An innovative Concept for the complete and low-NO_x Combustion of non-carbon Eco-fuels using a thermo-acoustically-driven, hydrogen-powered Pilot Stage

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Abstract: The problem of climate change, triggered by a high concentration of pollutants in the atmosphere and the scarcity of fossil resources, increases the need of low emission thermal utilisation of novel, non-carbon eco-fuels such as hydrogen, ammonia (both for energy and propulsion) or hydrogen sulphide (sulphuric acid production). While all of these listed eco-fuels have the potential to decarbonise industry and the energy sector, they also pose demanding challenges regarding combustion. To address these challenges the consortium consisting of Combustion Bay One e.U., P&P Industries AG and FH JOANNEUM GmbH is working on the project called BLUETIFUEL, supported by the FFG.

The idea of BLUETIFUEL is to combine the advantages of current low-NO_x technologies in terms of ultra-lean combustion with a precisely controlled, forced flame turbulence generated by a pulsation apparatus. The aim of the project is to develop a safe and highly digitalised combustion technology for the complete and low-NO_x combustion of hydrogen, ammonia and hydrogen sulphide, including a three-staged burner design for application in the megawatt range with multi eco-fuel capacities and a fully automated control loop for the combustion process.

In this paper the project BLUETIFUEL is introduced including its vision and strategy. This is followed by a detailed explanation of the principle, new features and improvements of the pulsation apparatus called Siren E, especially designed for the industrial use. Furthermore, a method and its implementation for detecting eigenfrequencies of the flame by using Siren E and an acoustic sensor are presented. Afterwards, a detailed description of initial combustion experiments and their test setup is given. The experiments were performed with hydrogen up to a thermal power of 7.5 kW. First, different methods for the injection of hydrogen were tested in terms of their combustion stability and flashback tendency. Then, their response to thermo-acoustic excitation via loudspeaker and Siren E was investigated, resulting in a prioritised premixing variant. This is followed by the discussion of the early results out of non-reactive and reactive CFD simulation and the experiments with hydrogen, leading to the conclusion of this paper.

Keywords: Combustion, Hydrogen, Thermo-acoustics, Eco-fuels

1 Project BLUETIFUEL

1.1 Vision and Strategy

BLUETIFUEL stands for *blue* flames for low emission combus*ti*on using non-carbon eco-*fuels*. The strategy behind: The Power-to-X technology provides promising energy storage for renewable resources. Excess electricity from solar, wind or hydro power can be used to generate a non-conventional, non-carbon eco-fuel such as hydrogen, ammonia or hydrogen sulphide, which can be thermally utilised in high-temperature applications in process engineering, chemical and metallurgical sector or to cover the electrical residual load or heat demand of a country. The overall vision of the project is illustrated in Figure 1.

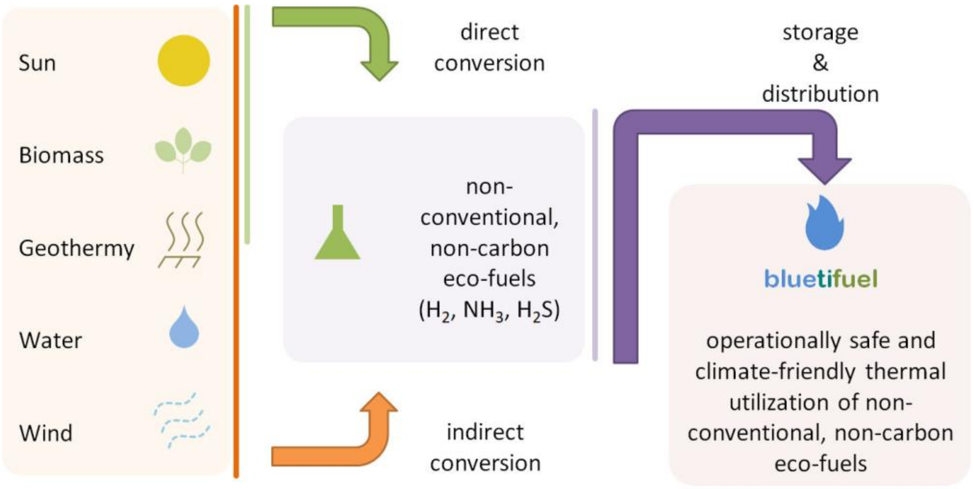


Figure 1: *The vision of the project BLUETIFUEL - Excess energy from renewables stored in non-carbon eco-fuels for the subsequent thermal utilisation.*

