion[[15]](#footnote-16) enhances local composition and density inhomogeneities, which consequently enhance indirect noise generation mechanisms. The overall aim of the Network is stated as follows.

In HyNOISE, the direct and indirect noise generated by hydrogen flames will be studied to overcome current limitations in hydrogen combustion and design innovative, quiet, and stable combustion devices. The overall aim of this partnership is to advance the understanding of the physical mechanisms driving flame-acoustic-entropy interactions with the objective of defining new models and tools able to correctly predict hydrogen flame dynamics and its resulting pressure field, and, on this basis, developing control and mitigation methods. Previous works from the Network partners have demonstrated huge potential in predicting and controlling broadband and tonal noise in the context of fossil fuels. Extension to hydrogen is not straightforward, requiring consideration of its peculiar properties and different coupling dynamics with acoustics and turbulence. With coordinated experimental, numerical, and theoretical work, HyNOISE will focus on these items while providing key knowledge and technologies to enable fast transition to zero-carbon energy and transport sectors. It will also train a new generation of highly specialized engineers and researchers in a field where they are critically needed.

The principal research objectives of HyNOISE are: (i) to advance the understanding of the physical mechanisms leading to combustion noise and flame/acoustics coupling in hydrogen flames; (ii) to develop tools that will lead the design and optimization of novel zero-carbon combustion technologies for the full and efficient utilization of hydrogen in key sectors, including aeronautics and power generation, and (iii) to train a new generation of European scientists in the critical field of H2 combustion and flame dynamics. The developed technologies will stimulate the green transition in the power generation and transportation sectors, thus promoting deep decarbonization, starting with the existing energy infrastructure. Given that most of the earlier work on noise has been conducted for combustion systems operating with classic hydrocarbons, HyNOISE aims to bring relevant expertise together and to pursue solutions for hydrogen through integration and combination of unique theoretical, high-fidelity modelling and experimental expertise. The specific research objectives (RO), related to the research work packages (WP2 to WP5) that will be pursued by the proposed Network, are detailed hereafter and in Section 3.1 with more details. WPs for management, training, and dissemination -- WP1, WP6 and WP7, respectively -- are also part of the Network programme.

**RO1 - WP2: Noise and flame dynamics during hydrogen ignition process.** The objective is to unveil the dynamics and sound pressure level generated during ignition process in both single-sector and annular combustion systems. High-fidelity numerical simulations will complement the experiments to assess their ability to correctly capture peak pressure and flame dynamics during the ignition phase in a single sector and annular light-round. The effects of differential diffusion on the flame structure, of flashback and acoustic boundary conditions on the flame dynamics and sound levels will also be investigated and control strategies will be proposed.

**RO2 - WP3: Direct noise sources in turbulent hydrogen flames**. The broadband sound generated due to the coupling between unsteady flame dynamics and flame-flame interactions, hydrodynamic and thermo-diffusive instabilities and turbulence will be investigated by combining experiments and first-principles numerical simulations. These studies will be performed in both anechoic and confined systems with controlled impedances. The data will be exploited to develop sub-grid scale closures for less computationally demanding simulation methods such as Large Eddy Simulations and Reduced-Order Modelling, considering turbulence/instabilities interactions with both physical and data-driven approaches.

**RO3 - WP4:** **Thermoacoustic instabilities and control.** The tonal sound generated by acoustic-flame interactions will be investigated to understand physical mechanisms leading to the onset of thermoacoustic instabilities coupled with different modes at low and high frequencies. Both single flame and annular configurations will be investigated with experiments and simulations. Fuel staging and injection strategies, injector design and tunable passive systems will be investigated as a fundamental step towards practical implementation of control strategies on realistic engines.

**RO4 – WP5:** **Contribution of convective waves to combustion noise and thermoacoustic instabilities**. Indirect combustion noise of H2 flames will be examined via dedicated experimental facilities. High fidelity numerical simulations, together with theoretical formulations, will complement experimental observations to understand the role of entropy disturbances and vorticity waves in indirect combustion noise and thermoacoustic instabilities. Indirect noise sources will be extracted from data, making use of supervised learning approaches, and integrated in low-order models for combustor and turbine acoustics, allowing us to conduct stability analysis and noise prediction of an entire engine.

### Pertinence and innovative aspects of the research programme

Engines powered by turbulent flames experience high levels of noise generation, due both to direct and indirect sources of combustion noise. For standard hydrocarbon fuels, direct sources, due to unsteady volumetric expansion in flames, have been widely studied in both canonical configurations and in confined systems to evaluate global enhancement of the overall noise radiated by a turbulent flame[[16]](#footnote-17),[[17]](#footnote-18). Investigations involving H2/air flames are less common. As H2 flames are much thinner due to their high reactivity with a strong imbalance between heat and species diffusivity, their interactions with turbulence have recently been shown to substantially differ from those of standard fuels[[18]](#footnote-19). Observations conducted in Direct Numerical Simulations (DNS) and pressurized vessel experiments with spherical expanding flames show that the topology of lean premixed H2/air flames is highly wrinkled, adopting cellular shapes with high curvatures and locally intense burning in positively curved regions. These regions are formed by preferential concentration of hydrogen, in contrast with ultra-lean hydrogen concentration with local weak burning in negatively curved regions[[19]](#footnote-20). In turn, this induces more flame pockets and accelerated flame surface destruction[[20]](#footnote-21), leading to intense noise radiation[[21]](#footnote-22) within systems that are more susceptible to trigger thermoacoustic instabilities[[22]](#footnote-23). Another outcome of the high burning intensity of H2/air flames is their shorter characteristic dimensions compared to hydrocarbon flames, leading to a shift of the radiated noise to higher frequencies and making them more responsive to high frequency acoustic incoming waves[[23]](#footnote-24).

On the experimental level, there is only a limited number of studies dealing with the interplay of flow, hydrogen flames, and acoustic pressure fluctuations. Recent experiments on low-swirl jet flames reveal the potential of synchronized optical flame measurements and acoustic pressure recordings in the far-field to further understand the sources of direct combustion noise[[24]](#footnote-25). In swirling configurations, recent investigations have led to the understanding of hydrogen flame stabilization mechanisms in complex swirled multi combustion regime flows[[25]](#footnote-26), to a better description of its dynamics during ignition[[26]](#footnote-27) and, more recently, to the analysis of low and high frequency instabilities. Other studies have shown that, with a separated injection, hydrogen could enhance the stability of the system[[27]](#footnote-28). However, the broadband noise produced by these flames has not been characterized so far. Noise radiation mechanisms are important to understand the thermoacoustic resonant coupling taking place with the eigenmodes of the combustion system[[28]](#footnote-29). Annular geometries add another level of complexity to the problem, as they give rise to pairs of degenerate acoustic modes associated with clockwise and counter-clockwise spinning waves[[29]](#footnote-30). Depending on their relative amplitudes and phases standing, spinning or mixed self-sustained combustion oscillations may develop. These azimuthal instabilities can have serious consequences because they may be accompanied by partial flame extinction[[30]](#footnote-31) or flashback[[31]](#footnote-32). In a pressurized annular configuration, it has been shown that blends containing more hydrogen give rise to lower amplitudes, because higher harmonics cancel out along the flame brush[[32]](#footnote-33). Nevertheless, pure H2 flames have not yet been characterized.

Experiments in canonical configuration24 and Direct Numerical Simulations have shown that transient flame generation/destruction processes such as flame ignition or flame annihilation by flame/flame, flame/wall, or flame/vortex interactions, constitute strong sources of noise in turbulent combustors. While noise generation by flame annihilation in flame-flame interactions has been studied extensively[[33]](#footnote-34),[[34]](#footnote-35), noise generation by flame/wall interactions has received less attention[[35]](#footnote-36). Only one numerical study focusing on the sound generated by a one-dimensional hydrogen flame impinging on a wall is currently available in the literature[[36]](#footnote-37). Finally, although the dynamics of flame-vortex interactions is a canonical problem used to mimic the effects of turbulent eddies on flames[[37]](#footnote-38), the noise produced by vortices interacting with H2 flames has not been characterized yet to the best of our knowledge. When it comes to turbulent flames, Large Eddy Simulation (LES) has demonstrated its capacity to provide relevant predictions of complex flow dynamics in turbulent reacting flows. However, to reach such a status and capability, High Performance Computing (HPC) as well as highly turbulent flow and combustion physics modelling need to be mastered[[38]](#footnote-39). Indeed, LES codes proposed to industry are currently dedicated to hydrocarbon fuels for which, from a theoretical point of view, flame behaviours are reasonably well understood. With the transition to H2 combustion, new physics is at play and new fundamental questions arise at the level of the turbulent combustion processes. An example are thermo-diffusive instabilities that, while acting at the small scales of the flame microstructure are not resolved in conventional LES frameworks, but have significant impact on global flame propagation and front stabilization[[39]](#footnote-40). Although active research is ongoing to answer these questions and challenges around H2 combustion, less is currently being done in terms of model adaptation, development or even validation and, today, subscale models for hydrogen flames are still an active area of investigation.

Finally, computationally less expensive but nonetheless reliable methods are required for parametric studies and optimization, to speed up the design process of combustion systems. One solution is the use of linearized mean-field methods, often used a posteriori to reveal the instabilities driving turbulent flow dynamics. These methods could also be used a priori to predict the flow dynamics and its sensitivity by exploiting the linear adjoint approach[[40]](#footnote-41). Quite popular in the aeroacoustics community for jet noise modelling[[41]](#footnote-42), this approach can predict turbulent core noise, but must be extended to reactive flows, where unsteady heat release from the flame must be included in the model[[42]](#footnote-43). The vast amount of data on combustion noise produced from experiments and high-fidelity simulations can be used for this and exploited with data-driven or data assimilation approaches to derive closure equations for Low Order Models (LOM)[[43]](#footnote-44) or used in a Bayesian framework with physics-based priors[[44]](#footnote-45) to develop fast and accurate prediction tools.

Indirect noise is a non-negligible component of the overall combustion noise10,12. While the distinction between acoustic, entropic and vorticity modes has been known for a long time10, their nonlinear interactions causing the generation of indirect noise and the triggering mechanisms for secondary instabilities are still not fully understood. From an experimental point of view, this is mainly caused by the difficulties of isolating indirect noise in the overall combustion noise traces. On the numerical side, for standard hydrocarbons hybrid approaches relying on LES and reduced order models (ROM)have been developed to study flow/flame/acoustic interactions[[45]](#footnote-46). The introduction of hydrogen raises further questions. Indeed, in H2 flames indirect noise levels will be highly impacted by the enhanced density difference between fuel and air, together with the more frequent presence of hot spots generated by stronger flame surface oscillations. Existing analytical and numerical modelling tools need to be upgraded to correctly reproduce these effects.

**According to this description, there is a clear scientific gap in the understanding of noise production in H2 flames. Addressing this gap will establish new knowledge and numerical tools optimized for hydrogen flames. The effective prediction and control of H2 combustion noise will pave the way to the development of innovative, new generation gas turbines, which surpass the current limitations and will represent a step change in addressing the climate emergency.** State-of-the-art numerical and experimental techniques will be employed by the Network partners to investigate the interaction between combustion and acoustic waves at all levels, from direct noise generation to ignition, thermoacoustic instabilities and entropy spots leading to indirect noise. The investigation proposed here is unprecedented and the Network combines unique expertise in Europe. The proven expertise of the partners on the different approaches and physics makes this proposal unique and complementary to the goals pursued for hydrogen in other EU and international projects. The research proposed as part of this Network is strongly linked to the activities on H2 combustion funded by the EU, as well as to previous EU-funded and national projects where the present project partners have been involved. INPT, CS, TUM and TUB collaborated during the French-German ANR-DFG NOISEDYN projects aiming at developing state space representations of acoustic boundary conditions for noise predictions in methane swirled flames, recently extended to hydrogen flames in ANR-DFG DESCRESCENTE project. INPT and POLIBA have collaborated on passive damping devices for flame stabilization. A Bayesian framework for thermoacoustic applications is the object of joint UCAM and POLIBA studies. TUM, TUB, NTNU, CERFACS, UCAM, CS, UT have already participated in previous MSCA-2017-ITN ANNULIGhT and MAGISTER with a specific focus on the study of thermoacoustic combustion instabilities in annular chamber and spray flames, respectively. HyNOISE will complement these research activities by specifically focusing on the production and control of hydrogen combustion noise. Hydrogen is the main topic for INPT, CERFACS and TUB through the ERC Advanced Grants SCIROCCO, SELECT-H and HYPOTHESis and the EMMY Noether Grant recently granted at TUB by Thomas Kaiser. INPT and NTNU have been recently awarded the ERC Synergy grant HYROPE on pressurised H2 combustion on sequential combustors. Furthermore, INPT, CERFACS, CUT and CS cooperate in the EU project HESTIA focusing on hydrogen combustion in aeroengines. CIEMAT, INPT and CERFACS have already collaborated in multiple projects to propose numerical models to study clean combustion. Furthermore, CERFACS, POLIBA and TUB are involved in the MSCA-ITN INSPIRE, which focuses on novel technologies that utilize alternative thermodynamic cycles to increase gas turbine efficiency and reduce fuel consumption and emissions. TU Delft and TUB have collaborated in the EU’s FP7 programme AHEAD projects focused on flame dynamics and combustion instabilities of swirl-stabilized combustion and are beneficiary of the HORIZON-JU-RIA project ACHIEVE on the combustion of hydrogen and ammonia blends.

## Soundness of the proposed methodology

### Overall methodology

The proposed work plan is organized through seven **(7) work packages (WPs)** (see also Section 3.1). WP1 offers the logistical framework for the overall programme organization. Its tasks include creating committees in charge of organizing and managing the various components. The scientific components of the programme are divided into four (4) interconnected, technical WPs (Fig. 1). WP2 focuses on sound pressure levels and flame dynamics generated during ignition phases, including the impact of acoustic impedances at boundaries and their capacity to mitigate pressure excursions. WP3 is devoted to direct noise generation by H2 flames in both anechoic and confined environments. WP4 is focused on the study of tonal noise resulting from the coupling of longitudinal and/or annular acoustic modes with flames and to define control strategies. Finally, WP5 is devoted to indirect combustion noise, aiming to understand and model mechanisms interconnecting acoustics-convected entropy-vorticity waves accelerated at the combustor exit and their links to thermoacoustic oscillations.



Fig. 1 – (Top) Graphical representation of the HyNOISE programme with the interconnections between the four research workpackages. (Bottom) Overview of experimental configurations that will be studied in HyNOISE recently operated with hydrogen by HyNOISE members

By integrating simulations and experiments, the scientific approach examines state-of-the-art techniques to analyse the relationship between acoustics and hydrogen combustion. Experiments in both single flame and annular combustor configurations will be performed to study noise generation of multiple archetypes of flames, namely laminar V-type and M-type, turbulent swirl and jet flames, typical of air-breathing hydrogen combustion systems. The indirect noise and entropy wave/acoustic interactions will be investigated in a dedicated test rig. LES and DNS simulations will complement experiments providing more insight into the mechanisms leading to noise generation and coupling between acoustic, entropy waves and combustion dynamics. These datasets will be exploited via theoretical and data-based methods, such as Supervised Learning (SL) and Physically Informed Neural Networks (PINNs) to extract noise source mechanisms and define sub-models. These will be incorporated into low-order models (LOM) and Linearized Navier-Stokes solvers with the objective of predicting the entire engine stability and noise levels with a lower computational cost.

Finally, experimental investigations and the developed numerical tools will be used to design new concepts of passive noise control devices. One of the objectives of this work programme is to bring together traditionally separate disciplines, viz., fluid mechanics, combustion, acoustics, and machine learning, to establish new paradigms and tools for designing quiet and stable hydrogen flames. It is paramount to recognize that while the four research WPs are organized to deal each with a specific component of combustion noise, these are highly interconnected, contributing to the total noise emitted by an engine. Therefore, exchanges between each Doctoral Candidate (DC) affiliated with a WP to the other WPs will be established through collaboration, knowledge transfer, coupled numerical approaches, and experimental validations. Additionally, WP6 is structured to prepare the trainees for this collaboration while providing exposure to the full scope of the program.

These engagements are most often achieved through **secondments** (both in person and remote)and the sharing of configurations, experimental data, simulations results, tools, and sub-models. Additionally, trainees will be encouraged to interact regularly with the other DCs and WPs through visits, networking events, and training activities. In particular, the novel *HyNOISE Training Programmes* (Section 1.3) will provide an additional hub for exchange and synchronization between all the fifteen DCs. A more detailed description of the methods, objectives and goals involved in each WP is provided below.

WP2 will focus on the noise emitted and flame dynamics during the ignition process of hydrogen flames in both single and multiple burners annular combustion systems.

Four DCs are involved in this WP. DC1 (INPT) and DC2 (CNRS) will be mainly involved in experimental studies in both single burner and multiple burner annular chambers. The dataset produced will be used for validation of high-fidelity numerical analysis performed by DC3 (CERFACS) and DC4 (CUT). Experimental and numerical results will unveil the interaction between turbulent mixing, flame dynamics and sound radiation produced by hydrogen flames during ignition and (possibly) autoignition events. Active control methodologies will be tested for suppression of turbulent flow and flame interactions to reduce the noise level. Close collaboration between DCs performing experiments and simulations is expected. Furthermore, interaction with WP4 is also foreseen to investigate the thermoacoustic instabilities triggered by violent ignition processes (POLIBA, CERFACS).

* **Experiments** of ignition of swirled turbulent hydrogen flames will be performed in the rigs available at the IMFT laboratory at INPT and EM2C laboratory at CS. Two different H2-based combustion systems will be characterized: the double swirl HYLON injector designed by Prof. Schuller and operated in the MIRADAS test rig at IMFT laboratory (INPT)25 and a jet in swirling crossflow proposed by Prof. Renaud, Prof. Candel, and Dr. Durox at EM2C laboratory (CNRS)[[46]](#footnote-47). Both facilities are equipped with imaging systems and laser diagnostics for flow characterizations (OH\* high speed imaging, PIV and OH-PLIF) and acoustic measurements (hot-wires and microphones arrays). In particular, the HYLON test bench at INPT has the capability of a Tunable Acoustic Boundary (TAB), which will allow for simulating different engine-like configurations leading to a shift and reshape of the spectral signature of the radiated noise towards different frequency ranges. The light-round dynamics will be studied in the annular MICCA test bench[[47]](#footnote-48) at CNRS to evaluate the impact of the corresponding pressure wave on the transient flow leading to an established combustion regime.
* **LES** of ignition dynamics and sound levels will be performed at CERFACS and CUT, respectively, to assess predictive capabilities of two different turbulent combustion models: at CERFACS, simulations will be performed with the proprietary code AVBP (https://www.cerfacs.fr/avbp7x/) using the flame thickening approach extended for H2 combustion38. In an in-house code developed in Prof. Tyliszczak group at CUT, LES will be performed by combining the Eulerian stochastic field[[48]](#footnote-49) and data-driven approaches improving existing combustion modelling. Capabilities of both combustion models to correctly predict preferential diffusion and stretch effects on hydrogen flames during ignition will be evaluated, and corrections will be implemented to retrieve time evolution and dynamics of the flame, mandatory for reproducing the correct evolution of heat release rate and, therefore, pressure sound levels. Specific modelling will also be introduced to capture ignition and auto-ignition kernels[[49]](#footnote-50).
* An **active control** strategy to modify turbulent mixing and ignition dynamics will be numerically investigated at CUT. Air/fuel lines will be optimally forced to lead to the stabilization of safer lifted flames reducing at the same time the risk of blowoff.

WP3 deals with direct noise emitted by laminar and turbulent flames when interacting with turbulence and hydrodynamic instabilities in both confined and anechoic chambers.

Seven DCs are involved in this work-package. DC5 (NTNU) will experimentally investigate noise generated by laminar canonical flames submitted to controlled turbulence. DC6 (TUB) will study the noise produced by a turbulent hydrogen-air jet flame in an anechoic chamber. DC1 will participate to this WP by studying the impact of acoustic boundaries on the sound pressure level of a turbulent swirled flame in a confined chamber with tunable acoustic boundaries. DNS of sound sources and sound generation mechanisms of laminar lean H2 flames interacting with vortices will be performed by DC7 (CIEMAT), while DC8 (NTNU) will perform DNS of the turbulent flames. Numerical datasets will be exploited by DC9 (POLIBA) and DC10 (TUB), via analytically derived and/or data driven approaches, to define sub-grid functions and combustion efficiencies to be included in LES and Linearized Navier Stokes equations for reliable and less expensive predictions of noise characteristics, respectively.