The idea is to combine the benefits of an ultra-lean combustion in terms of NO_x-performance with precisely controlled, forced flame pulsation. A three-staged burner concept with multi eco-fuel capacities introduces lean premixed hydrogen into the combustion chamber via the pilot stage. On the one hand, the pilot stage has the task of supplying the necessary thermal energy for the self-ignition of the eco-fuels ammonia or hydrogen sulphide and ensuring complete burnout. On the other hand, the hydrogen-powered pilot stage acts as a thermo-acoustic driver of combustion. Therefore, the pilot stage is downstream connected to a pulsation apparatus type siren. Ammonia or hydrogen sulphide is introduced via the main stage of the burner. The third burner stage enables cooling of the walls and an additional dilution of the flue gas. If necessary, a second pulsation apparatus also type siren can be connected to the air stream of the main stage or the dilution stage. To avoid the occurrence of a flashback phenomenon when the flame is extinguished, the pilot stage is purged with nitrogen.

For performing combustion with hydrogen sulphide or ammonia, a flue gas treatment is necessary to capture the SO_2 or possible unburned NH_3. The flue gas treatment is realised by a sodium hydroxide scrubber and a wet electrostatic precipitator. In the framework of the project, two technology demonstrators for combustion of eco-fuels in the kW-range and MW-range will be realised. The conceptual PFD (process flow diagram) of the kW-demonstrator is displayed in Figure 2 and includes the aspects described above.

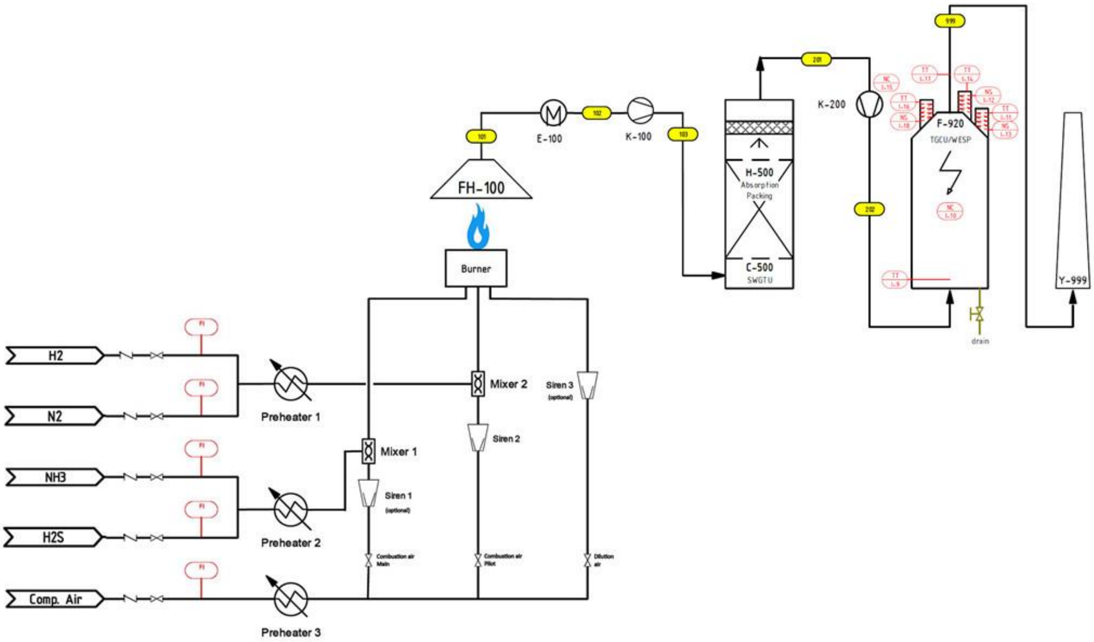


Figure 2: *Process flow diagram of the kW-demonstrator with subsequent integrated flue gas treatment system. Preheating of the reactants is possible. The siren can be connected downstream of each burner stage or, if necessary, a second identical siren can be connected downstream of another stage.*