* **Turbulence-flame interaction** will be investigated experimentally for multiple flame archetypes. Stable V-shape and M-shape flames submitted to different levels of turbulence generated via an active grid[[50]](#footnote-51) will be studied in a novel test rig developed by Prof. Dawson at NTNU. The interactions between turbulence, hydrodynamic instabilities and flame in a fully turbulent jet hydrogen flame will be investigated at the facilities of Prof. Paschereit at TUB. This will be operated in an anechoic chamber to avoid interactions with reflected acoustic waves[[51]](#footnote-52). Finally, direct noise of thermoacoustically stable swirled lifted and attached flames will also be recorded at INPT. In these experimental facilities, advanced optical (PIV, OH\*) and acoustic measurements will allow for a detailed characterization of the turbulent flow, flame dynamics and radiated sound. Furthermore, DCs will take advantage of a collaboration with Prof. Woisetschläger at TU Graz to develop capabilities “camera-based laser interferometric vibrometer” (CLIV) optical techniques for density fluctuations measurements[[52]](#footnote-53) and of test rig available at Prof. Sanchez group at UC3M[[53]](#footnote-54).
* **DNS of sound** produced by a cellular hydrogen flame annihilation due to interactions with a counter-rotating vortex pair and walls will be performed at CIEMAT. Simulations will be carried out using the NTMIX code[[54]](#footnote-55), originally developed at CERFACS and used now by Dr. Jimenez’s group. NTMIX includes high-order low-dispersion and dissipation numerical schemes, detailed chemistry, and complex transport properties to solve lean hydrogen flames featuring thermo-diffusive instabilities. Flame/flame interactions as a source of noise in turbulent reactive flows configurations will be studied at NTNU using the high-fidelity DNS code S3D/Legion[[55]](#footnote-56) developed at Sandia National Laboratory and in use at Dr. Gruber’s group. Here, an analytical approach is adopted proceeding in steps of increasing complexity: firstly, noise sources and emissions from interacting pseudo-turbulent flame branches will be studied by performing 2D DNS calculations that span a wide range of turbulent intensities, reactants temperature, pressure and composition; secondly, once the impact of flame microstructure and local strain on noise emissions is fully characterized and understood, fully-fledged 3D DNS of the turbulent flame experiments from NTNU and TUB will be planned and performed for opportunely selected target conditions.
* **LES** capability of reproducing hydrogen flames direct noise will be investigated at POLIBA. At first, following previous studies of Prof. Laera[[56]](#footnote-57),[[57]](#footnote-58) and in collaboration with CERFACS, the DNS dataset from CIEMAT and NTNU will be exploited to expand existing turbulent combustion subscale models to include hydrogen preferential diffusion and thermo-diffusive instabilities effects in the framework of the thickened flame model in AVBP. Furthermore, a novel boundary conditions based on the TDIBC[[58]](#footnote-59) approach will be implemented allowing correct reproduction of acoustic impedances at computational boundaries. POLIBA and TUB will use the developed models to predict direct noise radiated by HYLON and turbulent jet configurations, respectively.
* Once validated, LES data will be exploited with physics-informed neural networks (PINNs)[[59]](#footnote-60) to extract physics-grounded closures for Linearized Navier Stokes equations containing information on dominant flow structures and their interactions with flame dynamics and noise. These will be used to extend **low-order modelling of optimal forcing modes** developed in Prof.Oberleithner group45 at TUB to perform quantitative noise prediction of hydrogen flames allowing for performing parametric studies to investigate the influential parameters of flame noise.

WP4 will investigate tonal noise generated by acoustic/flame thermoacoustic coupling in longitudinal and multi-injector annular chambers.

Eight DCs will contribute to this WP. DC1 and DC2 will participate in this WP by studying resonant coupling of broadband noise and acoustic waves leading to self-sustained thermoacoustic instabilities of swirled flames coupled with low/high frequency longitudinal and azimuthal acoustic modes triggered in single/multi-injector configurations, respectively. Characterization of flame response (FTF/FDF)[[60]](#footnote-61) with respect to longitudinal and azimuthal perturbations at multiple frequencies and amplitudes will be also performed by DC2, DC5 and DC6. DC3 and DC11 will conduct LES for both forced and self-sustained configurations. DNS will be performed by DC7 to characterize the response of laminar thermo-diffusive unstable hydrogen flames complementing the turbulent dataset. Low-order models able to predict system stability maps will be then proposed by DC2 and DC12(UCAM) using either experimental FTF/FDFs or data assimilation from both laboratory scale and real engines, respectively. Finally, combustion noise damping strategies will be investigated. DC11 will collaborate also with DC1 to design, test (in MIRADAS rig), and model passive devices which will be able to attenuate broadband and tonal noise. DC6 will design passive noise controllers based on chevron nozzle designs.

* **Thermoacoustic oscillations** will be studied experimentally in setups at INPT and CNRS to investigate coupling mechanisms with low-frequency longitudinal and/or high-frequency transverse modes. Instabilities coupled with azimuthal modes will be further investigated in the MICCA annular setup at CNRS. Synchronised acoustic, PIV, and flame optical measurements, available in all laboratories, will unveil acoustic-flow-flame dynamics synchronization procedure. Furthermore, results achieved from WP1 and WP2 will be used to detect triggering mechanisms due to violent ignition or direct noise, respectively. Experimental response of both longitudinal and transverse forcing of the turbulent jet flame at TUB will unveil complex coupling mechanisms between hydrodynamic instabilities and acoustic fields. Turbulence-acoustic interactions will be investigated at NTNU by acoustically forcing the canonical flames submitted to artificially controlled turbulence.
* LES of swirled and jet flames under **acoustically forced and self-sustained limit cycle conditions** will be investigated numerically (POLIBA) to complement experiments gaining an understanding in interactions of thermo-diffusive instabilities with system acoustics. The sub-grid closures developed by DC9 and DC4 in WP3 will be further proven to correctly account for peculiar hydrogen combustion characteristics in the context of tonal noise. CERFACS will fully exploit the high capability of AVBP code on CPU/GPU cluster architectures to simulate thermoacoustic instabilities coupled by azimuthal modes observed in the MICCA annular combustor from CNRS and full-scale SAFRAN aeroengine. DNS simulations will be performed at CIEMAT by DC7 to predict the linear acoustic response to longitudinal acoustic forcing of laminar planar lean thermo-diffusively unstable hydrogen flames stabilized in narrow channels, to gain knowledge on the impact of the coupling between thermo-diffusive instabilities and acoustics[[61]](#footnote-62).
* Control strategies will be developed. At INPT the TAB will be used to design optimized **passive dampers** to reduce the noise level over the broadest frequency range[[62]](#footnote-63). Experimental characterization of innovative designs will be performed at POLIBA in an already existing impedance tube equipped with driver units, advanced acoustic measurements, possibility of preheated bias flow and grazing flow. AVBP numerical simulations will complement experimental observations driving the design phase. The capability of the device on real scale Ansaldo Energia GT will be also investigated. At TUB, experimental and numerical findings on jet flames will be employed to design passive noise controllers based on chevron nozzle designs. Using additive manufacturing, different nozzle shapes will be tested, and resultant noise compared.
* **Low Order Modelling**. A LOM for prediction of azimuthal instabilities in MICCA will be developed at CNRS in collaboration with Prof. Orchini at TUB[[63]](#footnote-64) by using an experimental database of FDFs measured in the single sector combustor (SICCA). In addition, UCAM will develop a tool for designing quiet hydrogen injectors less susceptible to thermoacoustic instability. These will be obtained using systematic assimilation of data from laboratory experiments (UCAM), large eddy simulations (TUB), and industrial experiments (RRD) thanks to an in-house accelerated inference and optimization method (AXIOM)[[64]](#footnote-65).

WP5 will address indirect noise generated by the convection of inhomogeneities of gas temperature or composition through nozzles.

Four DCs are involved in this work-package. DC13 (TU Delft) will develop an experimental infrastructure to generate, isolate and accelerate the entropy/composition spots produced by a swirled/jet hydrogen flame and develop measurement techniques capable of quantitatively characterizing the strength of the entropy spots as well as the sound generated by their acceleration. Interactions with DCs in charge of simulation and modelling is expected. DC14 (UT) focuses on numerical and theoretical modelling entropy-vorticity coupling as indirect noise sources. DC15 (TUM) will quantify sources of entropy waves and the contributions to combustion noise and flow-acoustic instabilities, integrate models from the literature for entropy wave propagation, dispersion, and conversion to build a complete model for thermoacoustic interactions (transfer of knowledge from WP4). Finally, extension of developed linear modelling to transport entropy waves exploiting DC13 experimental dataset is proposed for DC10. Interaction with all the DCs involved in the other WPs is also foreseen for model development and reactive simulation data exchange.

* The experimental facility to measure indirect noise will be developed at TU Delft in the group of Dr. De Domenico as PI[[65]](#footnote-66). This rig will allow the controlled generation and acceleration of entropy spots and application of suitable measurements techniques, i.e., the fs-rotational and vibrational CARS set-up (available at TU Delft[[66]](#footnote-67))and optical measurement techniques to **quantitatively measure the strength of entropy spots (their temperature and composition).** Density fluctuations measurements will be also carried out in collaboration with TU Graz. The infrastructure for hydrogen combustion is already operational at TU Delft.
* **Systematic numerical-simulation** studies to understand interactions between vorticity and entropy waves will be performed at UT. Both high fidelity LES and lower computational demanding URANS will be performed on canonical setups available in the literature and TU Delft rig to understand their limits and capabilities. Simulations of turbulent swirl LES simulations in WP2 and WP3 will define initial conditions. Starting from Dr. Hirschberg previous work[[67]](#footnote-68), with the support of UdeS[[68]](#footnote-69), CFD data will be used to define analytical (or semi-analytical) models for describing vorticity/entropy wave interactions, extending the classic hydrocarbons formulation to hydrogen.
* **LES** ofturbulent hydrogen flames will be studied with a customized version of OpenFOAM developed in Prof. Polifke’s group at TUM. The formulation of the entropy wave source terms will account for the effect of a flame’s displacement on local entropy fluctuations, to eliminate spurious contributions to entropy wave generation. Furthermore, the effects of preferential diffusion of hydrogen, in particular the generation of inhomogeneities in fuel/air premixture, on entropy wave generation will be considered[[69]](#footnote-70),[[70]](#footnote-71). Results will be validated against experiments at TU Delft. Finally, the developed methodology will be applied to real engines (RRD).

Training and dissemination activities will be the primary focus of the remaining WP6 (Training) and WP7 (Dissemination, Communication & Exploitation). The training activities in WP6 are covered in more detail in Section 1.3, while the disseminations activities in WP7 are described in Section 2.3.1.

### Integration of methods and disciplines to pursue the objectives.

The research proposed in HyNOISE has a highly inter-disciplinary character combining fluid mechanics, aero-acoustics, combustion, and nonlinear system dynamics. It incorporates experimental and numerical techniques from across configurations with reacting and non-reacting flows, accounting for highly temporally unsteady conditions, many of which are at the limits of current capabilities.

* **Experimental measurements of direct and indirect radiated noise**: the proposed work plan incorporates experimental synchronised measurements for pressures, temperatures, velocities, flow visualizations, etc. at highly resolved time scales and with quite large amplitudes. Novel optical density measurements will be also setup for density fluctuations measurements. Complicating matters, experiments involving highly unsteady and/or turbulent flow present one of the most extreme combustion environments possible in terms of the short time scales combined with extreme temperatures and pressures requiring robust sensors, two constraints that are typically at cross needs. The members of the HyNOISE consortium however have a great deal of experience in these regimes with laboratories that are equipped to handle these requirements.
* **Highly resolved numerical simulations and LOM**: the work plan incorporates a significant number of highly resolved, reactive and non-reactive simulations aimed at different purposes at both component and system levels. DNS of several hydrogen flame archetypes are considered in isolated configuration to allow for greater parametric variation and more detailed investigation of physical mechanisms that lead to noise generation. At the same time, complete coupled systems are also studied to capture the interaction between injector, acoustic combustor, and exit nozzle in longitudinal and annular geometries. For this, to not lose the required fidelity DNS results are exploited to derive physics-based and data-driven turbulent combustion models to improve LES capabilities to reproduce the peculiar properties of hydrogen in complete single- or multi-injector combustion chambers. Finally, both DNS and LES support the development and optimization of lower order models to be capable of providing reliable predictions in complex configurations.
* **Combined experimental and numerical studies**:one of the strongest benefits of the plan of work in HyNOISE is that nearly all of the planned work has a connected experimental and numerical component. This is well suited to multi nature and sources of radiated noise in hydrogen flames, which pushes the limits of both experimental and numerical capabilities. Additionally, modern Machine Learning techniques will be applied to the interpretation of experimental results and development of LOM to further link experiments and simulations. By this approach, the experimental results can help validate the numerical results, which can then help inform and supplement the experimental measurements beyond their capabilities alone. Together, the capacity of each approach is leveraged to allow for a much deeper interpretation of the results than would be possible individually.

Beyond the scientific methods broadly classified above and in more detail in the project descriptions in Table 3.1.f, the network will enable the dynamic integration of all scientific methodologies and disciplines through training, communication, and dissemination activities to train a new class of researchers capable of taking on the challenges that will ineluctably be encountered in future low-emission technologies burning hydrogen. This programme incorporates the existing expertise of 12 leading research institutes in Europe, for the direct supervision of DCs, together with three associated industrial and three academic partners into a single network, whose interconnections result in a capability greater than the sum of the parts. The existing experimental and numerical facilities of each grantee are augmented by the expertise of the other partner organizations to uniquely address these multidisciplinary challenges. Members of HyNOISE employ the most advanced cutting-edge research methods available world-wide. The programme is designed so that the DCs within the four technical WPs can access the necessary skills and profit from the expertise of other DCs through a tailored secondment plan.For each DC, **two physical** and **one virtual** **secondment** have been scheduled to maximize the exchanges among network partners.Training activities and novel *HyNOISE Training programmes* will also provide other opportunities to exchange data, knowledge and, furthermore, will serve as **synchronization points** for the different DC activities.

### Gender dimension and other diversity aspects

The HyNOISE network is committed to recruit a balanced mix of DCs, without any form of discrimination, including but not limited to gender, race (viz., colour, nationality, citizenship, ethnic or national origins, migrant or refugee status), social class and wealth, human physical parameters (size, weight), gender identity, sexual orientation, LGBTQIA+ issues, disability, and age. To this scope, a mandatory training session for all project staff is scheduled at the beginning of the project to raise awareness about gender-based and diversity biases, including unconscious biases and stereotypes. A gender-balanced selection panel will be ensured in the recruitment process by all partners. Job descriptions will be reviewed to ensure no biases of any kind. Blind recruitment strategies will be also implemented to evaluate candidates based on skills and qualifications rather than demographic or gender factors. To attract female researchers to the project, the recruitment strategy will be advertised towards webpages of organizations concerned with the advancement of women in science (e.g., Association of Women in Science, Women in Combustion from Combustion Institute). Facilities that would be attractive for families (e.g., the provision of highly commendable child-care) will be considered as well as dissemination and exploitation channels that can raise awareness of relevant gender and diversity issues (e.g., through publication of appropriate articles in newspapers or magazines). Routes for researchers to report gender/equality issues will be communicated, including bullying and harassment. During the preparation of the HyNOISE proposal, the guidelines on strategies and methods of gender aspect analysis have been considered by referring to the Engineering Checklist of Gendered Innovations Project[[71]](#footnote-72).

* + 1. ***Open science practices***

The HyNOISE DN will opt in regarding the Pilot on Open Research Data. The open science practices will include early and open sharing of research results, research data management, adherence to the FAIR (Findability, Accessibility, Interoperability and Reusability) principles and providing open access to research outputs. For all peer-reviewed articles related to the project results, the publication (at least the post-print version) must be accessible under either (i) Green open access: publication is self-archived in a repository and accessible immediately or after an embargo period, or (ii) Gold open access: publication is accessible the day of its publication and the Beneficiary pays a fee to give free access to the readers. The publications will be uploaded to trusted institutional or disciplinary repositories under a CC BY or equivalent license. Other types of CC BY licenses will be considered for monographs and long text publications. Presentation posters and videos of workshops or training courses will be uploaded to publicly accessible platforms such as the project website and YouTube channel. A LinkedIn and ResearchGate account will be created to spread out the DCs advancements, publications, conference attendances and training. Research data will also be open access through EOSC compliant repositories such as OpenAIRE’s repository, Zenodo, or the EUDAT B2\* infrastructure and services. All code developments will be versioned, for in-house and open-source codes distributed via specific GitHub pages. Regarding commercial codes, best practice and methodology guidelines will be provided for future use. The HyNOISE topics will be included in theoretical and practical teaching activities. Semi-public workshops are scheduled (DE1-2 in Table 1.3) where project progress and results will be presented to a knowledgeable audience Project data will be managed following the FAIR principles and the good practices of Data Management in open science.

### Research data management and management of other research outputs

The Data Management Plan (DMP) will be critical for HyNOISE’s operation. In the DMP, it will be described how the project will collect, share, and protect the data produced during its execution, defining how to balance open access and protection of scientific information, commercialization, and Intellectual Property Rights (IPR), privacy concerns, security as well as data management and preservation issues. The DMP will be updated over the project execution whenever necessary: major updates are expected at M12, M24, M36 and M48. A DMPR (Data Management Project Responsible) will be identified at the Kick-Off meeting and will be responsible to ensure the integrity of all the dataset, their compatibility, the criteria for the data storage and preservation, the long-term access policy, the maintenance policy, quality control, etc. The HyNOISE project is expected to mainly generate and manage the following research data: designs, simulation results, testing results, defect apparition statistics and other research output (software, models, methodologies, etc.). In addition, the project is expected to collect and manage personal data from partners’ personnel involved in the project, and of participants in project events. HyNOISE project will set up a private dedicated Open Access Database, which will be accessible through the project websites and where a selection of the obtained results will be stored. The complete set of open research data disseminated will be stored on the public repositories GitHub, and Zenodo (http://zenodo.org). All hard drive and servers used by the partners for storage of digital data will be backed-up on a regular basis and periodically stored in offline systems to avoid loss of data. Personal data will be managed according to EU 2016/679 GDPR/national Data Regulations (WP1-5, part A-ethics), specific provisions and mechanisms (storage, secured and controlled access, data treatment procedure, etc.) will be described in the DMP. The use or purpose of the different research outputs and their format will be defined in the DMP. For this purpose, the following categories are defined: Research data, Other Research Output and Personal data. In addition, different openness levels are established: Open (O), Restricted (RE) and Confidential (CO). For reuse of open data, the FAIR principle will be applied. Nevertheless, CO and RE datasets metadata will also be elaborated and released offering readers’ information (incl. Digital Object Identifier (DOI)) as to where and how to apply for access to data and under which conditions this access would be granted. A list of relevant datasets to be generated during the project will be included in the DMP, and any updates reported in the D&C deliverables. To be further compliant with FAIR, the following Data publishing strategy will be implemented: Datasets will be deposited under the latest version of the CC BY license, CC 0 license, or equivalent license. Any tools, documentation, explanation, or software needed for reading, processing, or reusing data of a dataset will be provided in the metadata, enabling reusability, and giving an insight of research output quality.

## Quality and credibility of the training programme

### Overview and content structure of the doctoral training programme

HyNOISE brings together leading researchers, institutions, and companies in the European aeroengines and land-based gas turbine sector to provide structured training of DCs in a diverse, international, interdisciplinary, and innovative environment. Through this, HyNOISE promotes their future careers perspectives and enhances their impact on society. The primary goal of HyNOISE training is to educate **future experts in combustion noise** with a strong focus on innovation, entrepreneurial skills, and sustainability focus. To this end, the training combines activities for the acquisition of technical expertise in aerospace and gas turbines engineering with the development of transferable skills in the fields of entrepreneurship, innovation, and sustainability. The structured doctoral training programme is based on “*The Seven Principles for Innovative Doctoral Training*”[[72]](#footnote-73). On the foundation of these principles, three training pillars support the DC’s personal career development: **1) host institution training; 2) network-specific training (workshop and summer schools) and 3) external training.** The structured training programme will provide each DC with a quality-assured training, tailored to account for their personal interests and aspirations. The personalized training includes a well-balanced approach, considering technical skills and expertise, transferrable skills, multi-sectoral exposure, and interdisciplinary experience. Once recruited, each DC will be supported by their own **Career Development Team (CDT),** which will include, besides the DC, the **Supervisor** and a **Mentor**. The DC Supervisor is the PI from the host institution and is responsible for the guidance of the DC through their PhD work/studies. Beyond the supervision of the scientific progress, the Supervisor coordinates the technical training of the DC, necessary for a successful completion of the PhD project, while supporting the DC’s professional aspirations. The Mentor role is taken over by another PI within the network, preferably from the institution where DC’s secondment is planned. The Mentor will add an international and/or inter-sectorial dimension to the CDT and will be responsible together with the Supervisor for the coordination of transferrable skills training. The CDT will develop a personal Career Development Plan (CDP) and a structured training programme tailored to achieve this plan. The career development plan will be reviewed annually within the CDT. To assure training quality for all DCs, the **Training Supervisory Committee (TSC)** will monitor the progress of all CDPs at the end of every year and report to the network Supervisory Board (see Fig. 2). This additionally enables the TSC to have a continuous overview of all educational units and to identify eventual challenges or new developments. This overview will help the board to identify and propose adaptations of the network-specific educational units offered in consultation with the Supervisory Board.

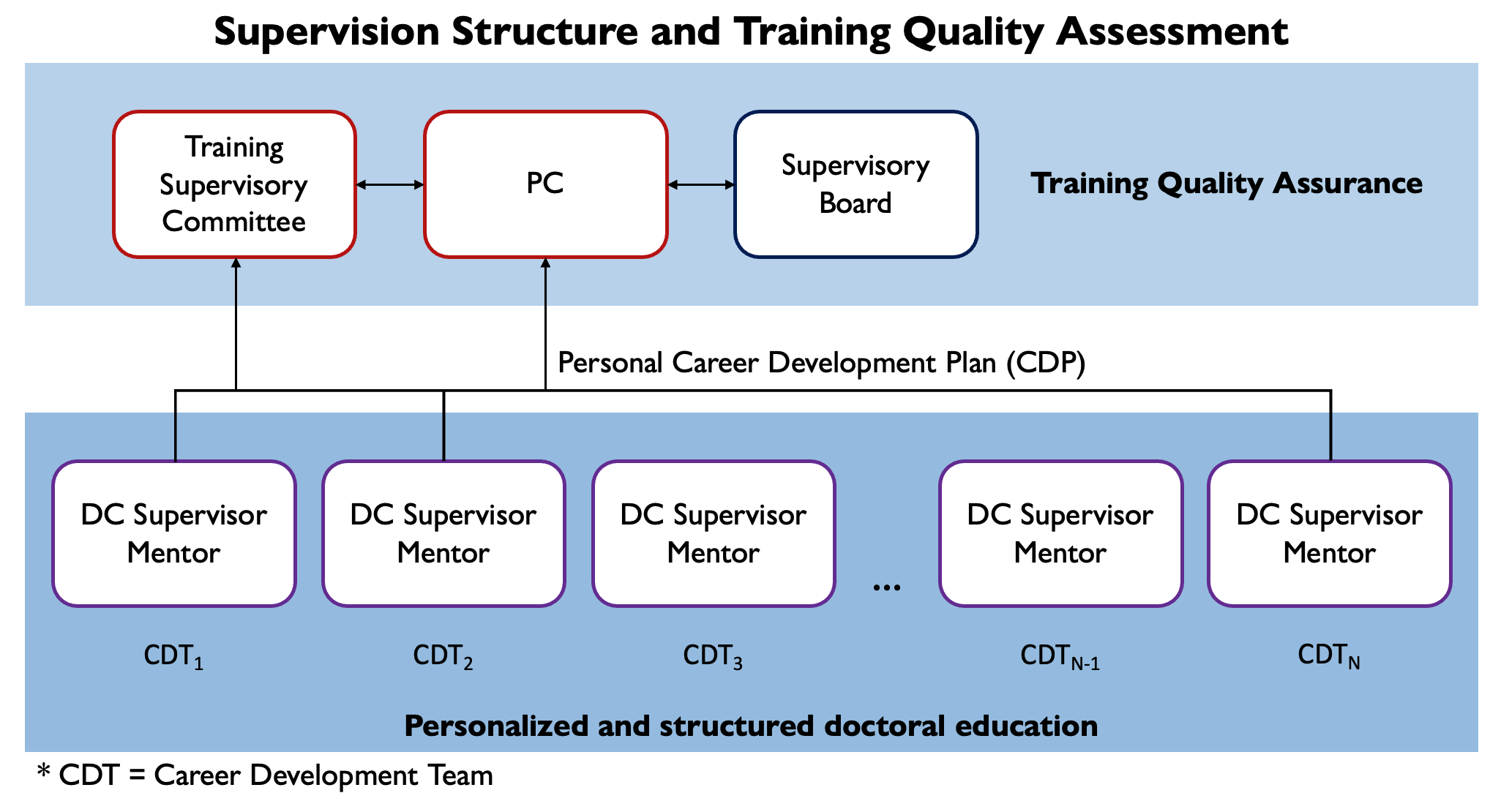


Fig. 2 - HyNOISE-DN supervision structure and training quality

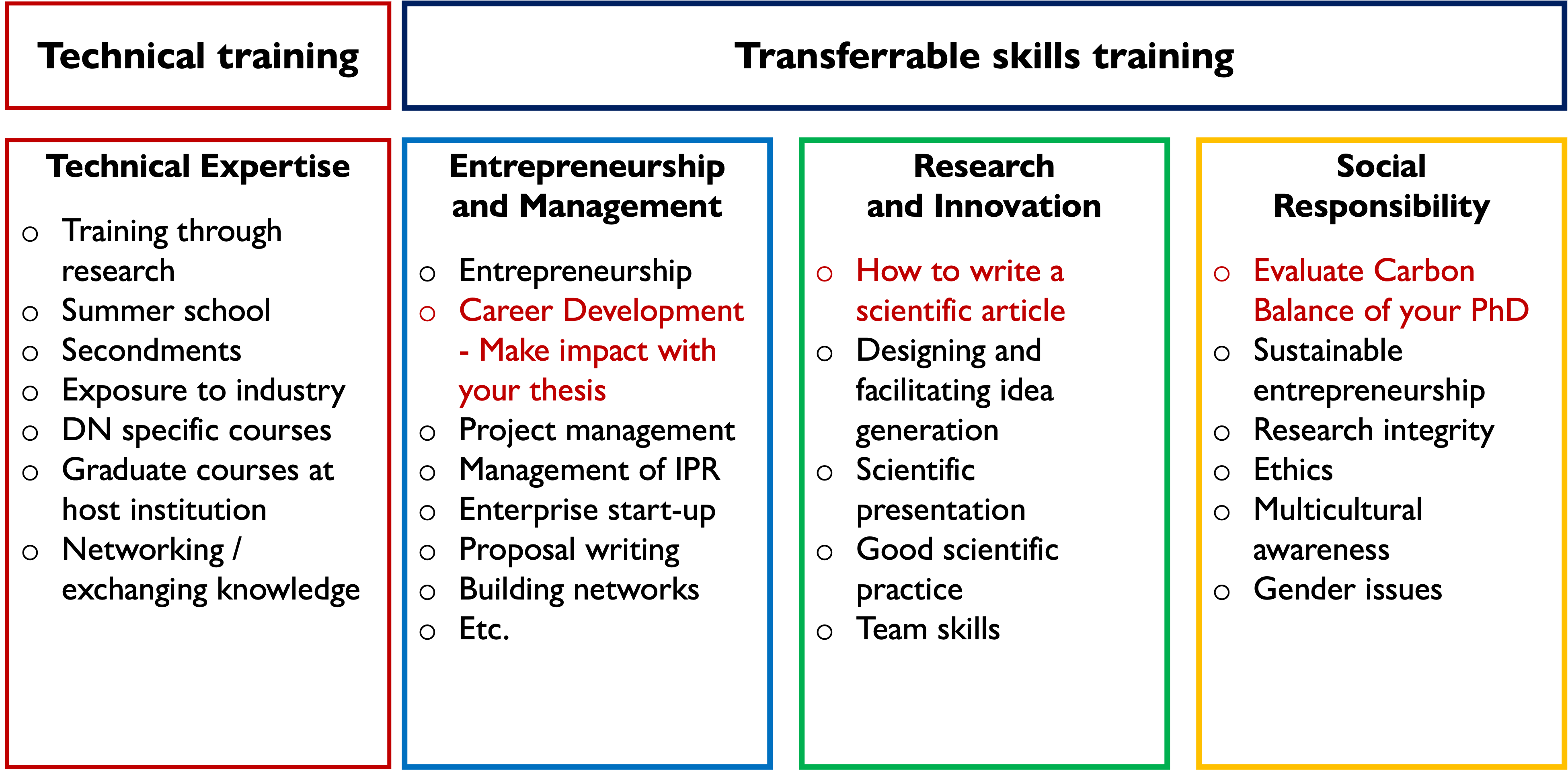


Fig. 3 - HyNOISE training program: content structure

### Content structure of the HyNOISE training programme

The HyNOISE training programme aims at educating future engineers with a special emphasis on hydrogen combustion and noise prediction and control. Therefore, besides the necessary technical expertise, training elements focused on innovation, social responsibility, and entrepreneurship are an intrinsic part of the training programme. A mix of online and in-person courses will be organized to guarantee the balance between sustainability and network building. Furthermore, to **further reduce its carbon footprint, HyNOISE proposes to concentrate all in-person workshops in fewer, but longer training events.** A tailored training content has been developed with a focus on technical as well as transferable skills training, as sketched in Fig. 3. **Technical training** The technical training will be realized through various measures. Each DC will undergo training through research, while working on strongly innovative topics (see Section 3). State-of-the-art research methods and techniques will be applied with the continuous support of the supervisor. Furthermore, each DC will gain additional technical knowledge and experience through secondments and exposure to industry. A series of graduate level courses on relevant scientific topics are available at host institutions and will be complemented with specific courses provided by the HyNOISE network. In this context, the strong interdisciplinary aspects of the network will be fully exploited to provide unique educational units to the DCs. Finally, through networking and knowledge exchange, the technical training of DCs strongly benefits: (1) Members of the network; (2) Visiting researchers from the academic or non-academic sector; (3) Members of other relevant networks, e.g., INSPIRE MSCA-ITN, or ICHARUS-DN; (4) Researchers from the international scientific community through participation in international conferences. **Transferable skills training** According to the described training concept, the transferrable skills training is grouped into three pools: (1) entrepreneurship and management; (2) research and innovation; (3) social responsibility. Proposed training for each pool is shown in Fig. 3. The Training Committee will choose the topics for each pool in cooperation with the Supervisory Board, considering the DCs’ career-development plans. Each DC is obliged to attend at least two training courses from each pool. Training marked in red in Fig. 3 is considered essential for the HyNOISE training concept and will be provided as network-specific training. Training participation shall be obligatory for all DCs. Other training can be chosen by each DC (supported by their CDT) according to personal needs, interests, and aspirations, and will be detailed in their personal CDP. This DC-specific transferrable skills training will be provided locally by each host institution. In addition to the transferrable-skill examples discussed below, the CDP will encourage the development of language skills for DCs in foreign host countries.

**Organization structure of the training events** All available courses and training, both network specific and at various hosting institutions, will be listed and described on the web and be available to all DCs. Detailed descriptions of different educational units are given in the following.

*Host Institution Training* Each host institution provides an attractive working environment for the career development of the trainee. At all academic beneficiaries, **graduate-level courses** on relevant topics such as combustion, fluid mechanics, CFD, etc. are available and will be outlined with the CDP. Furthermore, all academic partners regularly host seminars where **knowledge exchange** with internal and invited researchers will be facilitated. Additionally, each DC has access to local career guidance services and transferrable skills training. Typically, this includes language courses, scientific writing, presentation skills, project management, preparation for job application, and more. If a specific training activity is not available at a host institution, but considered essential by the CDT, the DC will attend it at another beneficiary institution, e.g., at a secondment institution.

*Network-specific training* The inherently interdisciplinary concept of the HyNOISE network provides an exceptional training environment. Experience has taught us that barriers to clear and efficient communication between DCs can develop when distributed across a broad network and specialized in different disciplines. These barriers can hinder effective communication and knowledge exchange in an interdisciplinary team. To prevent these barriers from arising and to facilitate fruitful exchanges among the DCs, unique interdisciplinary network-specific training will be provided and shall be mandatory for all DCs. This network-specific training will focus on the enhancement of the quality of interaction between DCs. A combination of e-learning, blended learning, and problem-based learning will be employed. This approach is expected to be extremely efficient, as it accommodates different learning preferences, especially considering the heterogeneous backgrounds of DCs in such interdisciplinary DNs. The network-specific ***workshops (WS), courses (OC) and (novel) Training Programme (TP)*** will be offered according to Table 1.3. Training events have been structured to achieve the right balance between providing the soft skills and technical training needs to enhance the career prospects of the DCs. The WS1 has been scheduled four months after the end of the recruitment process to be safe from possible delays, while WS2 is close to the internal mid-term review meetings of the program. Furthermore, aiming to find a good balance between sustainability and development of interpersonal relations, a choice of the HyNOISE consortium members is to **concentrate all the in-person workshops in fewer but longer training events.** This is what inspired HyNOISE novel ***training programmes*** *(TP) “Modelling Center”* and *“Experimental Atelier”.* These are conceived as events offering at the same time advanced training and a collaborative environment, where the ERSs will be challenged to co-operate to solve modelling and experimental problems linked to HyNOISE’s scientific objectives. These will be complementary to specific DC main activities and will complete their training. At the same time, in addition to secondments, this training will also serve as a **synchronization hub,** given that these are unique occasions, where all 15 DCs and their supervisors are gathered in a single place for a sufficiently long time (one month) to allow for cross-WP data/knowledge exchange between DCs.

**Table 1.3 Main network-wide training events, conferences with contribution of each member**

|  |  |  |  |
| --- | --- | --- | --- |
|  | **Main Training Events & Conferences** | **LI** | **Date** |
| WS1 | Workshop: **Hydrogen Combustion: Fundamentals, Challenges and Experimental/Modelling Tools**  This course will provide a concise overview of the state of combustion with a focus on the challenges of hydrogen as a fuel. It will be held shortly after recruitment is complete and has the objective of quickly familiarizing the trainees with the multi-disciplinary topics within hydrogen combustion. Being the first in person course, it will also have the objective of improving communication between the WPs and the DCs. TUB will host and organize the event with a contribution from all the partners and external experts in the lectures program. | TUB | M10 |
| TP1 | **HYNOISE programme: Modelling Center. Advance modelling and data-driven techniques in combustion noise**  The HyNOISE Programme: Modelling Center will be the innovative training/synchronization event proposed in the HyNOISE project. All 15 DCs will be gathered for one month to receive advanced training on modelling strategies for the four different hydrogen flame noise generation mechanisms investigated in HyNOISE: ignition, direct noise, thermoacoustics and indirect noise. In addition to the lectures, DCs will be asked to solve scientific challenges in collaborative groups on topics in line with HyNOISE’s scientific objectives. Relying on his long experience in organizing similar training events (e.g., https://www.poliba.it/it/didattica/bari-automotive-summer-school-IT), POLIBA will host and organize the event with input from ALL partners and EXTERNAL experts. Results will be summarized in proceedings published on the consortium's website. This will be a unique opportunity for the 15 partners to work together in one place and to exchange data/knowledge between the DCs working in different WPs. | POLIBA | M18 |
| WS2 | Workshop: **Industry perspectives on hydrogen combustion in gas turbines and aeroengines**  This 3-day workshop will be hosted and organized by INPT. It will gather the contributions by associated industries in the network (SAFRAN, Rolls Royce, Ansaldo Energia, GE) to provide DCs with key design perspectives on combustion noise in gas turbines for power generation and aeroengine propulsion, together with design solutions to achieve stable and quiet combustion. | INPT | M24 |
| TP2 | **HyNOISE programme: Experimental Atelier. Acoustic and laser diagnostic techniques in combustion noise**  This two-week course will provide DCs fundamental knowledge on state-of-the-art combustion noise diagnostics. Focus will be given to acoustic and optical laser-based diagnostics such as PIV, LIF and CARS. Like WS2, together with lectures, practical activities on laboratory scale experimental rigs will complement lecturers offering DCs the opportunity to directly feel and measure the noise generated by a hydrogen flame. The course will be organized and hosted by NTNU and will see contributions from INPT, TUB, CNRS, TU Graz and TU Delft. The mid-term supervisory board will be performed at the end of the workshop. | NTNU | M36 |
| OC1 | Online Course: **Gender equality in recruitment and career progression**  The principal investigators are the intended audience for this workshop, in contrast to the other network-specific courses and workshops offered to DCs. All the network's major investigators will take part in the workshop, keeping both the life-long learning culture and the theme of social responsibility as an essential educational component of HyNOISE in mind. This will consist of an online training to be organized prior to the start of the recruiting process with the goal of increasing awareness of gender issues in recruitment. This is in addition to the anti-bias initiatives that each beneficiary's human resources have already created. | TU Delft | M1 |
| OC2 | Online Course: **Fundamentals of thermoacoustic instabilities**  The online SPOC course provided by CERFACS will offer all DCs the basic knowledge to understand the fundamentals of acoustic and flame coupling leading to thermoacoustic combustion instabilities. This course presents the theoretical background and introduces practical tools needed to tackle such problems. The course will be delivered by Dr. Thierry Poinsot (INPT/CERFACS). It will be repeated every year in April or November. It lasts 4 weeks and requires typically 2 hours per week, online and easily available for each student. | CERFACS | M12 |
| TS1 | Online Course: **How to compute a carbon balance. Evaluate carbon footprint of your PhD**  The course will offer the opportunity to PhD students to assess the carbon footprint of the activities carried out during their PhD courses (e.g., travels, experimental and numerical activities, manuscripts writing, etc.). Tools and institutional references will be used to assess the CO2,eq emissions related to different activities to understand how sustainable the research is. | POLIBA | M13 |
| TS2 | Online Course: **Career Development – Making impact with your Thesis**  DCs practise how to think in an entrepreneurial way and develop their own business ideas based on their PhD research. | TU Delft | M38 |
| TS3 | Online course: **How to write a scientific article**  This online course will cover how to go about writing a manuscript for a scientific journal or conference, ethics in publishing, what to expect from the review process and rebuttal strategies. | UT | M15 |
| DE1 | Dissemination Event: **HyNOISE Academia meets Industry workshop**  Experts in the fields of combustion noise, acoustics and combustion dynamics from across the globe, representing industry, government, and academia will meet in NTNU at the end of TP 2. During the event, DCs will present their completed and planned work to experts during a special poster session. This session will be structured with the workshop attendees to encourage a critical discuss and DCs will receive feedback from the community. DCs will learn to present and discuss their work, while interacting with experts in the field. | NTNU | M36 |
| DE2 | Dissemination Event: **YouTube live streaming Event**  This virtual dissemination event using YouTube, where a live streaming event will be organized giving to DCs the possibilityes to present their work to a more general audience. DCs speech will be structured following the template of “My thesis in 3 minutes”, exercise that will force each DC to identify the main strengths of their research. This will be followed by a panel discussion on challenges of hydrogen combustion, noise and GTs moderated by a professional YouTube scientific reporter. | POLIBA | M40 |
| DE1 | Dissemination Event: **Capstone Symposium**  At the completion of the training programme, DCs will present their final results during this capstone symposium to the community. Representatives from a range of internal and external partners in industry and academia will be invited to attend. Invited experts will give plenary talks, and a portion of the symposium will be open to the public, with the intention of communicating the activities of the network. This will be organized at POLIBA by the project coordinator with the contribution of all beneficiaries and associated partners. | POLIBA | M46 |
| **WS** - workshop; **TP** - Training Program; **OC** - Online Course; **TS** – Transferable Skill; **DE –** Dissemination Event. **LI** - Leading Institution | | | |

## Quality of the supervision

### Qualifications and supervision experience of supervisors

Each DC will be assigned a main supervisor who has the time and relevant expertise needed to ensure they successfully complete their research and training objectives (indicated by the DC column of Table 1.4.).