The main strategic objective of the project is to develop a combustion technology which guarantees a safe, stable, complete and low-emission thermal utilisation of eco-fuels. This should be ensured via the thermo-acoustic excitation of the flame. The pulsation of the flame has two main functions. The first one is to ease premixing in the region prior to the flame. The second one is to make a positive use of thermo-acoustics in order to improve the combustion performance (stability, LBO, emissions). This technology is in line with prior application of pulsed combustion [1]. Since ultra-lean mixtures tend to suffer from uncontrolled combustion instabilities, which can lead to sudden flame-out, forced thermo-acoustic pulsation of the flame is intended to ensure a complete burnout of the partially toxic reactants. Uncontrolled combustion instabilities are caused by the in-phase coupling of sound pressure and the unsteady heat release [2]. Flames with thermo-acoustic instabilities are characterised by their specific noise, in which the broadband sound energy tends to concentrate in a specific frequency peak (eigenfrequency), and by their ability to amplify the sound. Using this coupling effect in a well-controlled manner allows an increase in the rates of heat, mass and momentum transport [3]. This makes it a promising combustion method for our purposes.

In a previous study conducted 2017, in which the combustion behaviour of low heat value gas under thermo-acoustic pulsation was investigated, good results have already been obtained. The pilot flame was constantly excited at an eigenfrequency while an alternate feed of diluted fuel in the main zone happened. It could be shown that the combustion domain of a low heat value gas was extended by a well-controlled, forced, thermo-acoustic pulsation while simultaneously reducing the fuel content. A detailed description of the test rig and the conducted experiments can be found in [4,5]. The combustion methodology is derived from this study.

The safety concept and the precise and efficient control of a thermo-acoustic excited flame require a fully automated closed control loop. On the one hand, it must be ensured that when a hazard occurs, whether it originates from the combustion or the chemicals, the hazard will be detected as quickly as possible and countermeasures will be initiated. On the other hand, it is necessary to react as quickly as possible to changes in pulsation conditions resulting from an increase in the flue gas temperature and thus from changes in the sound speed. Therefore, a closed loop control will be implemented. The flame will be real-time monitored via fast-responding optical and acoustic sensors. Temperature measurements will be done in the flue gas channel and the combustor walls. Flue gas measurements will be carried out to check the complete burnout of the partially toxic reactants, and to determine the current NO_x emissions. The closed control loop is prioritised on safe and complete combustion, followed by minimizing the NO_x emissions.

The technology demonstrator generating thermal power in the kW-range is used for the evaluation of the three-staged burner design, for the investigation of the effect of thermo-acoustic excitation of eco-fuels via a hydrogen-powered pilot stage, for the implementation of the closed loop control and the optimisation of the safety concept. Based on the experimental results in the kW-range and the results out of the digital twin, the proven combustion methodology will be scaled up to the MW-range.

2 The Siren E

A siren is an electro-pneumatic fast-valve that generates powerful noise levels and effective air flow modulation with the possibility to operate under combustion conditions. Such actuators were developed to reproduce the conditions where combustion instabilities occur to investigate the physics of this interaction and eventually control them. Many combustion laboratories perform successfully flow modulation by means of a loudspeaker. Considering the inclusion in power systems, however, using loudspeakers is unrealistic due to the aggressive operating conditions (elevated temperature and pressure conditions) and their limited acoustic power. While the first siren model only enabled the variation of the pulsation frequency, the third generation of CBOnes' sirens offers the possibility to precisely control the pulsation frequency and noise level amplitude independently. More details about the third generation of sirens can be found in [6,7].

These further developments emerged additional fields of application for the siren. Beside the main reason of development, the third generation of sirens can be used for calibration of dynamic pressure transducer, for an acoustic characterisation of a combustor assembly or for flow control and flame forcing.

The principle of the siren relies on a sonic air jet, generated by a critical nozzle, which is sheared periodically by a cogwheel rotating with a given speed. The pulsation frequency is set by the number of teeth on the cogwheel multiplied by the shaft's rotational speed. The pulsation amplitude and therefore the noise level depends on the coverage of the nozzle cross section and this is controlled by the position of the cogwheel relative to the nozzle outlet. The higher the coverage through a tooth is, the higher the pulsation amplitude is. Since the siren works with a sonic jet, perturbations and instabilities downstream have no impact on the functionality which is very convenient for control purposes.