**Table 1.4** **Qualifications, expertise and experience of the supervisors**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Organization** | **Supervisor** | **Expertise & Graduate students tutoring/co-tutoring experience.** | **DC** | **Role** |
| INPT | Thierry Schuller | Combustion, flame dynamics; 22 years’ experience; supervised over 25 PhDs. | 1 | SB, TSC |
| CNRS | Dr. Antoine Renaud | Combustion dynamics, flame stabilization; 6 years’ experience; supervised 7 PhDs (completed and ongoing). | 2 | SB, TSC |
| Prof. Sebastien Candel | Combustion, aeroacoustics; 65 PhD students, more than 240 articles in peer-reviewed journals | SB, SSC |
| CERFACS | Dr Laurent Gicquel | Turbulent reactive flows, CFD, combustion instabilities; more than 25 years’ experience; supervised over 80 PhDs ; more than 90 articles in peer-reviewed journals. | 3 | SB, DCC |
| Dr Thierry Poinsot | Two ERC advanced grants on combustion; supervised 110 PhDs; 250 articles in peer-reviewed journals. | SB, SSC |
| CUT | Prof. Artur Tyliszczak | Turbulent reactive flows, CFD; four National Science Center grants on combustion; 20 years’ experience; supervised 8 PhDs; more than 100 papers. | 4 | SB, DCC |
| NTNU | Prof. James Dawson | Combustion, turbulent flows, experimental methods; ERC Synergy grant in hydrogen combustion; 20 years’ experience; supervised 15 PhD students (completed); over 60 journal publications. | 5, 8 | SB, TSC, SSC |
| Dr. Andrea Gruber | First-principles numerical simulations of turbulent reactive flows (DNS); 25 years’ experience in fundamental/applied research at SINTEF; supervised MSc students and PhDs. | SB |
| TUB | Prof. Oliver Paschereit | Two ERC AdGs and one PoC on thermoacoustics and emissions; supervised over 90 PhDs; over 500 articles in journals and conferences. | 6 | SB, SSC |
| Prof. Alessandro Orchini | Thermoacoustics and reduced order modelling; 11 years’ experience; supervised 5 PhDs. | SB, TSC |
| Prof. Killian Oberleithner | Dynamic modelling, combustion, aeroacoustics, flow control; 12 years’ experience; supervised 121 PhDs and 3 PostDocs; over 85 peer-reviewed journal articles*, 12 grants over 5 M€* | 10 | SB, DCC |
| Dr Thomas Kaiser | Emmy Noether Grant Holdert, CFD, Thermoacoustics, combustion dynamics, 8 years’ experience, co-supervised 3 PhDs. |
| CIEMAT | Dr. Carmen Jimenez | Combustion, flame dynamics and thermoacoustics simulations; supervised 3 PhDs and 3 MSc students. | 7 | SB, RGA |
| POLIBA | Prof. Davide Laera | Combustion and thermoacoustics; 12 years’ experience; supervised over 10 PhDs; 28 peer-reviewed journal articles. | 9 | PC |
| Prof. Sergio Mario Camporeale | More than 30 years’ experience on combustion, thermoacoustics and acoustic damping; supervised over 20 PhDs; over 50 peer-reviewed journal articles and 100 conference papers. | 11 | SB, RGA |
| UCAM | Prof. Matthew Juniper | Bayesian inference, adjoint methods, thermoacoustics, flow instability; 22 grants totalling over €5M; 20 years’ experience, supervised 24 PhDs; over 130 papers. | 12 | SB, DCC |
| TU Delft | Dr. Francesca De Domenico | Thermoacoustics and laser diagnostics; 8 years’ experience; supervised 4 PhDs. | 13 | SB, RGA |
| UT | Dr. Lionel Hirschberg | Fluid Dynamics, Aeroacoustics, Indirect combustion noise, Indirect combustion noise driven self-sustained pressure pulsations; supervised 2 PhDs. | 14 | SB, RGA |
| TUM | Prof. Wolfgang Polifke | More than 25 years’ experience in thermoacoustics and flame dynamics; supervised over 40 PhDs (completed); over 300 peer-reviewed journal articles. | 15 | SB, SSC |
| **PC** – Project coordinator; **SSC** - Scientific Supervisory Committee; **TSC** - Training Supervisory Committee; **RGA** - Recruitment and Gender Aspects Committee; **DCC** - Dissemination and Communication Committee; **APR** – Associate Partner Representative | | | | |

### Quality of the supervision arrangements

The supervision for each DC is designed to optimize the efficiency of both scientific and training programs. A Career Development Team (CDT) for each DC includes a direct supervisor, a co-supervisor, and a mentor. This structure not only fosters collaboration but also facilitates the exchange of ideas within the network, going beyond planned secondments, due to the complementary aspects of partner projects. The CDT team structure serves as a valuable support system in instances of conflicts between a DC and their supervisor or other relationships within the network, helping to mitigate conflicts and reduce risks to the projects.

#§REL-EVA-RE§#

# Impact #@IMP-ACT-IA@#

## Contribution to structuring doctoral training at the European level and to strengthening European innovation capacity

HyNOISE will strengthen European innovation capacity by: (i) generating new scientific and technical understanding leading to design of new and efficient hydrogen-ready combustion gas turbine concepts by 2050, (ii) providing Europe with a set of highly trained researchers with the scientific and technical skills needed to develop these concepts and drive technical innovations over the course of their career, with particular knowledge and mindset to support the development of technologies for sustainable transport and energy sectors and (iii) increasing the competitiveness of European manufacturers across the energy and transport sectors.

Meaningful contribution of the non-academic sector to the doctoral training Three industrial partners participate in

HyNOISE, i.e., SAFRAN, RRD, AE, and one non-academic research organization, i.e., CERFACS. SAFRAN, RRD,

AE are major players in the gas turbine field, either in the aviation sector (SAFRAN, RRD) or in power generation

(AE). Industrial partners will provide mentorship, guidance, and networking opportunities for the DCs, by helping them to build relationships and connections with industry professionals and providing them with exposure to potential future employers. In terms of local training, SAFRAN will host the physical secondment of DC3 with the objective to apply the numerical methodology developed by the student to proprietary technologies under development for H2 combustion. A virtual secondment is also scheduled with DC9 for exchanges on support of developed models. RRD will host secondment of DC15 focusing on low-order modelling of indirect noise and of DC12 to exchange on experimental database for data assimilation purposes. RRD will also interact with NTNU to exchange technical knowledge on advance noise measurements. A secondment in AE is planned for DC11 to apply the numerical methodology developed by the student on prediction and damping of thermoacoustic instabilities on real scale gas turbines for power generation. DC10 will also perform a secondment in AE to apply developed LOM for instabilities prediction on real gas turbines. These secondments will be a unique training experience for the DCs, who will be exposed to a wide variety of aspects within the aeroengine/gas turbine industry, a working environment that focuses on innovation, technical support as well as a vital industry perspective to complete their research project. In addition to hosting secondments, as companies that design and manufacture aeroengine and gas turbines, Safran, Rolls Royce and Ansaldo Energia will provide valuable expertise and hands-on training to doctoral researchers involved in the project by contributing to the development of training programs and the identification of research topics that are relevant to industry's needs. Indeed, a workshop “*Industry perspectives on hydrogen combustion in gas turbines and aeroengines”* is scheduled at INPT (M24) among training activities in which HyNOISE industrial partners, but also invited speakers from other EU GT industries, will provide an encompassing outlook on both aeronautic and power generation sectors. CERFACS is a recognized leader in the field of CFD modelling of turbulent, unsteady, and reacting flows, with R&D consulting ranging from aeroengine to power generation sectors. CERFACS has a long and consolidated experience in the supervision of DC, with more than 150 PhDs supervised. DC3 will be supervised in the context of HyNOISE at CERFACS with a research project on CFD modelling thermoacoustic instabilities and direct noise in both longitudinal and annular combustion chambers.

Developing sustainable elements of doctoral programmes after the end of the DN funding.Promoting sustainability in training programs and fostering cooperation are crucial aspects of contemporary educational initiatives. Multiple are the elements introduced to enhance the sustainability of HyNOISE doctoral programme. At training level, a good balance is given between in presence and online training. The material that will be specifically developed for the training events detailed in Table 1.3 will be shared and made available to all partners, so that it can be integrated into the specific courses of the different European doctoral schools and, thus, be useful for the training of future PhD students outside the consortium. To this scope, a specific cloud space to store educational materials will be made available to all HyNOISE members. Widespread use of training events focusing on soft skills (TS1-3) is expected. Because of their inherently versatile nature, these events are intended to be extended to all doctoral programs, regardless of the specific scientific themes pursued. Finally, the strategic scheduling of training events, incorporating a combination of fewer yet more extended in-person sessions (*training programmes*), along with online courses and workshops, will contribute to the reduction of HyNOISE's carbon footprint, thereby enhancing the overall environmental sustainability of the entire HyNOISE doctoral network.

The establishment of strong cooperation between partners (beneficiaries and associates without distinction) is what inspired the design of the HyNOISE project. This is confirmed by the multiple interactions envisaged through secondments (between in presence or virtual secondments, each DC will collaborate with at least 3 project partners), joint training or dissemination events. All partners are keen to promote ongoing partnerships beyond the current project duration. This includes the deliberate exploration of potential synergies with major European initiatives such as Erasmus+ for student and teaching staff exchanges, or MSCA initiatives for staff exchanges or postdoctoral research, as well as specific national or regional calls, e.g., the Vinci program between Italian and French universities, French/German ANR-DFG initiatives for researcher/teacher mobility, University-founded visiting periods, among others. Finally, entrepreneurial initiative will take advantage of the presence in the consortium of major European GT manufacturers as well as the synergies between MSCA and European Institute of Innovation and Technology (EIT) to help the development of innovative products and/or services.

## Credibility of the measures to enhance the career perspectives and employability of researchers and contribution to their skills development

To enable greater market penetration of renewable energy sources, green hydrogen (H2) technologies are critical. Indeed, the use of H2 in gas turbines is one of the most promising technical solutions to achieve environmentally sustainable and flexible reliable energy production. Similar technical solutions are also planned for the aviation sector[[73]](#footnote-74). Therefore, it is of the highest importance, amongst the HyNOISE project outcomes, to create a group of experts in combustion and noise generation who will, in service of the EC objectives in terms of CO2 emissions reduction by 2050, lead the design of the next generation of sustainable aviation and power generation technologies. They will be trained in a mix of competences, including numerical modelling, hydrogen combustion, chemistry, acoustics, and data-driven approaches. Moreover, these young researchers will be trained in thermoacoustics, experimental diagnostics, applied mathematics, and high-performance computing. This multidisciplinary research training in theoretical, numerical, and experimental methods applied to multiphysics problems will make them highly sought by the gas turbine industries (energy and aviation). Those competences are transferable with several industrial sectors including energy efficiency, renewable energy (including biofuels production and processing technologies) and automotive technologies. HyNOISE researchers will also be able to pursue an academic career as well as to develop their own patents and cooperate with the major industries through new start-ups. The HyNOISE training will undoubtedly expand the potential career of DCs. Independently of the current proposal, all HyNOISE members have long been and continue to be committed to the career perspectives of their students and researchers. Nearly all graduates from the HyNOISE members experience a seamless transition into post-graduation employment. Due to the close industry/academia partnerships among HyNOISE members, graduates who hope to find placement in industry face no difficulty, with some of them hired at gas turbine industry HyNOISE partners Safran, Rolls Royce, Ansaldo Energia, as well as Baker Hughes, Siemens, MTU, AvioAero and others. One key aspect of the success is the utilization of secondments, short stays and training programmes events that are designed by the HyNOISE partners to have a positive impact on the DCs’ careers. DCs will develop the working skills needed to adapt to different environments and organizational structures. By working directly with researchers across the network, combining studies based on experiments and simulations, DCs will learn and understand the constraints and potential of other disciplines. The HyNOISE teams are well-established top-level research institutes, which will help DCs to develop track records, contacts and collaborations that will have a lasting impact throughout their careers.

## Suitability and quality of the measures to maximize expected outcomes and impacts, as set out in the dissemination and exploitation plan, including communication activities #@COM-DIS-VIS-CDV@#

### Plan for the dissemination and exploitation activities, including communication activities

HyNOISE’s approach to dissemination will focus both internal and external network outreach. Internal dissemination amongst the network partners and local research groups will include progress reports, internal reports, presentations, codes, and data. These will be uploaded to the project website, data (Zenodo) and code (GitHub) repositories for sharing. As common in DN programmes, knowledge transfer will happen directly through DC secondments, short stays where DCs will share data, new insights, and implement new codes/methods. The HyNOISE consortium will offer a **novel channel for internal dissemination** during the *Training Programmes* (TP1-2). Indeed, these extended training sessions where all DCs are gathered in one single place will create the perfect conditions for knowledge exchange between DCs working in the same and different WPs. The primary channels for external dissemination of research results will take the following forms:

* **The project website**, set up at the beginning of the project, will outline the project aims and general activities of the HyNOISE network for the outside world. It will be a direct communication link between the HyNOISE team and the member institutions for public engagement, as well as the main portal used by the network partners for internal dissemination as discussed above.
* **Direct public engagement events,** as for example public forums or lectures delivered by HyNOISE members when travelling to partner organizations for the training or secondments event (see Table 1.3). Two dissemination events DE1 and DE2 will give DCs the opportunity to disseminate results of H2NOISE as a consortium. DE1 details hosting of a workshop where academia will interact with industry sectors on combustion noise produced by hydrogen flames. DE3 describes the Capstone Symposium where the final results will be presented. All of these direct engagement events are targeted toward increasing the awareness of the objectives of the HyNOISE programme.
* DCs will publish their results in **peer-reviewed scientific and technical journals**, by addressing Horizon Europe rules regarding open access. Target journals are “Combustion and Flame”, “Proceedings of the Combustion Institute”, “Journal of Fluid Mechanics”, “Journal of Sound and Vibration”, “Journal of the Acoustical Society of America”, “Flow, Turbulence and Combustion”, “International Journal of Hydrogen Energy”, “Journal of Propulsion and Power”, “Journal of Engineering for Gas Turbines and Power”, amongst others.
* Attendance at **international conferences** such as ASME Turbo Expo, International Symposium on Combustion, International Congress on Sound and Vibration, AIAA SciTech/CEAS/FDC, and others.
* Proceedings of the specific activities performed during the HyNOISE Training Programs (TP1-2) will also be published on the project website.
* **HyNOISE will provide several outward facing dissemination activities.** A YouTube channel will be created for the network that will host the recordings of the online trainings OC1-OC2, and (2) where each DC will upload a short video (5-10 mins) describing their project to the public, to be rolled out 3 times, i.e., at the end of each TPs and at the end of the project, and highlighting the motivation, scientific progress, and public benefit of the project. DCs will also be directly connected with industry through the project LinkedIn page, where relevant news, project outcomes and successes, and project videos will be posted to amplify their dissemination. Lastly, beneficiaries will be encouraged to promote their activities during the events organized in the frame of the European Researcher’s Night aimed at increasing awareness of research in the fields of green energy and propulsion, thus raising the interest of young people in careers in STEM fields.

As of 2022, gas turbine technologies have been designated as dual use. It is therefore important to the consortium to state explicitly that the research plan and activities in HyNOISE are of a strictly civilian nature. This is consistent with the strict civilian clause in the charters of several of the consortium members and the objectives of the MSCA-DN. The consortium will only interact with civilian branches of the industrial partners. Furthermore, the target technology readiness level of the research plan is TRL-3, which is designated as fundamental research. With respect to the dissemination plan, additional consideration is given to export control of project results out of an over-abundance of caution. The low TRL exempts the project results from additional control, however the **Dissemination and Communication Committee (DCC) will coordinate the review of dissemination activities with the legal offices of the beneficiaries headed by POLIBA** to ensure both compliance with export control regulations and applicable regulatory frameworks as well as strict adherence to the civilian use requirements. The DCC will also oversee the monitoring of the effectiveness and completeness of the dissemination strategies that each DC will include in its CDP, proposing contingency solutions if necessary (Table 3.1g).

### Strategy for the management of intellectual property, foreseen protection measures

Exploitation of the HyNOISE results will be achieved, firstly, via direct exploitation into the aerospace and energy industries and via technology transfer into other sectors. Direct exploitation by the industrial partners is a natural first step, however additional action will be taken to further increase effectiveness. The HyNOISE programme will be a first proof of concept to other industry members, reducing hurdles to adoption by mitigating the initial perceived product risk. **The technology transfer offices of the member organizations will be enlisted to facilitate the exploitation of these results.** The progress made greatly help to increase industrial awareness and encourage participation. This objective will be supported by several outward facing events which will be focused on connecting HyNOISE results with industry leaders. These events will offer opportunities for members to identify hurdles other industry members are encountering and better adapt to these issues through WS2 GT Industry Perspectives. The second exploitation pathway is through technology transfer, which has a lot of potential with the HyNOISE programme. There are direct applications of the results of HyNOISE to other similar topics. For example, HyNOISE results will be useful in the topics of generation of new combustion solutions, and combustion of synthetic and hydrogen enriched fuels (which has more recently become an important question to the combustion community). Because hydrogen and sound generation and control-based technologies bring so many separate fields together, it provides many opportunities for knowledge and expertise to exchange.

From a logistical standpoint, **the establishment of a Consortium Agreement (CA), including intellectual property rights and other governance aspects of the network will follow the example of the League of European Research Universities (LERU).** LERU provides a CA template – based on the DESCA model – that is fit to the special requirements of the MSCA DN actions. The final, specific details of the agreement regarding existing and developed IP and other issues will be settled upon project acceptance, however this template agreement has previously provided an excellent starting point and platform to finalize the agreement. #§COM-DIS-VIS-CDV§#

## The magnitude and importance of the project’s contribution to the expected scientific, societal and economic impacts (project’s pathways towards impact)

### Expected scientific impact(s)

HyNOISE’s key output is a new generation of a well-trained PhD-degree-holding researchers and engineers, with multi-disciplinary skills, mixed industry/research experience and a sustainability, zero-carbon operations, and entrepreneurial mindsets at the centre of their decision-making process. To achieve the scientific goals of developing technologies and numerical models capable of handling both unstable and silent hydrogen combustion in GTs. HyNOISE DCs will face interdisciplinary challenges across physics, chemistry and engineering. HyNOISE will establish novel numerical and experimental methods and develop novel knowledge, which will become a reference for the scientific community working in the energy and mobility sectors. Among others, it is worth mentioning ammonia-hydrogen or hydrogen-piloted or SAF combustion for GTs, two applications where modelling and knowledge developed in HyNOISE can be easily transferred. Being able to understand, detect and predict sources of combustion noise is essential for the definition and development of innovative active/passive flame control technologies, e.g., using nano-pulsed plasma discharges, which may lead to further possible research investigations and new future breakthrough technologies. Relevant scientific impacts will be achieved through several key areas: (1) the flame dynamics during flame ignition and re-ignition phases in order to define the quieter and stable procedure in both single and multi-injector configurations, (2) turbulence-flame interaction and their link to noise generation in flames, (3) the impact of hydrogen peculiar properties on acoustic-flame coupling leading to tonal noise due to self-sustained thermo-acoustic instabilities (4) high-dimensional optimization techniques for the design of active and passive system in order to stabilize the flames, (5) entropy noise assessment and control, and (6) derivation of novel computationally cheap LOM to drive the design of quieter GT systems. A large number of institutions and fundamental subjects will benefit from advances in these research areas.

The direct involvement of industry and the secondments will facilitate knowledge transfer, promote innovation, and additionally increase the competitiveness of European industry and research institutions. In this context, the strong contribution of GT companies to HyNOISE is important. This involvement will provide the following benefits at European level: (1) development of strong interactions between fundamental sciences and applications, (2) increased experience and transfer of knowledge for scientific driven technical innovation, (3) promotion of future, long-term collaborations and (4) enhancement of the research capacity for all partners and a recruitment pool for industry, as well as research opportunities for academic and research institutions.

While the results outlined above will have profound implications outside the GT community, the scientific impact of studying the noise in GTs will be highly significant. Most of the studies performed in the last decades on the subject of combustion noise, thermoacoustic and entropy noise involved methane or other conventional carbon-based fuels, while much fewer investigations have been carried out considering hydrogen[[74]](#footnote-75). The results of this project will help to highlight the progress in scientific understanding in this application and will identify pathways to continue developing the technology for civilian applications in power generation and aviation, and for hydrogen adoption.

### Expected economic/technological impact(s)

The adoption of less noisy and more thermoacoustically stable combustion technologies for aviation or power generation will have a direct impact on the economics of green and sustainable fuels and the replacement of fossil fuels. Indeed, although individual aircraft have become about 75% less noisy over the past 30 years, the number of commercial aircraft and business jets is expected to double in the next 20 years, exposing EU citizens to higher noise levels. For this reason, in 2021 EU adopted the Zero Pollution Action Plan[[75]](#footnote-76) with the objective to further limiting the share of people chronically disturbed by transport noise by 30% by 2030, surpassing the Regulation (EU) No. 598/2014. Overseas, NASA has set ambitious targets in the reduction of cumulative noise emissions for this decade, aiming at a decrease of 71 dB compared to the current Chapter 4 noise standards from the International [Civil Aviation](https://www.sciencedirect.com/topics/earth-and-planetary-sciences/civil-aviation) Organization (ICAO). Meeting these goals will require the reduction of combustion noise[[76]](#footnote-77). The introduction of hydrogen as a clean fuel will bring additional challenges. Knowledge developed in HyNOISE programme anticipate these goals and will help aeroengines companies with the developing of GT technologies in line with these future regulations. Furthermore, mastering the control of flames has the potential to yield simultaneous increases in overall system efficiency and reductions in specific fuel consumption while using hydrogen. Indeed, instabilities (both thermoacoustic and thermodiffusive nature) is one of the major factors limiting GT operability in ultra-lean mode. Exploiting hydrogen wide flammability limit, HyNOISE outcomes will help the development of ultra-lean GT technologies with a direct consequence in fuel consumption, which is not unreasonable to be foreseen in the vicinity of 10% or more. Extremely lean flames will also lead to an effective reduction in NOx emissions, bringing future H2 GTs in line with the most stringent emissions for natural gas (<15 ppmv at 15% O2), which are still far off today. Finally, leaner flames will reduce the risks of flashback and explosion, increasing the safety levels of such technologies. **Concluding, the large-scale impact of HyNOISE outcomes is a clear win in terms of higher efficiency, lower fuel consumption, and the economics of hydrogen utilization.** The direct impact of HyNOISE is to clearly demonstrate this potential and lower the barrier to entry of further development in the civil aviation and power generation sectors with a major economic benefit to decreasing the cost of hydrogen adoption. Furthermore, there are direct applications of the results of HyNOISE to other similar topics. The impact of the technologies, diagnostics and tools conceived in HyNOISE as concrete options for next generation hydrogen combustion will be maximized by the strong and long-lasting connections of several partners with most relevant European GT and aeroengines manufacturers, in addition to the companies already involved in the network (in some cases, also through specific high-level agreements). Whether produced by experiments (e.g., stability margins, emissions, combustion dynamics) or from modelling and computational studies (e.g., turbulent combustion models), HyNOISE results will be useful also outside the GT sector. For example, HyNOISE results will be useful in the topics of generation of new combustion solutions, and combustion of synthetic and hydrogen enriched fuels (a more and more important issue for the combustion community). Since hydrogen and sound generation and control-based technologies bring so many separate fields together, HyNOISE provides many opportunities for knowledge and expertise to exchange and benefit different disciplinary areas.