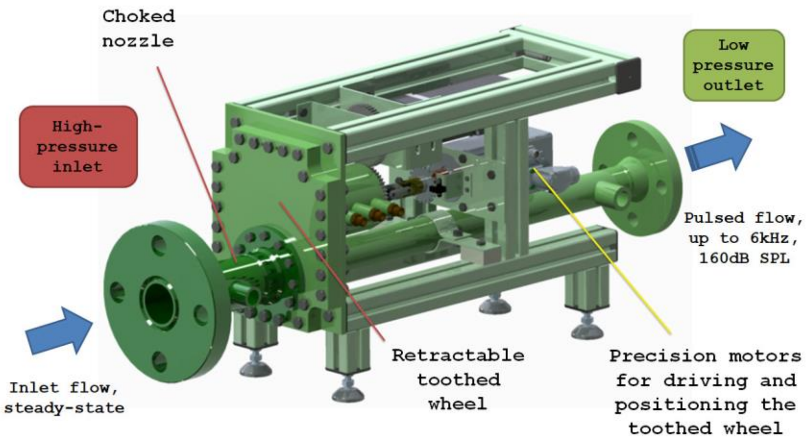


Figure 3: *The new model Siren E of CBOne's third generation of sirens especially designed for the demanding need in industrial use.*

The Siren E, displayed in Figure 3, represents the latest model of CBOne's third generation of sirens, especially designed to meet the demanding needs of an industrial application. The technology used in Siren E is similar to the one of Siren 3G, therefore it belongs to the same generation. No drastic changes were done. It is simply more robust and more powerful. Siren E is the industry-ready version of Siren 3G, which is more like a laboratory-scale pulsator. The Siren E is designed to meet pressure levels up to 80 bar on the high-pressure inlet with a maximum pressure drop of 40 bar over the nozzle. The performance of the device was improved to achieve pulsation frequencies up to 6000 Hz with noise levels beyond 160 dB SPL. To conclude, the Siren E is a much more robust and powerful version of Siren 3G with almost no gain in the main dimensions.

3 Automated Control of Combustion

3.1 Closed Control Loop

For reasons of both safety and precision, an automated closed-loop control system is being developed for the combustion of the eco-fuels. The heart of the control system is the control unit. Currently, the control unit is realised via a National Instrument Labview interface. This is sufficient for the experiments in the kW-range. For the MW-demonstrator, the control unit will be implemented using SIMATEC S7 PLC-technology. The control unit processes the supplied data based on an algorithm and passes on commands for further actions to the actuators. The algorithm is prioritised on safe, stable and complete combustion of toxic reactants, followed by minimization of NO_x emissions. The task of control systems is not only the process control but also the achievement of safe conditions in the event of malfunctions. The safety concept is based on redundancy and diversity. The instrumentation is executed redundantly and is actively and passively secured via different measurement methods. Combustion is monitored in real time via optical and acoustic sensors. The temperature in the combustion chamber as well as in the flue gas duct is measured. The flue gas flow is monitored for NH_3, H_2S, SO_2 and NO_x. The mass flows of ammonia, hydrogen sulphide and hydrogen are controlled by mass flow controllers. Pressure and temperature are measured in all supply lines. A schematic representation of the closed control loop for safety and process control is displayed in Figure 4.

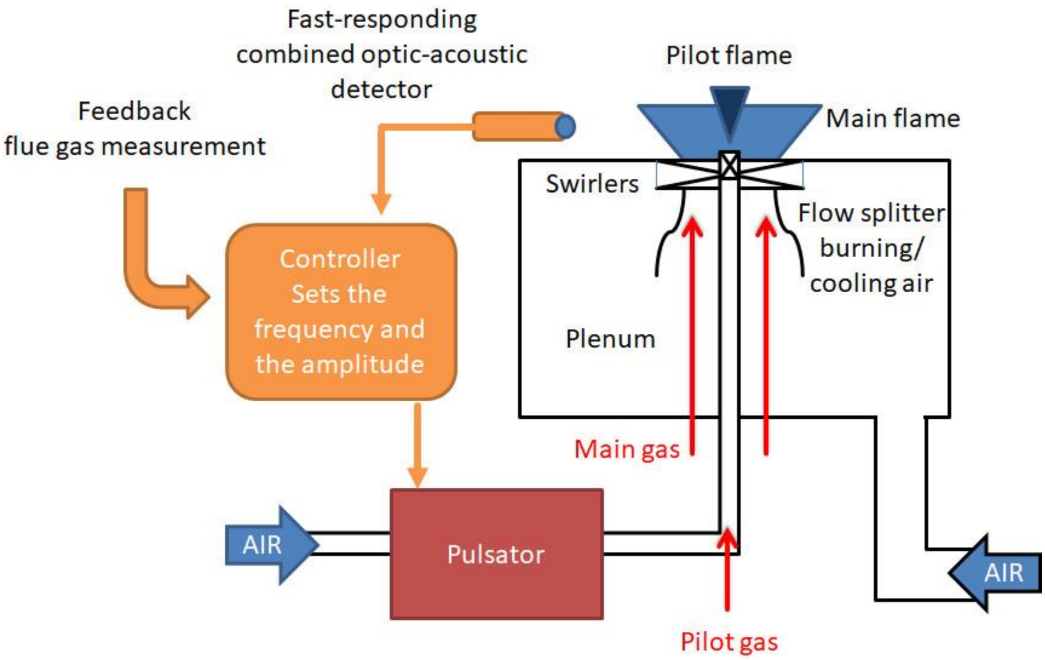


Figure 4: *Schematic representation of the automated control system for the precisely controlled, thermo-acoustically excited combustion of eco-fuels.*

3.2 Method for detecting Eigenfrequencies

In the 2015 study by CBOne [4], it was shown that in order to influence and control a flame in the lean domain by means of thermo-acoustic excitation, an eigenfrequency of the flame must be hit. The paper introduced a method for detecting eigenfrequencies using a loudspeaker controlled by a Python script and a microphone. While most experiments so far with this method were conducted in an open loop manner with separate data analysis, the principle is now automated. A fully automated closed control loop is necessary to adapt to changes in operation points and flow temperature, which is relevant for the thermo-acoustics. For instance, due to the heat-up of the flue gas and the increase of the temperature, the sound speed is affected resulting in a rise in eigenfrequency. This shift in frequency must be detected and subsequently the new frequency must be excited.

Based on the method from 2015, a modified procedure was developed in closed loop manner including Siren E, an acoustic sensor and a real-time analysis with opportunity for post-processing. The modified procedure is divided into three sequences. First, a global frequency scan is performed over a defined range with maximum pulsation amplitude and given speed in Hz/s, while simultaneously acquiring and analysing the data. Then, a second scan is done over the same domain at half the pulsation amplitude with simultaneously acquiring and analysing. The determined frequencies of the first and second sequence are compared. If the deviation of both results is within an acceptable error range, a sensitivity analysis is performed by varying the pulsation amplitude from 0-100% on the determined frequency. The sensitivity analysis in the third sequence is used to determine the minimum required pulsation amplitude at which a significant effect on the flame occurs. If the deviation exceeds an acceptable error range, an additional refinement of the frequency range can be performed, where the two determined frequency peaks are included.