### Expected societal impact(s)

In addition to the direct environmental and economic impact of a quieter and cleaner GT, HyNOISE will demonstrate the ability to handle hydrogen and highlight proposed solutions for disruptive technologies for future aircraft and green power generation. The direct outcome of this impact is the increased public perception and awareness of new technologies necessary **not only to achieve the stated climate with a decrease of the environmental impact, but also to significantly improve the citizens’ quality of life and general health in agreement with Zero Pollution EU targets.** The societal impact will be amplified by HyNOISE's robust dissemination plan, which explicitly targets knowledgeable specialists, experts in other sectors, and the general public through means tailored to that audience. The dissemination efforts targeted toward GT experts will increase the awareness of the scientific progress in HyNOISE. Further efforts through conferences and public channels will research experts in neighbouring fields. And the dissemination efforts targeted toward the general public will directly spur engagement with students and researchers, as well as policy makers and industry members. An additional societal impact will be achieved through the strong diversity, gender, and inclusivity efforts in the recruitment plan. These efforts will have further expression in the YouTube video series, where perspective students from underrepresented groups will be able to see fellow graduate students perform cutting-edge research in the aeronautics and power generation fields – potentially for the first time. While difficult to quantify, seeing inclusive researchers will inspire individuals to pursue careers in these and other industries. #§IMP-ACT-IA§#

# Quality and Efficiency of the Implementation #@QUA-LIT-QL@# #@WRK-PLA-WP@# #@CON-SOR-CS@# #@PRJ-MGT-PM@#

## Quality and effectiveness of the work plan, assessment of risks and appropriateness of the effort assigned to work packages. #§CON-SOR-CS§# #§PRJ-MGT-PM§#

### Work Package (WP) List

**Table 3.1a Work Package (WP) List**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **WP No.** | **WP Title** | **No. Lead Beneficiary** | **Start Month** | **End month** | **Activity Type** | **Lead Beneficiary** | **Researcher involvement** |
| WP1 | Management and coordination | 8 | 1 | 48 | Management | POLIBA | - |
| WP2 | Noise and flame dynamics during ignition process | 1 | 6 | 48 | Research | CNRS | DCs: 1-4 |
| WP3 | Direct noise sources in turbulent hydrogen flames | 6 | 6 | 48 | Research | TUB | DCs, 1, 5-10 |
| WP4 | Thermoacoustic instabilities and control | 3 | 6 | 48 | Research | CERFACS | DCs: 1-3, 5-7, 11-2 |
| WP5 | Contributions of convective waves to combustion noise and thermoacoustic instabilities | 12 | 6 | 48 | Research | TUM | DCs:10, 13-15 |
| WP6 | Training | 5 | 1 | 48 | Trainings | INPT | ALL |
| WP7 | Dissemination, Communication & Exploitation | 8 | 1 | 48 | Dissemination | POLIBA | ALL |

### Description of Work Packages

**Table 3.1b Description of Work Packages**

|  |  |  |
| --- | --- | --- |
| **WP Number** | **WP1** |  |
| **WP Title** | **Management and coordination** | |
| **Objectives**  Create a strong management framework and support the training of a new generation of researchers. To ensure effective coordination among work packages, individual Doctoral Researchers (DCs), and training events, optimizing benefits for trainees, and enhancing the public dissemination of programme results. | | |
| **Description of Work and Role of Specific Beneficiaries / Associated partners**  Ensure the implementation of the organizational structure outlined in the current proposal, including the establishment of a management board responsible for executing the individual components of the programme.  T1.1 – [POLIBA] Participation and representation in diverse management boards for the organization. Monitor programme budgets and financial matters, generate semi-annual financial statements, mitigate risks, and offer project guidance to ensure adherence to the programme budget.  T1.2 – [POLIBA/ALL] Establishment of the Scientific Committee.  T1.3 – [POLIBA/ALL] Training Committee: organize transferable skill and training events and monitor mentoring activities.  T1.4 – [TUD/ALL] Delegates nominated for recruitment and gender-related matters: organize recruitment procedures and ensure adherence to gender and equality considerations.  T1.5 – [POLIBA/ALL] Reporting and dissemination officers: compile regular reports and statements as mandated by the Commission and oversee the effective dissemination of the required documentation.  T1.6 – [CERFACS/ALL] Webpage development and maintenance, updated necessary publicly available financial and progress reports. | | |
| **WP Number** | **WP2** |  |
| **WP Title** | **Noise and flame dynamics during hydrogen ignition process** | |
| **Objectives**  Investigate the noise emitted and flame dynamics during the ignition process of hydrogen flames in both longitudinal and annular combustion chambers. At first, experiments will be performed in a single-injector combustor where the ignition dynamics of different types of injector design will be tested and compared. A tunable acoustic boundary will allow for simulating different engine-like configurations leading to a shift of the noise towards different frequency ranges. The light-around dynamics in a multi-injector annular combustion chamber will also be investigated to evaluate the impact of flame-to-flame interactions on noise. The dataset produced will be used for validation of high-fidelity numerical simulations. Experimental and numerical results will unveil the interaction between flame dynamics and sound characteristics produced by hydrogen flames during ignition and (eventually) autoignition of events. Active control strategies to stabilize lifted flames will also be investigated numerically. | | |
| **Description of Work and Role of Specific Beneficiaries / Associated partners**  T2.1 – [DC1]: INPT will perform detailed acoustic characterization and laser diagnostic measurements to investigate ignition dynamics and overpressures of a swirled turbulent hydrogen/air combustor, initially developed during the ERC advanced grant SCIROCCO. A tunable acoustic boundary condition system will allow variation of acoustic properties at the inlet, while a perforated plate will be used to adjust reflections at the outlet section. A dataset will be delivered to develop knowledge on ignition flame dynamics and noise for different acoustic BC in support to numerical results from T2.4.  T2.2 – [DC2] CNRS will investigate the ignition dynamics of a novel hydrogen injector where fuel is injected in crossflow with respect to the swirling air. Experiments in a longitudinal combustor will be followed by measurements performed in an annular combustion chamber, where the flame dynamics during a full 360 light-around will be measured. A dataset comprising detailed acoustic measurements and optical images of the flame will complement the one produced in T2.1 deepening the knowledge of the impact of flame-flame interactions in collaboration with the numerical analyses of T2.3 and T2.4.  T2.3 – [DC3] Developed models in WP3 will be employed by CERFACS to perform simulations of the full 360 light-around dynamics recorded in T2.2. Impact on flame dynamics and noise level of the heat exchange at the walls will be accounted via Conjugate Heat Transfer LES simulations.  T2.4 – [DC4] CUT will perform LES simulations of the ignition process in the partially premixed configurations from T2.1 and T2.2 allowing a deeper understanding of the role of multi-scale mixing processes between large and small turbulent scales in strongly unsteady phenomena of forced (spark) or auto-ignition to identify processes accompanying the initial flame propagation (e.g., pressure/acoustic wave) and influencing its further development and sound generation. Advanced numerical methods based on Eulerian stochastic field and data-driven approaches will be implemented to extend existing modelling to hydrogen combustion allowing for correct consideration of interaction between ignition and auto-ignition kernels with the turbulent combustion models.  T2.5 – [DC4] CUT will develop and apply an efficient active flow control methodology for enhancement/suppression of interactions between the turbulent flow and flame. The flow control will rely on the application of excitation to oxidizer and/or fuel mass flow stream at specific frequencies and amplitudes to facilitate the stabilization of lifted flames, which minimize the risk of flashback and the thermal load on injector walls. Optimal forcing will be searched for to minimize the blowout risk. | | |
| **WP Number** | **WP3** |  |
| **WP Title** | **Direct noise sources in turbulent hydrogen flames** | |
| **Objectives**  Investigate the direct noise produced by of both laminar and turbulent flames when interacting with turbulence and hydrodynamic instabilities in both confined and anechoic chambers. Experiments will be performed considering different type of hydrogen flames archetypes, i.e., laminar premix V- and M-type flames, turbulent premixed and partially premixed jet flames, and partially premixed swirling flames, with the objective of a comprehensive understanding of noise source and characterization. This experimental dataset will be further exploited by advanced computational fluid dynamics simulations with the objective of complementing experimental observations and gaining in understanding. DNS simulations are also performed in this WP to investigate the role of intrinsic thermo-diffusive instabilities and turbulence coupling in the noise spectra. DNS results will be used to inform the development of sub-grid scale model for LES, to consider the impact of unresolved unstable wavelength in the framework of the artificially thickened flame model. Finally, data assimilation methods based on physics-informed neural networks (PINNs) will be employed to extract and define physics-grounded closures for the Linearized Navier Stokes equations, containing information about main dominant flow structures and their interaction with flame dynamics and noise that will be implemented in less expensive low order models, to perform parametric studies to investigate the influencing parameters of flame noise characteristics. | | |
| **Description of Work and Role of Specific Beneficiaries / Associated partners**  T3.1 – [DC5] NTNU will perform experiments for the investigation of the noise generated by canonical V-type and M-type flames submitted to turbulence. This will be artificially generated in a novel test rig equipped with active grids to control turbulence levels and characteristics.  T3.2 – [DC6] TUB will add additional information by doing experimental investigations of turbulent jet perfectly and partially premixed flames. These experiments will be performed in a unique facility equipped with an anechoic chamber, to study the coupling between turbulence and hydrodynamic instabilities with the flame, while avoiding interactions with reflected acoustic waves.  T3.3 – [DC1] INPT will complete the experimental dataset by investigating the direct noise generated by the HYLON partially premixed turbulent swirling flames at the variation of inlet and outlet acoustic boundary conditions. Detailed characterization will provide information for the development of new passive controlling devices developed in WP4.  T3.4 - [DC7] DNS simulations of canonical cellular hydrogen flame annihilation due to the interaction with a counter-rotating vortex pair and walls will be performed at CIEMAT. These simulations will be used in T3.6 to derive the sub-grid combustion models for LES simulations.  T3.5 – [DC8] Flame/flame interactions as a source of noise in decaying homogeneous isotropic turbulence will be studied via DNS at NTNU, at first in canonical hydrogen premixed combustion. DNS of noise generated from sheared-flow configurations will be then investigated. These will be used to unveil the sound generation mechanisms due to turbulent eddies interaction on stabilized V-type/M-type flames from T3.1 and jet flames of TUB characterized in T3.2.  T3.6 – [DC9, DC3] LES simulations of direct noise emitted by canonical flames subjected to turbulence (T3.1) and swirled lean hydrogen flames tested at INPT (T3.3) will be performed using the AVBP code. The DNS dataset from CIEMAT (T3.4) and NTNU (T3.5) will be exploited to expand existing turbulent combustion subscale models to include hydrogen preferential diffusion and thermo-diffusive instabilities effects in the framework of the thickened flame model. Furthermore, a novel boundary conditions based on the TDIBC approach will be implemented allowing correct reproduction of acoustic impedances at computational boundaries.  T3.7 – [DC10] TUB will use the modelling developed in T3.6 to simulate the turbulent hydrogen jet flame. Comparison with DNS predictions of T3.5 will be used to further benchmark the novel subgrid model developed in T3.6. Finally, both LES and DNS dataset will be used as data base to develop physics-informed neural networks (PINNS) closure for less computationally demanding Low-Order Modelling methods, which will be used to perform sensitivity analyses on parameters impacting noise characteristics. | | |
| **WP Number** | **WP4** |  |
| **WP Title** | **Thermoacoustic instabilities and control** | |
| **Objectives**  Study the tonal noise generated by thermoacoustic instabilities. Experiments will be performed in the longitudinal chambers studied in the previous WPs, where self-sustained oscillation conditions coupled with low-frequency longitudinal modes and high-frequency radial/transverse patterns can be observed. In addition, oscillation dynamics and pressure oscillation levels will be characterized in the MICCA annular combustor for rotating, stationary or mixed azimuthal modes. The non-linear response of swirled and jet flames to longitudinal perturbations at different frequencies and amplitudes will also be measured. The LES modelling developed in WP2 and WP3 will be extended to thermoacoustic studies in both self-sustained and forced configurations, to better understand the coupling mechanism between flame/acoustic and intrinsic hydrogen flame instabilities. Finally, the results of WP3 and WP4 will be exploited to design, test, and model passive devices capable of attenuating broadband and tonal noise. | | |
| **Description of Work and Role of Specific Beneficiaries / Associated partners**  T4.1 – [DC1] Low/high frequency thermoacoustic instabilities triggered in the MIRADAS test rig equipped with the HYLON injector will be investigated at INPT. Results from WP1 and WP2 will be used to investigate violent ignition and direct noise instabilities triggering mechanisms.  T4.2 – [DC2] Both forced and self-sustained instabilities in longitudinal and annular combustion systems will be experimentally studied at CNRS. In collaboration with TUB, a theoretical model based on the experimental Flame Describing Functions will be developed to retrieve stability maps of both longitudinal and azimuthal systems.  T4.3 – [DC6] The turbulent hydrogen jet flame studied in WP2 at TUB will be acoustically excited at multiple frequencies to identify unstable frequencies and their contribution to the overall noise characterized in WP4.  T4.4 – [DC5] NTNU will investigate the effect of turbulence levels on the thermoacoustic linear and nonlinear response of the canonical flames from T3.1 to harmonic forcing.  T4.5 – [DC3] CERFACS will perform LES modelling of the combustion instabilities coupled with azimuthal modes in the MICCA annular combustor tested at CNRS. Modelling developed in WP3 (T3.6) will be used.  T4.6 – [DC11] POLIBA will perform LES simulations of swirled flames under self-sustained instabilities coupled with a longitudinal mode. The response to longitudinal acoustic forcing of both canonical flames of NTNU and swirled flame tested at CNRS will be also investigated with the objective of understanding the coupling mechanisms between turbulence, acoustics, and flame dynamics.  T4.7 – [DC7] CIEMAT will perform DNS simulations to predict the linear acoustic response to longitudinal acoustic forcing of laminar planar lean thermo-diffusively unstable hydrogen flames stabilized in narrow channels to gain knowledge about the impact of the coupling between instabilities and acoustics.  T4.8 – [DC1, DC6, DC11] Passive flame strategies able to control both broadband and tonal noise will be designed, tested, and modelled. POLIBA, in collaboration with INPT, will study them, both via LES and experiments on a novel perforated plate design with a tunable acoustic actuator. Complementarily, TUB will use both experimental (T3.2, T4.3) and numerical (T3.5, 3.7 and T4.5) datasets to develop a novel injector design based on state-of-the-art chevron nozzles.  T4.9 – [DC12] UCAM will develop a tool for the design of hydrogen injectors that are quiet and not susceptible to thermoacoustic instability. These will be derived via assimilation of experimental (UCAM) and numerical (TUB) data produced by academic and industrial (RRD) partners. Developments will be performed in the framework of the in-house adjoint-accelerated inference and optimization method (AXIOM). | | |
| **WP Number** | **WP5** |  |
| **WP Title** | **Contributions of convective waves to combustion noise and thermoacoustic instabilities** | |
| **Objectives**  Characterise convective waves, i.e., convected inhomogeneities of gas temperature, composition, and vorticity, to quantify their contributions to combustion noise and thermoacoustic instability (WP4). Both experimental, numerical, and theoretical studies will be carried out with the following objectives: (1) develop advanced optical techniques to isolate and quantitatively measure the strength of entropy spots, i.e., their temperature and composition, (2) investigate vorticity-entropy-acoustic interactions due to flow acceleration, (3) characterize sources of entropy waves in hydrogen flames, including the impact of preferential diffusion of hydrogen, in particular the generation of inhomogeneities in fuel /air premixture, (4) define analytical or semi/analytical modelling for describing entropy wave generation in hydrogen flames and such interactions, to be used in LOM for stability/noise predictions. | | |
| **Description of Work and Role of Specific Beneficiaries / Associated partners**  T5.1 – [DC13] TU Delft will design, manufacture, and operate a novel test rig equipped with advanced fs-CARS, acoustic and optical measurement techniques to quantitatively measure the strength of entropy spots (their temperature and composition) and the indirect noise generated by their acceleration. Detailed characterization will be used to update and validate analytical and numerical models of entropic and composition noise.  T5.2 – [DC14] Systematic numerical simulation studies to understand interactions between vorticity and entropy waves will be performed at UT. CFD datasets will serve as a basis for analytical or semi/analytical modelling, for describing such interactions in both reactive and non-reactive conditions for hydrogen flames and compare results with established formulations already validated for hydrocarbons.  T5.3 – [DC15] TUM will perform high-fidelity LES simulations of turbulent hydrogen flames to characterize the mechanisms of entropy wave generation. The formulation of the entropy wave source terms will consider the effects of flame displacement on local entropy fluctuations to eliminate spurious contributions. Furthermore, modelling from WP3 and 4 will allow inclusion of the effects of preferential diffusion of hydrogen in the generation of inhomogeneities in fuel /air premixture. Results will be validated against experiments at TU Delft (T5.1).  T5.4 – [DC10] Extension of the LOM developed in T3.7 to indirect noise and validation with experiments performed in T5.1. | | |
| **WP Number** | **WP6** |  |
| **WP Title** | **Training** | |
| **Objectives**  To train a new generation of researchers in combustion noise produced by hydrogen combustion flames. The objective is to provide trainees with the skills needed to thrive in the contemporary research and industrial environment, encompassing proficiency in addressing innovative and entrepreneurial endeavours, considerations related to gender issues and social responsibilities, and fostering international cooperation. | | |
| T6.1 - [INPT, ALL] Coordination of all training activities, headed by the TSC with assistance by the training hosting organization and the remainder of the consortium as required.  T6.2 - [TU Delft, POLIBA, INPT] Organization of the mentoring activities between trainees, supervisors, and mentors, including the generation and periodic revision of Personal Career Development (PCD) plans.  T6.3 - [POLIBA, ALL] Organization of external transferable skills training. | | |
| **WP Number** | **WP7** |  |
| **WP Title** | **Dissemination, Communication & Exploitation** | |
| **Objectives**  To enhance the effectiveness of the training network, the distribution of results, programme components, and public engagement is prioritized. Dissemination and communication follow a two-phase approach. In the initial phase, research findings and programme advancements are shared through peer-reviewed journal publications, conference participation, publicly accessible reports, public engagement events such as seminars and lectures, and the program's webpage. The subsequent phase extends beyond the program's timeframe, by establishing a cohort of researchers trained in hydrogen combustion studies, equipped with the skills to conduct socially responsible, innovative, and entrepreneurial research. | | |
| T7.1 – [POLIBA] During the regularly scheduled Technical Workshops and Management Meetings, the internal dissemination of research progress will be presented. Planning for secondment activities and the development of corrective measures, in case of unexpected project delays, will also be addressed.  T7.2 – [ALL] External dissemination of commission reports and publicly available progress reports will be communicated through the tasks of WP1.  T7.3 – [ALL] Peer-reviewed publications detailing research progress will be made Open Access wherever available and permissible.  T7.4 – [ALL, Reporting and Dissemination Officers] A reporting and dissemination strategy will be formulated early in the programme to establish guidelines concerning the publication of both public and proprietary information, as well as Open Access procedures. Additionally, the officers will prioritize the creation of public engagement activities through lectures and seminars involving visiting researchers. | | |

### Deliverables List

**Table 3.1c Deliverables List**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| ***Scientific Deliverables*** | | | | | | |
| **Nr.** | **Deliverable title and short description** | **WP No.** | **Lead Benef.** | **Type** | **Diss.**  **Level** | **Due Date** |
| D2.1 | Experimental characterization of ignition dynamics and sound generated in longitudinal (T2.1) and annular chambers (T2.2) | 2 | INPT/CNRS | R | PU | M24 |
| D2.2 | LES simulations of ignition dynamics (T2.3, T2.4) | 2 | CERFACS/CUT | R | PU | M36 |
| D2.3 | Active control of flames during ignition phase (T2.5) | 2 | CUT | R | PU | M42 |
| D3.1 | Experimental characterization of direct noise radiated by different archetype of hydrogen/air flames: canonical V/M-shape (T3.1), turbulent jet (T3.2) and swirled flames (T3.3). | 3 | TUB/INPT/NTNU | R | PU | M36 |
| D3.2 | Noise radiated by flame-vortex, flame-wall and turbulence/flame interactions (T3.4, T3.5) | 3 | CIEMAT, NTNU | R | PU | M40 |
| D3.3 | LES subgrid model to account for preferential diffusion and thermo-diffusive instabilities in turbulent combustion models (T3.6) | 3 | POLIBA, CERFACS, CIEMAT | R | PU | M24 |
| D3.4 | The novel TDIBC boundary conditions (T3.6) | 3 | POLIBA, CERFACS | R | PU | M30 |
| D3.5 | LES prediction of direct noise radiated by swirled (INPT) and jet turbulent (TUB) (T3.6, T3.7) | 3 | POLIBA, TUB | R | PU | M42 |
| D3.6 | Low Order Model for direct noise predictions (T3.7) | 3 | TUB | R | PU | M42 |
| D4.1 | Experimental characterization tonal noise generated by resonant coupling of heat release rate fluctuations with acoustic waves in single and multi-burner annular systems (T4.1, T4.2) | 4 | CNRS, INPT | R | PU | M30 |
| D4.2 | Linear and non-linear flame response of multiple archetypes of hydrogen flames investigated in the project. Experiments and LES comparison. (T4.3, T4.4, T4.5, T4.7) | 4 | NTNU, CNRS, TUB, CIEMAT, POLIBA | R | PU | M40 |
| D4.3 | LES prediction of self-sustained instabilities in both annular and longitudinal combustor (4.5, T4.6) | 4 | CERFACS, POLIBA | R | PU | M40 |
| D4.4 | Passive damping for both broadband and tonal noise (T4.8) | 4 | POLIBA, INPT, TUB | R | PU | M42 |
| D4.5 | Data-driven of tool for hydrogen injectors: application in both laboratory scale and industrial configurations (T4.9) | 4 | UCAM | R | PU | M40 |
| D5.1 | Experimental characterization of entropy and compositional noise (T5.1) | 5 | TU Delft | R | PU | M42 |
| D5.2 | Numerical studies on vorticity and entropy interactions (T5.2) | 5 | UT | R | PU | M42 |
| D5.3 | LES to unveil mechanisms leading to entropy waves in hydrogen flames (T5.3) | 5 | TUM | R | PU | M42 |
| D5.4 | PINNs model for indirect noise predictions and validation (T5.4) | 5 | TUB | R | PU | M42 |

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Management, Training, Recruitment and Dissemination Deliverables** | | | | | | |
| **Nr** | **Deliverable Title** | **WP No.** | **Lead Benef.** | **Type** | **Diss.**  **Level** | **Due Date** |
| D1.1 | Consortium Agreement | 1 | POLIBA | O | CO | M1 |
| D1.2 | Kick-off meeting | 1 | POLIBA | O | CO | M1 |
| D1.3 | Population of management boards, delegates and officers | 1 | POLIBA | ADM | CO | M3 |
| D1.4 | Documentation of recruitment strategy and management structures | 1 | POLIBA | R | CO | M1 |
| D1.5 | Dissemination of yearly progress and financial reports | 1 | POLIBA | R | PU | M12 |
| D1.6 | Mid-programme research status and trainee progress report | 1 | POLIBA | R | PU | M24 |
| D6.1 | Assignation of mentor/trainee pairs | 6 | POLIBA | ADM | CO | M7 |
| D6.2 | Personal Career Development (PCD) plans, with 12-month periodic updates | 6 | TU Delft | ADM | CO | M13 |
| D6.3 | Planning for the DN organized training activities | 6 | IMPT | ADM | CO | M6 |
| D5.4 | Technical training report - HYNOISE programme: Modelling Center | 6 | POLIBA | R | CO | M18 |
| D5.5 | Technical training report - HYNOISE programme: Experimental Atelier | 6 | NTNU | R | CO | M36 |
| D5.6 | Technical training report - Industry perspectives on hydrogen combustion in gas turbines and aeroengines | 6 | IMPT | R | CO | M24 |
| D6.7 | Transferrable skills training | 6 | IMPT | R | CO | M36 |
| D7.1 | Data Management Plan | 7 | POLIBA | R | CO | M13 |
| D7.2 | Establish website & secure portal | 7 | POLIBA | ADM | PU | M2 |
| D7.3 | Public dissemination and communication plan | 6 | POLIBA | R | PU | M12 |
| D7.4 | Public Dissemination: Academia meets Industry workshop | 6 | NTNU | PDE | PU | M36 |
| D7.5 | Public Dissemination: Capstone Symposium | 6 | POLIBA | PDE | PU | M42 |
| D7.6 | Final report on dissemination and communication activities | 6 | POLIBA | R | PU | M46 |
| **R** - Report, **O** - Other, **ADM** - Administrative, **PDE** - Dissemination, **PU** - Public, **SEN** - Sensitive **CO** - Confidential | | | | | | |

### Milestones List

**Table 3.1d Milestones List**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Number** | **Title** | **WP(s)** | **Resp.** | **Due Date** | **Means of Verification** |
| 1 | Kick-off meeting | WP1 | POLIBA | 1 | First meeting with all the partners to agree research and management plan set out in WPs. |
| 2 | Consortium Agreement | WP1 | POLIBA | 2 | The members of the consortium will sign the consortium agreement between each other. |
| 2 | Planned recruitment completed | WP1 | TU Delft | 7 | DC recruitment completed, all the fellows are in place at their host institutions and drafted their Personal Career Development Plan. |
| 3 | Open access database established | WP7 | POLIBA | 30 | Open access database established. |
| 4 | All recruited fellows enrolled in a PhD program | WP1 | POLIBA | 12 | All recruited fellows enrolled in a PhD program. |
| 5 | Project mid-term check | WP1 | POLIBA | 24 | Meeting between REA and Consortium. |
| 6 | Completion of DC research and PhD | WP1 | POLIBA | 48 | Completion of all research project. |
| 7 | Experimental setup for T2.1, T3.3 and T2.1 completed | WP2, WP3, WP4 | INPT | 18 | Experiment is running and first results presented to the partners. |
| 8 | Experimental setup for T2.2 and T4.2 completed | WP2, WP4 | CNRS | 18 | Experiment is running and first results presented to the partners. |
| 9 | Experimental setup for T3.1 and T4.4 completed | WP3, WP4 | NTNU | 18 | Experiment is running and first results presented to the partners. |
| 10 | Experimental setup for T3.2, T4.3 and T4.8 | WP3, WP4 | TUB | 18 | Experiment is running and first results presented to the partners. |
| 11 | Experimental setup for T5.1 | WP5 | TU Delft | 18 | Experiment is running and first results presented to the partners. |
| 12 | Implementation of hydrogen turbulent combustion model based on Eulerian stochastic fields and data driven approach in LES code | WP2 | CUT | 24 | Validation results presented to partners. |
| 13 | DNS simulations completed | WP3 | CIEMAT | 18 | First series of results available for post processing. |
| 14 | DNS simulations completed | WP3 | NTNU | 24 | First series of results available for post processing. |
| 15 | Implementation of hydrogen turbulent combustion model based on thickening flame model approach and TDIBC boundary conditions in LES code | WP2, WP3, WP4, WP5 | POLIBA | 24 | Validation results presented to partners. |
| 16 | Derivation of physics-informed neural networks (PINNS) closure for less computationally demanding Low-Order Modelling | WP3, WP5 | TUB | 24 | Validation results presented to partners. |
| 17 | Definition of framework for data-assimilation | WP3, WP4, WP5 | UCAM | 18 | Capability presented to partners. |
| 18 | Implementation of vorticity/entropy model completed | WP5 | UT | 24 | Validation results presented to partners. |
| 19 | LES simulations for entropy noise completed | WP5 | TUM | 24 | Results presented to partners. |

### Recruitment Table per Beneficiary

**Table 3.1e Recruitment Table per Beneficiary**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Doctoral**  **Researcher No.** | **Recruiting Participant**  **(short name)** | **PhD awarding entities** | **Planned Start Month**  **0-45** | **Duration (months)**  **3-36** |
| DC1 | INPT | INPT | 6 | 36 |
| DC2 | CNRS | UPSaclay | 6 | 36 |
| DC3 | CERFACS | INPT | 6 | 36 |
| DC4 | CUT | CUT | 6 | 36 |
| DC5 | NTNU | NTNU | 6 | 36 |
| DC6 | TUB | TUB | 6 | 36 |
| DC7 | CIEMAT | UC3M | 6 | 36 |
| DC8 | NTNU | NTNU | 6 | 36 |
| DC9 | POLIBA | POLIBA | 6 | 36 |
| DC10 | TUB | TUB | 6 | 36 |
| DC11 | POLIBA | POLIBA | 6 | 36 |
| DC12 | UCAM | UCAM | 6 | 36 |
| DC13 | TU Delft | TU Delft | 6 | 36 |
| DC14 | UT | UT | 6 | 36 |
| DC15 | TUM | TUM | 6 | 36 |
| Total 15 |  |  |  |  |