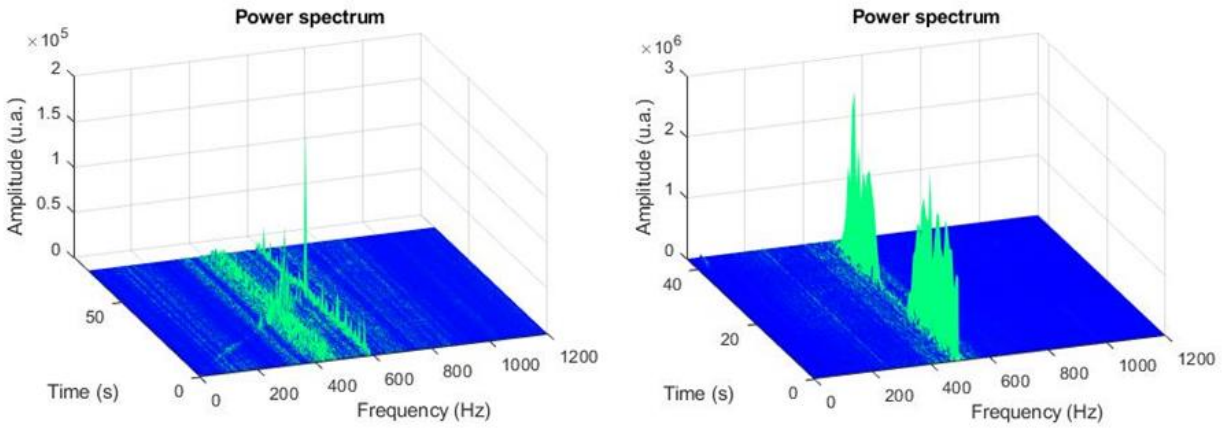


Figure 5: *Left: A global frequency scan through a desired range with constant pulsation amplitude recorded by a microphone. Right: Variation of the pulsation amplitude on a determined possible eigenfrequency of the flame.*

To verify the modified method, combustion tests were carried out with propane on the so-called MethaNull test rig. A detail description of the MethaNull test rig and all experiments conducted 2017 can be found in [4,5]. For the verification experiment, the siren is connected to the pilot stage of the burner. The air is distributed between pilot and main stage by a ratio 1:1, means one half of the total air is used as combustion air in the pilot, the other half is cooling air in the main. Only the pilot stage is fired. To get the acoustic response to the siren's excitation, a microphone is used. The automated procedure described above was run several times at the same operating point. The recorded data of a frequency scan from 0 to 1000 Hz with maximum pulsation amplitude (left) and a sensitivity analysis (right) is shown in Figure 5. Frequency peaks of interest were determined in the range of 400 Hz to 600 Hz, as visible in the plot on the left. The result from the study in 2017 could be repeated in a satisfactory manner. In the study, the pilot flame was constantly excited at a frequency of 580 Hz while alternate feed of diluted fuel in the main zone happened. It could be shown that with pulsation at this frequency the pilot flame remains when the main flame is turned off, whereas the pilot flame blows out under steady-state conditions when turning off the main flame. The detected frequency peak resulting out of the procedure is at 585 Hz. Repeatability was observed with a 0.33% uncertainty.

4 Premixed Hydrogen Combustion

4.1 CFD Simulation

Before performing the first combustion experiments a numerical model was studied to address the flow characteristics of the pilot stage using openFOAM.

First, the aerodynamic flow is investigated with taking into account the additional hydrogen content in the air mass flow, density and viscosity. The case is computed under non-reactive conditions at ambient pressure and temperature. The solver used is pisoFoam, a transient solver for incompressible flows with turbulence modelling, operating with the PISO algorithm. The chosen turbulence model is the common k-epsilon model. For the initial conditions, a fictitious combustion of premixed hydrogen at ϕ =0.5 and a thermal power of 5 kW was assumed. In order to take the fictitious hydrogen input into account, the calculated mass flow of hydrogen for a thermal power of 5 kW was added to the air mass flow, and the kinematic viscosity, defined in the transport properties, was adjusted from pure air to an hydrogen-air-mixture at ϕ =0.5.

Then, the formation and stabilisation (in terms of flame location and flashback tendency) of a premixed hydrogen flame is studied using the XiFoam solver. The appropriate combustion models of XiFoam are applied for partially- and fully premixed flames respectively. XiFoam realises the combustion process not chemically, but by the propagation of the flame front using the $b - Xi$ two-equation model, where b is the progress variable of the burnt products and Xi is the ratio between turbulent flame speed and laminar flame speed. The laminar flame speed model chosen is the “RaviPetersen” model for hydrogen in air. The correlation for laminar flame speed Su by Ravi and Petersen is:

$$Su = \left(\sum a_i \phi^i\right) \left(\frac{T}{T_{ref}}\right)^{\left(\sum \beta_j \phi^j\right)}$$

Where ϕ is the equivalence ratio, and α and β are polynomial coefficients given for a number of equivalence ratio and pressure points. The solver operates with the PIMPLE (PISO + SIMPLE) algorithm. The combustion of premixed hydrogen at ϕ =0.5 and a thermal power of 5 kW is investigated.

4.1.1 The numerical Pilot Stage

Since no specific injection method for hydrogen had been selected at the time of the simulation, the focus was placed on the flow of the air path. In all computed cases following, the method of hydrogen injection is neglected. The geometry used, representing the pilot stage, is displayed in Figure 6.

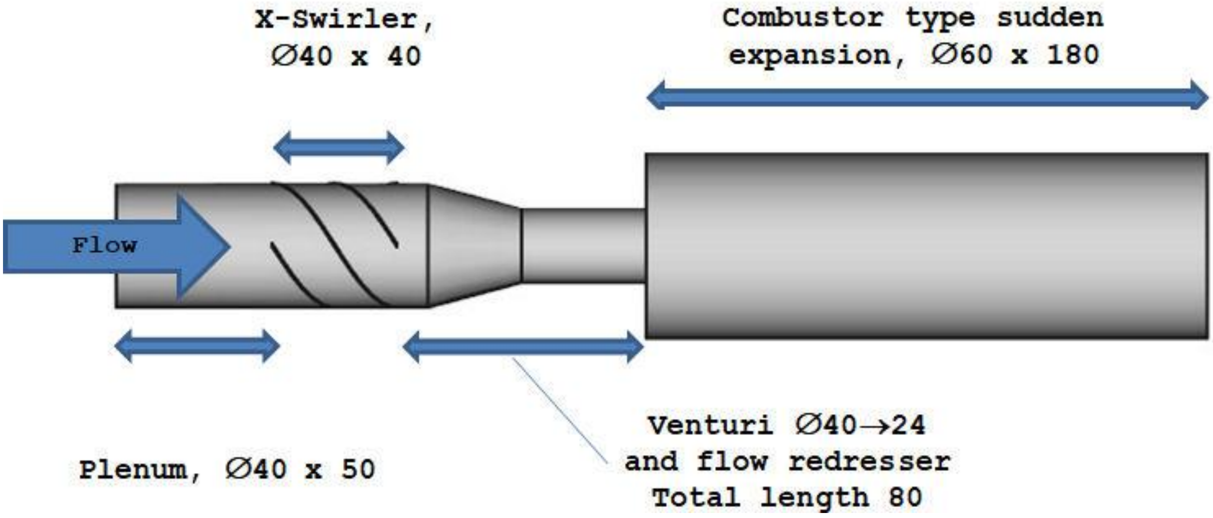


Figure 6: *Dimensions of the computed combustor type sudden expansion. Although the model is shown here lying down, the numerical computation was performed in the upright state with gravity included.*

The geometry starts with a plenum containing an axial swirler. The swirler has four helical blades with a 60 degree angle to the horizontal on the outer wall. The swirler is followed by a venturi with flow redresser, ending in a combustor type sudden expansion. The mesh is generated via GMSH and contains 524350 cells. In both, non-reactive and reactive cases the flow is introduced from the bottom of the geometry.

4.1.2 Simulation Results

The velocity vector field of the aerodynamic study is depicted as streamlines in Figure 7. The colours of the streamlines represent the flow velocity at a particular location with reference to the scale in m/s provided. A strong recirculation zone is observed in the first half of the combustor type sudden expansion. On the point, where the streamlines begin to recirculate, a clear V-shaped formation of the flow is visible. This numerical computation was performed to get a first idea about the possible flame positioning. Based on the computed result the flame is assumed to stabilise in the region of the reattachment zone (V-shape flow). The impacts of the hydrogen injection method or the thermo-acoustic excitation were not taken into account.

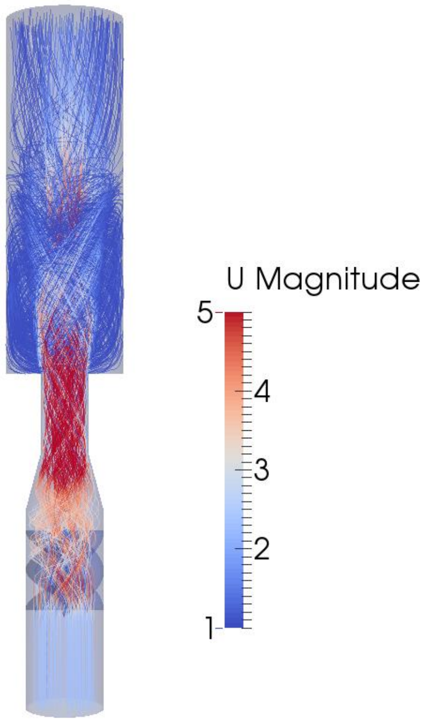


Figure 7: *Aerodynamic analysis of the flow conditions. The focus was put on the reattachment region of the flow.*