### Individual Research Projects, including secondment plan

**Table 3.1f** **Individual Research Projects**

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Fellow**  DC1 | **Host institution**  INPT | | **PhD enrolment**  INPT | | **Start date**  M6 | | **Duration**  36 months | | **Deliverables**  *2.1, 3.1, 4.1* | |
| **Project Title and related WP(s):** Impact of acoustic boundary conditions on broadband and tonal noise of H2/air flames, WP2, WP3, WP4 | | | | | | | | | | |
| **Objectives:** Direct combustion noise in anechoic environment (problem studied by TUB in HyNOISE) is a by-product of flame interaction with the unsteady flow and background turbulence of the flow field (problem studied by NTNU in HyNOISE). In a combustor, multiple reflections of acoustic waves on the solid boundaries and at the inlet and outlet of the combustor lead to feedback from acoustic waves with the turbulent flow field and the turbulent flame that can damp or amplify specific frequencies (tonal noise) and more generally shift and reshape the spectral signature of the noise towards different frequency ranges compared to anechoic environment. The objective of this task is to understand the fundamental mechanisms of this shift for hydrogen-air flames that feature much smaller scales than hydrocarbon fuel flames, by controlling the acoustic boundary conditions (BC) in laboratory scale swirled combustor well instrumented for acoustic and optical flow characterizations. The analysis will proceed by examining the impact of BC during steady operation with stabilized flames, the ignition phase of the combustor and undesirable during thermoacoustic instabilities. The knowledge gained will be used to design new passive damping devices adapted to broadband noise attenuation from H2/air flames. **Tasks:** (1) Experiments combining detailed acoustic characterizations and laser diagnostics (PIV coupled with OH-PLIF and high speed chemiluminescence) to scrutinize the flow and flame dynamics of swirled hydrogen flames stabilized on the MIRADAS test bench at INPT equipped with HYLON (HYdrogen LOw Nox) injector. (2) Study of impact of a tunable acoustic boundary conditions system from fully reflective to anechoic conditions at the combustor inlet. The impact of BC on the downstream side will also be characterized with a set of perforated plates. (3) Optimization of broadband noise dampers. **T2.1, T3.3, T4.1** | | | | | | | | | | |
| **Expected Results:** Detailed acoustic, flow and flame characterizations for different acoustic inlet and outlet BC (1) during steady operation, (2) during thermoacoustic instabilities, and (3) during ignition. (4) Development of acoustic dampers for H2/air broadband noise attenuation. | | | | | | | | | | |
| **Planned secondment(s):** 3 months at TU Graz (M18-M20) to develop experience on density fluctuation laser techniques and 2 months at POLIBA (M35-M36) for joint studies on acoustic dampers. A virtual secondment of 1 month (M24) is scheduled at CNRS to compare noise characteristics and flame dynamics in longitudinal and annular combustion chamber during ignition process (D2.1). | | | | | | | | | | |
| **Fellow**  DC2 | **Host institution**  CNRS | | **PhD enrolment**  UPSaclay | | **Start date**  M6 | | **Duration**  36 months | | **Deliverables**  2.1, 4.1, 4.2 | |
| **Project Title and related WP(s):** Combustion noise from H2/Air flames and dynamics during ignition and steady operation of H2/Air in longitudinal and annular combustors, WP2, WP4 | | | | | | | | | | |
| **Objectives:** This project aims to investigate noise radiated by confined H2-Air flames, light round ignition dynamics of these flames and combustion instabilities coupled by azimuthal modes in an annular configuration. The injector that will be used has the concept of a crossflow injection of hydrogen in a swirled air flow. Investigations of the noise emitted by H2-air combustion will be performed in the single injector setup called SICCA. Since it is possible to operate the rig with conventional hydrocarbons in premixed (for gaseous fuels) or spray (for liquid fuels) mode while keeping the same general injector geometry, comparisons will be carried out to highlight the specificities of the noise from hydrogen combustion. Flame Transfer functions will be measured and will also serve as an input for the third part of the proposed work, which aims to predict the stability of the annular chamber MICCA. The ignition dynamics of the annular chamber MICCA when operated with hydrogen will be also studied. Previous studies on liquid fuel flames have indeed shown that the light-round phase of the ignition process gives rise to a pressure excursion and a subsequent flashback of the flame into the injector. Because of the high burning velocity of hydrogen, one may expect that this phenomenon will occur as well in the present case. This will be studied using dynamic pressure sensors to record the pressure wave induced by ignition in combination with high-speed imaging of the flame during this process. The third goal is to investigate self-excited dynamics of the annular chamber under different operating conditions. Depending on the operating conditions, previous studies have shown that combustion can be stable or unstable, and in the latter case be coupled with azimuthal modes that can be spinning, standing or a mixed type. While these dynamics are well characterized with premixed propane-air combustion or with liquid fuels, the effects of hydrogen remain to be investigated. For this purpose, pressure fluctuation and heat release rate measurements will be carried out and coupled with LOM analytical models to develop predictive tools and find ways of reducing azimuthal combustion instabilities.  **Tasks:** (1) Measure combustion noise in the single injector test rig SICCA and compare with hydrocarbon flames. (2) Measure the Flame Transfer Functions of H2-Air flames in SICCA. (3) Set-up the annular chamber MICCA to operate with H2 injectors. (4) Perform experiments on ignition dynamics with hydrogen. (5) Measure stability maps of MICCA in a broad operating domain. (6) Combine the previous results into a reduced order model to investigate predictive capabilities. **T2.2, T4.2** | | | | | | | | | | |
| **Expected Results:** (1) Spectral signatures of H2-Air flame in SICCA and comparison to those of conventional hydrocarbons. Flame Transfer Functions will be documented. (2) Measurements of the light round time during ignition of the MICCA chamber (3) Stability map of the MICCA annular test rig burning hydrogen. A stability analysis will be carried out in parallel thanks to a data-driven low order analytical model leveraging flame describing functions and injection unit impedances measured on separate rigs. | | | | | | | | | | |
| **Planned secondment(s):** 3 months at CUT to exchange data on ignition process in SICCA and contribute to the design of the active control strategy (M18-M20). 2 months at TUB (M38-39) to develop the LOM for stability analyses in annular combustion chambers. A virtual secondment of 1 month (M35) is scheduled at NTNU to compare data on FTF of hydrogen flames (D4.2). | | | | | | | | | | |
| **Fellow**  DC3 | **Host institution**  CERFACS | | **PhD enrolment**  INPT | | **Start date**  M6 | | **Duration**  36 months | | **Deliverables**  2.2, 3.3, 4.3 | |
| **Project Title and related WP(s):** Large Eddy Simulations of hydrogen-air combustion dynamics and tonal noise during light-around and thermoacoustic in annular combustors, WP2, WP4 | | | | | | | | | | |
| **Objectives:** LES of turbulent reacting flows is a reliable and relevant tool to predict thermoacoustic instabilities of conventional fuel operated combustors. LES allows to account for the entire complexity of the problem including the geometry, the compressible nature of the fluid dynamics and the flame/turbulence interactions. While validated for conventional fuels, burning H2 induces complex and new physical interactions. These new features are fuel dependent, and, for H2, they require fundamental improvement of existing modelling strategies routinely used for kerosene or carbonated fuels. These new models will be validated for complex and fully annular burner geometries to predict flame dynamics and noise level during light-around and thermoacoustically unstable operative points. **Tasks:** (1) Specific modelling for considering hydrogen preferential diffusion effects and intrinsic instabilities will be implemented in the AVBP solver (in collaboration with DC9 activities) and tested in annular combustion chambers. (2) At first, the light-around of the MICCA annular combustion chamber operated at CNRS will be investigated. Conjugate Heat Transfer (CHT-LES) simulations will be performed coupling AVBP with the thermal solver AVTP. (3) LES of thermoacoustic unstable configuration of the MICCA combustor will also be performed to assess the models for predicting tonal noise and acoustic/flame coupling mechanisms in multi-injector configurations. (4) Finally, tonal/broadband combustion noise emitted by a Safran engine will be studied proving the transferability to industrial configurations of developed models. **T2.3, T3.6, T4.5** | | | | | | | | | | |
| **Expected Results:** (1) Development and validation of H2 sub-grid models (in collaboration with DC9). (2) Light-around of MICCA annular combustion chambers. Impact of heat transfer (conduction, convection, and radiation). (3) LES of self-sustained instabilities of MICCA annular combustion chambers coupled by azimuthal modes. (4) Study of tonal and broadband noise emitted by an industrial engine. | | | | | | | | | | |
| **Planned secondment(s):** 2 months at CNRS (M26-M27) to assist and participate at MICCA experiments and 3 months at Safran (M36-M38) to work on prediction of noise of a Safran engine. A virtual secondment of 1 month (M35) is scheduled at CUT to compare the capabilities of developed numerical strategies to correctly simulate ignition noise and flame dynamics (D2.2). | | | | | | | | | | |
| **Fellow**  DC4 | **Host institution**  CUT | | **PhD enrolment**  CUT | | **Start date.**  **M6** | | **Duration**  36 months | | **Deliverables**  2.2, 2.3 | |
| **Project Title and related WP(s):** Auto-and forced ignition in swirled stabilized flow configurations, WP2 | | | | | | | | | | |
| **Objectives:** The research will perform advanced LES methods combined with the Eulerian stochastic field and data-driven approaches for modelling of ignition dynamics and noise in longitudinal chambers of INPT and CNRS. The primary objectives of the project are the following: (i) to achieve a deeper understanding of the role of multi-scale mixing processes between large and small turbulent scales in strongly unsteady phenomena such as flame initiation (ignition), flame propagation/stabilization phases, or flame extinction; (ii) to identify processes accompanied ignition, e.g., pressure/acoustic wave, influencing the flame development; (iii) to develop and apply an efficient active flow control methodology for enhancement/suppression of interactions between turbulent flow and flame. The flow control will rely on the application of excitation to oxidizer and/or fuel mass flow streams at specific frequencies and amplitudes. A particular attention will be put on the analysis and generation of flow conditions facilitating spark or auto-ignition after which the flame stabilizes as lifted. The distance between the burner rim and the flame base constitutes a separation layer preventing the burner from thermal stresses or hydrogen corrosion. However, flame lifting increases the risk of flame blow-out, especially when combustion operates with lean mixtures. Within the project, the flow control methodology will be developed to minimize this risk. **Tasks:** Implementation and validation of data-driven model for combustion modelling. LES modelling of HYLON ignition in non-excited and excited configuration. Sensitivity analysis of ignition probability and flame position/shape in function of excitation parameters. **T2.4, T2.5** | | | | | | | | | | |
| **Expected Results:** Extended capabilities of inhouse software. Better knowledge of the fuel/oxidizer mixing processes and associated flame initiation/stabilization/extinction phenomena that are critical for the development of novel, efficient, and clean fuel use. Advanced active flow control methodology for an efficient tuning of mutual interactions between the flow/flame scales. Parametric ignition probability maps. | | | | | | | | | | |
| **Planned secondment(s):** 2 months at INPT (M23-M24) to participate to HYLON ignition experiments and 3 months at UCAM(M26-28) for optimization studies of the active flow control methodology via data-driven approaches. A virtual secondment of 1 month (M35) is scheduled at POLIBA to compare active and passive control strategies for hydrogen flames (D2.3). | | | | | | | | | | |
| **Fellow**  DC5 | **Host institution**  NTNU | | **PhD enrolment**  NTNU | | **Start date**  M6 | | **Duration**  36 months | | **Deliverables**  3.1, 4.2 | |
| **Project Title and related WP(s):** Controlled turbulence-acoustic interactions on the flame response, WP3, WP4 | | | | | | | | | | |
| **Objectives:** In lean turbulent premixed flames, direct combustion noise is produced by turbulence and its interaction with the fluctuating heat release rate which emits acoustic waves. The noise produced by the fluctuations in heat release rate depends on the fuel, stoichiometry, and the turbulence-chemistry interactions. When confined in a combustor geometry, these interactions between the broadband noise from turbulence, fluctuations in the heat release rate and acoustic modes of the geometry can occur. This can lead to changes in the spectral response and result in constructive feedback that amplifies specific frequencies that lead to thermoacoustic oscillations. The objective of this task is to actively control levels of turbulence and investigate the effect on the direct noise and thermoacoustic instabilities of hydrogen flames. A novel combustor configuration will be adopted, where an active grid (an array of randomly rotating paddles) will be placed upstream of premixed hydrogen-methane and pure hydrogen flames stabilized by a rod and/or a v-gutter. This will enable us to investigate the effect of different levels of well characterized turbulence without changing the mean flow. The combustor will also be equipped with speakers to investigate the effect of turbulence levels on the thermoacoustic response of flames to harmonic forcing by evaluating the Flame Transfer Function and the non-linear flame response. The combustor is well instrumented for acoustic measurements and provides optical access for advanced laser diagnostics including high speed OH PLIF, global chemiluminescence imaging, PIV. **Tasks:** (1) Characterize the turbulence and noise spectra produced before the flame using PIV and hot wire anemometry for a range of different operating conditions. (2) Investigation of the turbulence-flame interactions using combined high speed OH-PLIF and PI enabling two-point correlations between the turbulence and the rate of change of fluctuating reaction rate of hydrogen flames for different equivalence ratios and are essential to estimating direct noise. (3) The effect of turbulence on the thermoacoustic response of hydrogen flames will be investigated by combining the use of the active turbulence grid with harmonic forcing for loudspeakers to measure the flame transfer function using acoustic measurements and high speed chemiluminescence measurements. Harmonic forcing at amplitudes above and near the turbulence levels will be investigated as well as the effect of turbulence on triggering self-excited instabilities. **T3.1, T4.4** | | | | | | | | | | |
| **Expected Results:** Detailed acoustic, flow and flame characterizations for different turbulence levels and equivalence ratios. Two-point correlations for noise models. The effect of turbulence level on the flame dynamics. | | | | | | | | | | |
| **Planned secondment(s):** 2 months at TUB to acquire competences on direct noise measurements in the TUB anechoic chamber. 3 months at UC3M (M30-M32) to perform direct noise measurements on thermo-diffusive unstable hydrogen flames interacting will walls. A virtual secondment of 1 month (M40) is scheduled at RRD for transfer of knowledge. | | | | | | | | | | |
| **Fellow**  DC6 | | **Host institution**  TUB | | **PhD enrolment**  TUB | | **Start date**  M6 | | **Duration**  36 months | | **Deliverables**  3.1, 4.2, 4.4 |
| **Project Title and related WP(s):** Experimental quantification of direct noise and flame-flow-acoustic interactions in an unconfined hydrogen jet flame, WP3, WP4 | | | | | | | | | | |
| **Objectives:** The main objective of the project is to identify the key mechanisms that drive combustion noise in turbulent hydrogen jet flames. The interaction of turbulence and flame intrinsic instabilities is likely to affect hot spots formation which, when accelerated at the combustor’s exit, cause noise emissions. Therefore, the interaction of turbulence, flame dynamics and noise emissions will be investigated. The goal is to enhance our understanding of the interactions between these physical mechanisms, by employing simultaneously the experimental methods of Particle Image Velocimetry (PIV), OH\* chemiluminescence and microphone array recordings. Furthermore, the project will sample data to validate simulation in other associated projects (DR8, DR10, DR11). The experimental setup consists of a small-scale unconfined hydrogen jet burner test rig in an anechoic room, which allows for high quality acoustic near or far field measurements not affected by acoustic reflections. The air can be preheated and premixed with hydrogen while being acoustically excited axially or azimuthally. Hydrodynamic stability analysis and data analysis techniques such as POD, extended Spectral Proper Orthogonal Decomposition (eSPOD) will be conducted on the high-speed PIV and OH\* recordings of the hydrogen flames. The results will describe mode shapes and growth rates of unstable modes in relation to the broadband noise of the unexcited, unconfined flame. Moreover, the stability analysis defines the frequency range for subsequent experiments of the axially excited flame. Finally, to enhance the fundamental understanding of the noise generation in a turbulent reacting flow and extend the physical data base for validation of numerical simulations, the knowledge of the density and pressure fields are crucial. In a new approach, at first a physics-informed neural network (PINN) will be employed to uncover otherwise not-measurable fields from the available experimental data. The results will be validated by background oriented Schlieren (BOS) measurements that deliver a line-of-sight integrated density field. The density and pressure fields will be correlated with the far-field noise measurements to enhance the understanding of the link between flame and noise. The last project phase elaborates the findings to design passive noise control measures, based on established chevron nozzle designs. Using additive manufacturing, different nozzle shapes are applied to the burner. **Tasks:** (1) Flow and flame characterization. (2) Synchronized flow, flame, and combustion noise measurement. (3) Density field estimation (PINN + BOS). (4) Stability analysis and excited flame measurements. (5) Passive noise control. **T3.2, T4.3, T4.8** | | | | | | | | | | |
| **Expected Results:** (1) Description of the flow and flame dynamics including mode shapes of a hydrogen jet flame at different equivalence ratios, nozzle outlet velocities and levels of turbulence. (2) Determination of interaction of far field noise spectra of different hydrogen jet flames with flow and flame mode shapes. (3) Validation of density field reconstruction in a hydrogen jet flame. (4) Combustion noise control concept with proven influence on noise level and frequency range. | | | | | | | | | | |
| **Planned secondment(s):** 2 months at NTNU (M27-28) to gain experience on active grid methodology to control turbulence levels and characteristics. 3 months at UCAM (M37-M39) to applied advance data-driven modelling to improve density field reconstruction using experimental data. A virtual secondment of 1 month (M36) is scheduled at INPT to compare the swirled and jet hydrogen flame spectra and finalised, together with NTNU, the associated deliverable (D3.1). | | | | | | | | | | |
| **Fellow**  DC7 | **Host institution**  CIEMAT | | **PhD enrolment**  UC3M | | **Start date**  M6 | | **Duration**  36 months | | **Deliverables**  3.2, 3.3, 4.2 | |
| **Project Title and related WP(s):** DNS of noise produced by thermo-diffusive laminar flames submitted to flame/vortex interaction, flame/wall and flame/acoustic interactions, WP3, WP4 | | | | | | | | | | |
| **Objectives:** This project aims to unveil the effect of thermo-diffusive instabilities in the sound generated by hydrogen flames. To this end, high fidelity numerical simulations will be used to reproduce the sound produced in canonical configurations such as the interaction of a cellular hydrogen flame with a pair of counter-rotating vortices and the interaction of a cellular hydrogen flame with a wall. Additionally, we will also study the coupling of flame and acoustics in a hydrogen cellular flame stabilized in a narrow channel, to determine its response to acoustic perturbations (that is, the acoustic flame transfer function). Simulations of planar flames in the same configurations will be used as reference. These configurations will be investigated using direct numerical simulations of the compressible Navier-Stokes and energy-species transport equations, with high-accuracy finite differencing and using simplified and detailed chemical kinetics and transport models, and adequate non-reflecting boundary conditions (NSCBC). **Tasks:** (1) DNS of sound produced by a cellular hydrogen flame interacting with a counter-rotating vortex pair. (2) DNS of sound produced by a cellular hydrogen flame impacting on a wall. (3) DNS of the response of a cellular hydrogen flame submitted to acoustic perturbations. **T3.4, T4.7** | | | | | | | | | | |
| **Expected Results:** Results of the simulations will be analysed and compare to those of reference planar flames to determine: 1) the influence of thermo-diffusive instabilities in sound generation; 2) the influence of thermo-diffusive instabilities in the FTF of hydrogen flames. | | | | | | | | | | |
| **Planned secondment(s):** 3 months at CERFACS (M22-24) to work on the derivation of the subgrid model for hydrogen combustion with DC9 and DC3. 2 months at NTNU (M38-39) to work together with DC8 on the identification of direct noise sources in both laminar and turbulent hydrogen flames. A virtual secondment of 1 month at TUB (M40) for comparing direct noise of laminar and jet hydrogen flames. | | | | | | | | | | |
| **Fellow**  DC8 | **Host institution**  NTNU | | **PhD enrolment**  NTNU | | **Start date**  M6 | | **Duration**  36 months | | **Deliverables**  3.2 | |
| **Project Title and related WP(s):** Understanding direct combustion noise via a parametrized direct numerical simulation study of turbulent flame-flame interactions in hydrogen premixed combustion, WP3 | | | | | | | | | | |
| **Objectives:** The objective of this project is to acquire, utilizing first-principles direct numerical simulation (DNS), a more complete knowledge at an increased level of detail about the generation of direct combustion noise in hydrogen premixed combustion. A series of earlier DNS studies by Talei et al.33,34 of laminar premixed flames has indicated that flame annihilation caused by flame-flame interactions taking place in simple canonical configuration can lead to significant noise generation. This increases for decreasing flame thickness and gradients in the dilatation present within the flow field. In the present research activity, proceeding beyond earlier laminar-flames studies, a systematic DNS study of turbulent flames is proposed, spanning a wide parameter space, that will inform about the dependence of noise generation on reactants composition (hydrogen fraction and equivalence ratio), pressure and temperature, turbulence intensity (length and velocity scales) and flow characteristics (decaying turbulence, sheared flows etc). Crucially, this activity will complement the experimental activities providing an exact quantification of direct combustion noise for the selected range of mixture conditions and flow configurations: analysis of the DNS data jointly with the experimental measurements from canonical configurations (NTNU, TUB) will enable a more precise interpretation of these and an improved separation between the hydrodynamic and direct combustion components. **Tasks:** (1) In the first subtask of this research activity, a detailed characterization of direct combustion noise from canonical hydrogen premixed combustion and flame-flame interactions in decaying homogeneous isotropic turbulence (no mean shear) for different reactants compositions, temperatures, pressures, and turbulence characteristics will be provided. For comparative analysis with NTNU experimental data in subtask 3. (2) In the second subtask of this research activity, direct combustion noise from sheared-flow configurations will be investigated, including jet flames and temporally evolving shear layers. The characterization obtained from the DNS will be used to complement the experimental data from TUB in subtask 3. (3) The third subtask will consist of comparative analysis and interpretation of the DNS and experimental data from NTNU (T3.1) and TUB (T3.2). **T3.5** | | | | | | | | | | |
| **Expected Results:** Detailed description of the acoustic field in premixed hydrogen combustion in canonical configurations. | | | | | | | | | | |
| **Planned secondment(s):** 3 months at TUB (M22-M24) to participate to jet hydrogen flame experiments. 2 months at POLIBA (M38-M39) to perform joint DNS/LES simulations on V-type/M-type canonical flames and compare results. A virtual secondment of 1 month at CIEMAT (M40) is scheduled for comparing DNS results and collaborate on redaction of corresponding deliverable (D3.2). | | | | | | | | | | |
| **Fellow**  DC9 | **Host institution**  POLIBA | | **PhD enrolment**  POLIBA | | **Start date**  M6 | | **Duration**  36 months | | **Deliverables**  3.3, 3.4, 3.5 | |
| **Project Title and related WP(s):** Prediction of direct noise of turbulent hydrogen-air flames with Large Eddy Simulations, WP3 | | | | | | | | | | |
| **Objectives:** The research aims at predicting direct combustion noise of turbulent hydrogen flames via Large Eddy Simulations. LES will be performed using the high-fidelity code AVBP (developed at Cerfacs and in use at POLIBA). In the framework of the artificially thickened flame modelling approach (TFLES), novel sub-grid models will be developed, in collaboration with DC3, to efficiently consider the response of hydrogen flame to unresolved turbulence scales. These will be performed exploiting the DNS dataset produced by DC7. The so-derived H2 extended TFLES model will be applied to the canonical V/M-types flames submitted to turbulence operated at NTNU to prove its capability to correctly reproduce turbulence/flame interactions leading to noise emission. Being generated artificially, the NTNU test rig allows for model validation considering multiple turbulence intensity and scales leading to different turbulence/flame interactions. Once validated, the developed model will be used to predict combustion noise emitted by turbulent swirling flame. To this objective, the HYLON injector operated at INPT will be simulated. Both attached/detached flame configurations will be studied, and noise emitted compared. The impact of different acoustic boundaries will be simulated integrating in the code advanced NSCBC boundary conditions which are able to impose a specific acoustic impedance (TDIBC) to mimic the tunable device installed in the MIRADAS rig. LES results will be exploited to achieve a deeper understanding of the turbulence/flame interaction mechanisms leading to noise generation. **Task: (1)** Derivation of novel subgrid model and implementation in LES code. (2) LES of NTNU canonical flames submitted to artificially controlled turbulence (3) Implementation in LES code of TDIBC BC. (4) LES of HYLON injector and identification of noise sources. T3.6 | | | | | | | | | | |
| **Expected Results:** (1) H2-extended TFLES model. (2) Identification of noise sources in laminar flames invested by turbulence and turbulent swirl attached/lifted flames. (3) Impact of different acoustic BC on noise emitted. | | | | | | | | | | |
| **Planned secondment(s):** 3 months at CERFACS (M22-24) to derive novel subgrid model for hydrogen flames (M23-M24). 2 months at TUB to apply LOM developed by DC10 on investigated configurations and compared direct noise predictions with LES results. A virtual secondment of 1 month at SAFRAN (M39) is scheduled supporting on the application of developed modelling on real combustion chambers | | | | | | | | | | |
| **Fellow**  DC10 | **Host institution**  TUB | | **PhD enrolment**  TUB | | **Start date**  M6 | | **Duration**  36 months | | **Deliverables**  3.6, 3.5, 5.4 | |
| **Project Title and related WP(s):** Identification and modelling of hydrodynamic instabilities driving combustion noise in turbulent hydrogen flames, WP3, WP5 | | | | | | | | | | |
| **Objectives:** The main objective of the project is to identify the key mechanisms that drive combustion noise in turbulent hydrogen jet flames and to develop a physics-based, low-order modelling framework that can be used to optimize combustion systems. The focus will be on direct combustion noise of circular turbulent non-swirling jet flames caused by the dynamic interaction of turbulent structures of the underlying flow field and the flame front. To construct a comprehensive database, we execute compressible reacting Large Eddy Simulations, mirroring TUB’s experiments. Utilizing extended Spectral Proper Orthogonal Decomposition, we derive low-order dynamical models revealing dominant flow structures and their interaction with flame dynamics and noise. These insights inform a physics-grounded model of said structures, employing the linearized Navier-Stokes equations using an active flame approach. Addressing turbulence closure, we pioneer a data assimilation method employing physics-informed neural networks (PINNs). As next step, we employ the resolvent framework to estimate direct noise from the linearized model and compare with acoustic measurements conducted at TUB. For quantitative comparison, a low order model of the resolvent forcing will be developed. The model is then used in a parametric study to probe how diverse combustion conditions (i.e., Reynolds number, equivalence ratio, preheat temperature) affect noise. The PINN-based assimilation process obviates LES reruns by directly integrating experimentally determined mean fields. Through these efforts, we aim to untangle combustion noise intricacies, advancing combustion system design and operation. **Tasks:** (1) Compressible LES of hydrogen jet flame. (2) Empirical modelling using extended SPOD and clustering. (3) Assimilation of closure models of linearized reacting field equations using PINNs. (4) Resolvent analysis based on assimilated linearized mean field equations and comparison with empirical modes and noise. (5) Investigation and low order modelling of optimal forcing modes for quantitative noise prediction. (6) Parametric study to investigate the influencing parameters on flame noise. **T3.7, T5.4** | | | | | | | | | | |
| **Expected Results:** (1) Compressible LES of a turbulent hydrogen jet flame for experimental validation. (2) SPOD-based identification of turbulent structures driving combustion noise. (3) Linearized framework to model these mechanisms for optimization studies. | | | | | | | | | | |
| **Planned secondment(s):** 3 months at POLIBA (M25-27) for applying developed linearized model for noise estimation of LES dataset from DC9. 2 months secondment at AE (M38-M39) for assessment of developed LOM model on pressure oscillations amplitude in a real GT. A virtual secondment of 1 month at TU Delft (M40) aiming at extending developed linear modelling to transport of entropy waves exploiting DC12 experimental dataset support on developed LES subgrid closure (D5.4). | | | | | | | | | | |
| **Fellow**  DC11 | **Host institution**  POLIBA | | **PhD enrolment**  POLIBA | | **Start date**  M6 | | **Duration**  36 months | | **Deliverables**  4.2, 4.3 | |
| **Project Title and related WP(s):** LES investigation of combustion instabilities coupled with longitudinal mode and passive control, WP4 | | | | | | | | | | |
| **Objectives:** The main objective of this research is to investigate via LES the tonal noise generated by thermoacoustic instabilities in hydrogen flames. Complementing activities of DC3, the focus will be on single-injector system where oscillations are coupled with low-frequency longitudinal acoustic modes or high-frequency transverse mode. AVBP modelling developed in WP3 will be used, proving the capacity of the novel H2-TFLES to correctly reproduce acoustic/flame interactions. Multiple flame typologies will be investigated. At first, following the experimental activities from CNRS and TUB, the flame response of the CNRS swirled flame (DC2) and the TUB (DC6) jet flame when submitted to longitudinal and azimuthal acoustic forcing at multiple frequencies and amplitude will be computed, aiming to understand the impact of hydrogen preferential diffusion and specific response to stretch on coupling mechanism between acoustic, turbulence and flame. The self-sustained instabilities studied in the HYLON combustor (INPT) will then be targeted to gain knowledge on triggering mechanism leading to thermoacoustic instabilities. Finally, a passive control device able to dissipate broadband noise and tonal noise will be designed in joint actions between POLIBA and INPT (DC1). Experimental investigations of innovative design will be performed at POLIBA in an already existing impedance tube equipped with loudspeaker, advanced acoustic measurements, possibility of preheated bias and gazing flow. AVBP numerical simulations will complement experimental observations driving the design phase. The capability of the device to dissipated turbulent swirling flame noise will be experimentally verified in the MIRADAS test rig equipped with the HYLON injector and on real scale Ansaldo GT. **Task:** (1) LES simulations of flame response submitted to longitudinal and azimuthal forcing. (2) Self-sustained instabilities coupled with longitudinal mode. (3) Design, testing and experimental validation of novel passive device to damp broadband and tonal noise. **T4.6, T4.8** | | | | | | | | | | |
| **Expected Results:** (1) Novel understanding of H2 preferential diffusion on acoustic-turbulence-coupling. (2) LES results of self-sustained instabilities to investigate triggering mechanism. (3) Passive device for broadband and tonal noise. | | | | | | | | | | |
| **Planned secondment(s):** 2 months at INPT (M30-M31) to participate to experiments on thermoacoustic instabilities in the HYLON combustor. 3 months at Ansaldo Energia (M38-39) to numerically investigate design passive device on real GT. A virtual secondment of 1 month at (M40) at CERFACS to exchange on AVBP capabilities of predicting both longitudinal and azimuthal self-sustained instabilities and preparation of the corresponding deliverable (D4.3). | | | | | | | | | | |
| **Fellow**  DC12 | **Host institution**  UCAM | | **PhD enrolment**  UCAM | | **Start date**  M6 | | **Duration**  36 months | | **Deliverables**  4.5 | |
| **Project Title and related WP(s):** A systematic assimilation data model for prediction thermoacoustic instabilities, WP4 | | | | | | | | | | |
| **Objectives:** The overall objective is to optimize the design of hydrogen-fuelled gas turbine injectors, such that the combustors are quiet and not susceptible to thermoacoustic instabilities. This requires a quantitatively accurate model of the thermoacoustic system, which is the combination of a hydrogen flame with an acoustic network. This model will be obtained by systematic assimilation of data from laboratory experiments (UCAM), large eddy simulations (TUB), and industrial experiments (RRD). This data will be assimilated into thermoacoustic models using UCAM’s adjoint-accelerated inference and optimization method (AXIOM). The first intermediate objective is to extend AXIOM to typical hydrogen flame geometries using data from a laboratory scale combustor at UCAM. This combustor, which is fully automated and quick to run, can test several flame and acoustic models simultaneously. Bayesian model selection (a component of AXIOM) will be used to find the optimal component models for this simple system. The second intermediate objective is to extend AXIOM to industrial scale geometries using data from a real gas turbine fuel injector on an industrial test rig at RR Deutschland. Bayesian experimental design (another component of AXIOM) will be used to identify the experimental configurations that maximize the information that can be learned from a limited number of tests. The third intermediate objective is to develop and test several candidates mean field flame models with TUB and then to assimilate LES data into these models with AXIOM. This is an ambitious objective but the risk it generates is mitigated by TUB’s use of PINNs to achieve the same objective. The result will be a Bayesian framework that transfers data from experiments and numerical simulations into low order models. These models will steadily accumulate data and become more quantitatively accurate over time. They can therefore be used for optimization and re-optimization, as more data become available in the future and as future designs change. **Tasks:** (1) Assimilation of experimental data from laboratory scale combustor into thermoacoustic models and flame models. (2) Assimilation of experimental data from RRD industrial scale test rig into thermoacoustic models. (3) Development and testing of several candidate mean field flame models with TUB. (4) Assimilation of LES data into candidate mean field flame models and identification of optimal models. (5) Assimilation of experimental data from RRD industrial scale test rig into flame models. (6) Optimization of burner design to reduce susceptibility to thermoacoustic instability. (7) Continual re-optimization of thermoacoustic model and burner design as more data becomes available. **T4.9** | | | | | | | | | | |
| **Expected Results:** (1) Creation of a quantitatively accurate thermoacoustic model of the RRD industrial scale test rig containing an industrial burner, able to match experimental results from the RRD rig to within quantified uncertainty bounds and able to extrapolate to different configurations within predicted uncertainty bounds. (2) Creation of a quantitatively accurate mean field flame model of a turbulent hydrogen flame, able to match the LES results on which it was trained to within quantified uncertainty bounds, and able to extrapolate to unseen LES data. (3) Optimal burner design derived from the quantitatively accurate models obtained from outcomes 1 & 2, and a numerical tool for optimizing the design at different conditions and combustor geometries. | | | | | | | | | | |
| **Planned secondment(s):** 2 months at CIEMAT to perform data assimilation on cellular laminar flames (M22-M23). 2 months at TUB (M30-M31) manipulating both experimental and numerical data from DC6 and DC10. Application of developed model to improve mean fields reconstructions of non-measured quantities. Finally, 1 month at RRD (M36) to improve proposed model using real engine experimental data. A virtual secondment of 1 month at (M41) at TUM to check capabilities of LOM to predict indirect noise (D4.3). | | | | | | | | | | |
| **Fellow**  DC13 | **Host institution**  TU Delft | | **PhD enrolment**  TU Delft | | **Start date**  M6 | | **Duration**  36 months | | **Deliverables**  5.1 | |
| **Project Title and related WP(s):** Experimental investigation of indirect noise generated by hydrogen flames, WP5 | | | | | | | | | | |
| **Objectives:** The overarching goal of the PhD project is to experimentally investigate and characterize the indirect noise generated by hydrogen flames. Knowledge of the entropy-to-sound conversion in hydrogen flames is crucial to evaluate their thermoacoustic behaviour and stability, as well as the overall noise produced by the aeroengine. Knowledge of the causes and strength of the indirect noise and instabilities are crucial to develop strategies to abate them. The main objectives of the proposed PhD project are: (1) to develop the experimental infrastructure to generate, isolate and accelerate the entropy/composition spots produced by a hydrogen flame; (2) to develop measurement techniques capable to quantitatively characterize the strength of the entropy spots as well as the sound generated by their acceleration; (3) to provide the first validation and/or update the models for entropy and composition noise in hydrogen flames. **Tasks:** (1) Design, manufacturing, and testing of an optical and acoustic chamber for hydrogen flames, which will rely on the current infrastructure of the lab at TU Delft (hydrogen lines tested up till 8 bars and cooled exhaust duct). The rig should be suitable for high-pressure operation (3/4 bars) due to the necessity to accelerate the entropy/composition spots for generating indirect noise. (2) Deployment and application of fs-rotational and vibrational CARS and optical measurement techniques to quantitatively measure the strength of entropy spots (their temperature and composition). (3) Deployment and application of acoustic measurements techniques to acquire and isolate the indirect noise from the overall acoustic trace produced by the combustor, both upstream and downstream of the nozzle. (4) Comparison of the experimental data of entropy-to-sound conversion with analytical and numerical models of entropic and composition noise. **T5.1** | | | | | | | | | | |
| **Expected Results:** (1) Time-resolved measurements of the strength of entropy and composition spots in an enclosed chamber. These measurements will provide information on the dissipation and shear dispersion of the spots while travelling from the flame front location to the acceleration point. (2) Isolated trace of the indirect noise generated by the acceleration of the spots. Both the indirect noise reflected inside the combustion chamber as well as transmitted one downstream of the acceleration point will be acquired. (3) Comparison of experimental data with models (low order models for indirect and composition spots). Validation or update of the models for hydrogen flames. | | | | | | | | | | |
| **Planned secondment(s):** 3 months (M25-M27) at TU Graz to develop capabilities in density fluctuations measurements through unique laser-optical techniques. 2 months secondment at TUM (M38-39) for comparison of experimental data with low order models of indirect noise and composition spots. A virtual secondment of 1 month at (M12) at UT to exchange knowledge on vorticity/entropy noise mechanism and define indirect noise rig requirements for experimental investigations. | | | | | | | | | | |
| **Fellow**  DC14 | **Host institution**  UT | | **PhD enrolment**  UT | | **Start date**  M6 | | **Duration**  36 months | | **Deliverables**  5.2 | |
| **Project Title and related WP(s):** Simulation-based development of indirect combustion-noise theory, WP5 | | | | | | | | | | |
| **Objectives:** To remedyineluctabledeficiencies in the current understanding of indirect-noise generation, especially as it relates to hydrogen-fuelledsystems, Computational Fluid Dynamics (CFD) will be used. Initially, numerical analyses will focus on a previously characterized experimental setup operated at DLR. As a first step, non-reacting-flow modelling will be employed to definitively establish:the cogency of non-reacting-flow simulations for systems with reacting flow. Moreover, this analysis will make refining the comprehension of fluid dynamics, turbulence, and related phenomena in scenarios devoid of combustion possible. After that, the simulationswill be repeated with classical hydrocarbons (methane) and hydrogen comparing noise spectra levels and characteristics. The effect on indirect noise of the interplay between vorticity, compositional and entropy spots will then be investigated in a reactive case. Three-dimensional simulations using lower-order numerical models for compressible flow (Euler and URANS) will be compared to high-fidelity LES results to evaluate the predictive-quality of lower-order CFD methods. This numerical dataset will be then exploited to perform theory development, with the aim to extend existing analytical/semi-analytical modelling to hydrogen combustion. Ultimately, the proposed approach will be applied to characterize the experiments performed at TU Delft. **Tasks: (1)** CFD studies of vorticity inhomogeneities convected by a high-Reynolds-numberflow through a choked nozzle under non-reactive simulations. (2) Euler/URANS/LES-simulation comparison of entropy-vorticity interaction with a choked nozzle. (3) Cultivationof theoretical insight and where possible the development of analytical/semi-analytical models. (4) Application of developed modelling to TU Delft rig for indirect noise predictions. **T5.2** | | | | | | | | | | |
| **Expected Results:** (1) Vorticity/entropy interaction as a source of indirect noise. Comparison with classic hydrocarbons configuration. (2) Analytical model for indirect noise due to vorticity/entropy interactions | | | | | | | | | | |
| **Planned secondment(s):** 3 months at UdeS (M25-M27) for development of vorticity/entropy interaction analytical model. 2 months at TU Delft (M38-M39) for performing experiments on TU Delft indirect noise rig to extract data for validation of analytical modelling. A virtual secondment of 1 month at (M41) at UCAM to discuss on the use of data assimilation methods for capturing vorticity/entropy interactions. | | | | | | | | | | |
| **Fellow**  DC15 | **Host institution**  TUM | | **PhD enrolment**  TUM | | **Start date**  M6 | | **Duration**  36 months | | **Deliverables**  5.3 | |
| **Project Title and related WP(s):** Entropy waves in hydrogen combustion: Generation and contribution to combustion noise and thermoacoustic instability, WP5 | | | | | | | | | | |
| **Objectives:** The project strives to clarify and quantify the contributions of entropy waves to indirect combustion noise and thermoacoustic instability of hydrogen flames. The goal is to predict engine noise and combustor stability. The formulation of the entropy wave source terms shall consider the effects of flame displacement on local entropy fluctuations to eliminate spurious contributions to entropy wave generation. Furthermore, the effects of preferential diffusion of hydrogen – in particular, the generation of inhomogeneities in fuel /air premixture – on entropy wave generation shall be considered. Results shall be validated against experiments at TU Delft. Developed numerical procedure will be applied to predict direct and indirect noise of real hydrogen-fuelled Rolls Royce aeroengine. **Tasks:** (1) Identify and eliminate spurious contributions to entropy wave sources terms in turbulent reacting flow. (2) Carry out LES of turbulent hydrogen flames with broadband forcing to generate data for non-parametric system identification of hydrogen flame transfer functions and combustion noise source terms, including entropy wave generation.(3)Integrate models from the literature for entropy wave propagation, dispersion, and conversion, to build a complete model for thermoacoustic interactions. (4)Quantify the effects of preferential diffusion on indirect combustion noise in hydrogen flames. **T5.3** | | | | | | | | | | |
| **Expected Results:** (1) LES of turbulent hydrogen flame to identify combustion noise source. (2) Models for entropy wave generation, propagation, dispersion, and conversion. (3) Quantification of hydrogen preferential diffusion on indirect noise (4) Prediction of combustion noise of a real aeroengine. | | | | | | | | | | |
| **Planned secondment(s):** 2 months at TUD (M25-M26) to participate to the indirect noise measurements experiments, 3 months at RRD(M38-40) to perform noise predictions in a real aeroengine. A virtual secondment of 1 month (M41) at AE to investigate noise on land base GT. | | | | | | | | | | |

Immagine che contiene schermata

Descrizione generata automaticamenteA recap of the secondments planned in the HyNOISE DN, with the indication of their duration is shown in the following table (red: physical secondment; green: virtual secondment)

### Progress monitoring and evaluation of individual research project

The primary points of contact for all Doctoral Candidates (DCs) will be the main supervisors, co-supervisors, and mentors. They will consistently oversee the progress of each research project. The Scientific Supervisory Committee (SCC, as outlined in Part B2) chaired by Project Coordinator (PC) and composed by representative of each WP leaders (POLIBA, CNRS, TUB, CERFACS) will establish guidelines to ensure the quality of supervision and monitor progress during Supervisory Board (SB) meetings held every 6 months. Additionally, the first action of the committee SCC will draft a document outlining procedures related to scientific misconduct in accordance with the European Code of Conduct for Research Integrity. The SSC will address major issues, maintaining a Rolling Action Item List related to all DCs, which will be periodically reviewed by the entire SB. Reports detailing DC progress throughout the PhD will evolve, focusing more on training initially, and shifting towards publications in later phases. Key indicators of DC progress, such as submitted publications, attended conferences, participation in training and dissemination events, and employment objectives towards the program's end, will be crucial. In the case of changes to the DC’s project plan being necessary, this scientific supervision will verify the impact on other DCs and will guarantee the overall consistency of the project structure. If required, the PC will report any critical issues and changes to the research and training programme to the European Commission. The mid-term SB meeting will be opened to a representative of EU Commission, and it will constitute a toll gate event for their search and training activities. Additionally, a Training Supervisory Committee (TSC), chaired by Thierry Schuller (INPT), will oversee and delegate training activities, assist local hosts in coordinating and communicating within the network, and work to optimize the scheduling and timing efficiency of training events.

* + 1. **Implementation Risks**#@RSK-MGT-RM@#

The huge experience of HyNOISE beneficiaries in conducting and contributing to large research networks will strongly limit the impact of possible risk occurrence.

**Table 3.1 g** **Implementation Risks**

|  |  |  |
| --- | --- | --- |
| **Description of risk**  **(Likelihood, Severity)** | **WP(s)** | **Proposed risk-mitigation measures** |
| Experiments are difficult and may lead to problems. (Unlikely, Low) | WP2, WP3, WP4, WP5 | The experimental teams involved in HyNOISE have extensive years of experience working with combustion systems: this limits the risks. WP planned to utilize operational rigs. Experience and support by PI may also help to limit this risk. |
| Combustion experiments with hydrocarbon or H2 require additional precaution.  (Unlikely, High) | WP2, WP3, WP4, WP5 | The laboratories of the HyNOISE team have extensive experience in combustion. Existing infrastructure is equipped for safe operation and the lab culture is prepared for these experiments. |
| Delay in project dependencies. (Likely, Medium) | WP1, WP2, WP3, WP4, WP5, WP6, WP7 | DC projects are designed to be robust to delays, including possibilities to move forward despite delays in other sections of the program. |
| Underperforming DC.  (Moderate, Medium) | WP2, WP3, WP4, WP5 | The supervisor and mentor program, combined with oversight, should be able to address issues quickly. As above, delay in one project won’t destroy success of other projects. |
| Secondments are not made according to the initial plan. (Likely, Low) | WP2, WP3, WP4, WP5 | Secondments to be rescheduled considering, if necessary, another partner organization. Supervisors can easily address unexpected scheduling conflicts. Possibility of virtual secondments add more flexibility. |
| Training programme cannot be completed as planned.  (Unlikely, Medium) | WP6 | TSC provides regular review of training events scheduling, enabling responsive to conflicts. The consortium choice in organizing fewer but longer trains further reduce the risk of conflicts. Committee can configure replacement events should planned events become impossible. |
| DC or supervisor leaving the project or changing position. (Moderate, Medium) | WP1, WP2, WP3, WP4, WP5, WP6, WP7 | DC: help from partners for rapid recruitment, redistribute tasks if needed. Supervisor: appoint new supervisor if needed. Mentor can assist with supervision. Risk is further reduced by the fact that all supervisors are permanent or fixed-term employees whose contract will last for the entire duration of the project. |
| Insufficient communication and cooperation between network beneficiaries.  (Unlikely, Medium) | WP1, WP2, WP3, WP4, WP5, WP6, WP7 | Call extraordinary meetings of Supervisory Board to resolve, consult EU for recommended actions. Regular meetings and internal communication should mitigate risk. The HyNOISE novel “Programme” training has been conceived also to provide a fertile environment boosting synchronization between DCs. |
| Financial overspending.  (Unlikely, High) | WP1 | Stop activities, contact EU commission, audit, and reallocate resources to minimize effect on DC research and training programmes. Regular oversight by PC and Supervisory board should ensure a responsible burn rate. |
| Withdrawal of one of the beneficiaries due to financial issues or other reason.  (Unlikely, High) | WP1, WP2, WP3, WP4, WP5, WP6, WP7 | Actions will be considered to reincorporate the DC at one of the partner institutions. |
| The validation of CFD numerical models does not produce the expected agreement with experimental results. (Likely, Medium) | WP2, WP3, WP4, WP5 | For each developed feature at least 2 options will be considered in order to have backup solutions. The experience of involved partners will permit to quickly mitigate the risk. |
| Damage of optical instrumentation or combustion chamber. (Likely, Medium) | WP2, WP3, WP4, WP5 | Existing, reliable, maintenance contracts for onsite short time intervention will mitigate the impact on scheduling. Equivalent instrumentation available in the research institute. Prepare back-up parts for testing. |

## Quality, capacity, and role of each participant, including hosting arrangements and extent to which the consortium as a whole brings together the necessary expertise

### Appropriateness of the infrastructure and capacity of each participating organization

The research infrastructures available at facilities of HyNOISE partners will permit us to suitably satisfy the requirements pointed out in the proposed DC projects. INPT, TUB, CNRS, NTNU and TU Delft will provide state of the art combustion test rigs and optical diagnostic devices to support investigations of hydrogen flames and entropy noise. Said partners have the critical infrastructure needed to measure and fully characterise noise, instabilities, and hydrogen flame dynamics. Moreover, they have a proven track-record of having done these types of measurements. The available experimental facilities and the experience of involved supervisors will allow us to provide high-quality validation datasets to POLIBA, CIEMAT, CERFACS, CUT, TUB, NTNU, UT, TUM and UCAM teams in charge of high-fidelity numerical modelling. Those partners have decidedly cogent experience in LES, DNS, and Low Order Modelling of multi-physics problems. In addition, they will make available to the network state of the art numerical codes and High-Performance Computing infrastructure that will also be complemented by grants to access HPC resources at European level.

### 3.2.2 Consortium composition and exploitation of participating organizations’ complementarities

The HyNOISE network includes 13 Universities (9 beneficiaries), 2 public research organizations (beneficiaries), 1 private research organization (beneficiary) and 3 mains European aeroengine and gas turbine manufacturers (associate partners). The academic partners are worldwide experts in the numerical and experimental investigations of combustion processes in energy systems and aeroengines, with decidedly demonstrated skills and knowledge necessary for the investigation of reactive multi-physics processes. All the HyNOISE participant organizations are eminent in the field of high-fidelity combustion phenomena. The presence of two leading European aeroengine and one gas turbine manufacturers covers two massively important industrial sectors. Their involvement ensures that HyNOISE’s outcomes help meet the industry’s needs in terms of design requirements for a new generation of hydrogen-fuelled gas turbines. HyNOISE partners individually bring core competences and critical expertise to the table. The result is a well-balanced set of skills and crucial expertise. To boot, all stakeholders have a first-rate track record when it comes to collaborative-research activities, e.g., EU actions INSPIRE (POLIBA, CERFACS, SAFRAN) and HESTIA (INPT, CERFACS, CNRS, SAFRAN, TUM, CUT, RRD). HyNOISE’s WPs and DCs projects are organized according to the partner’s skills and research infrastructures. Secondments have been planned to optimize the DCs’ multifaceted growth. Each beneficiary has appointed one or more supervisors for recruited DCs. In addition to the DCs’ direct supervisors, all DCs will integrate well-established research teams, with consequential expertise, on which the DCs can also rely for guidance. Gender equality and inclusiveness is safeguarded at all involved institutions. Moreover, special care will be taken on these aspects in the recruitment phase. In short, the DCs will evolve in an assuredly safe, inclusive, and singularly inspiring work culture. In the following table, a breakdown of complementarity skills among partners is shown.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Core competences/Expertise** | **INPT** | **CNRS** | **CERFACS** | **CUT** | **NTNU** | **TUB** | **CIEMAT** | **POLIBA** | **TU Delft** | **UT** | **TUM** | **UCAM** | **TU Graz** | **UdeS** | **SAFRAN** | **RRD** | **AE** | **UC3M** | **UPSaclay** |
| Numerical methods for turbulent reacting flows |  |  | X | X |  | X | X | X |  | X | X | X |  | X |  |  | X |  |  |
| Combustion experimental diagnostics (Laser, Acoustics) | X | X |  |  | X | X |  | X | X |  |  | X | X |  | X | X | X | X |  |
| High-fidelity CFD modelling (LES, DNS) |  |  | X | X | X | X | X | X |  | X | X |  |  |  |  |  |  |  |  |
| Data driven and Low Order Modelling approaches |  | X |  | X |  | X |  |  |  | X | X | X |  |  | X | X | X |  |  |
| Analytical semi/analytical approach |  |  |  |  |  |  |  |  |  | X | X | X |  | X |  |  |  | X |  |
| Active and passive control | X |  |  | X |  | X |  | X |  |  |  |  |  |  |  |  | X |  |  |

### Commitment of beneficiaries and associated partners to the programme

By agreeing to be involved in this proposal, all the beneficiaries and associate partners hereby confirm their commitment to support the HyNOISE project. Each beneficiary has formal, internal approval by its legal representative to commit the organization in providing adequate resources to support the planned research activities as reported in the proposal. Associated partners have also committed to participating because of their interest in the proposed research. Moreover, they have pledged to take on an active role in the training activities or hosting secondment (both physical and virtual). Associated industries, moreover, are seeing the potential to recruit talented and skilled engineers required to develop innovative products. The contribution to the project of UT Graz will be to host secondments of DC1(INPT) and DC13 (TU Delft) (3 months each). UT Graz contributesoutstandinglaser-diagnostics expertise for turbulent flames. The US will host secondment of DC14 (UT) to develop theoretical modelling on indirect noise produced by hydrogen flames. In addition to having an administrative role (awarding of DC7 PhD degree), the UC3M will help provide training on theoretical modelling and experiments for hydrogen combustion (WS1-3). UC3M will host secondment of DC3 to perform joint experiment on unique test rig. The UPSaclay is the academic associated partner awarding DC2 PhD degree. The industrial partners (Safran, Rolls Royce Deutschland and Ansaldo Energia) will host one or more secondments (both physical and virtual), bringing expertise in industrial needs and applications and potentially taking advantage in exploring non-conventional innovative control strategies for noise produced by hydrogen fuelled burners and related dedicated numerical tools. #§QUA-LIT-QL§# #§WRK-PLA-

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