The temperature profile of the premixed hydrogen flame over time generating a flashback is shown in Figure 8. The corresponding velocity field is represented in Figure 9. The selected operating point (thermal power = 5 kW, phi = 0.5) seems to have an increased tendency for flashbacks based on the simulation data, where the impact of the hydrogen injection has not yet been considered. The regions with temperature gradients (represented by different shades of red) suggest an inhomogeneous distribution of the hydrogen mixture. Due to the high diffusivity of hydrogen, bubbles of hydrogen form, which lead to increased flame speeds. These bubbles of increased flame velocity can be seen in the velocity profile over time in Figure 9. This effect is mostly responsible for the increased occurrence of flashbacks during premixed combustion of hydrogen.

All results out of the simulation were taken into account for the first experiments.

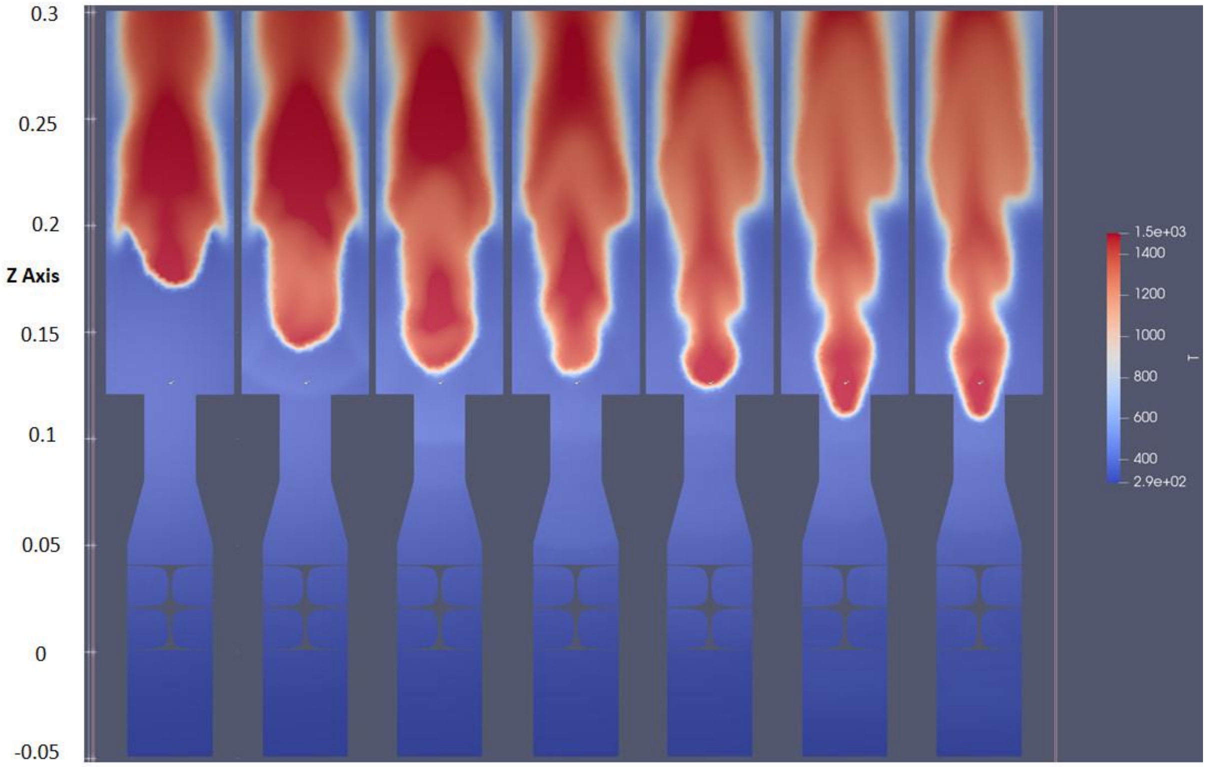


Figure 8: *Temperature profile of the flame performing a flashback over the time, computed with XiFoam for the case of premixed hydrogen at a thermal power of 5 kW and phi of 0.5.*

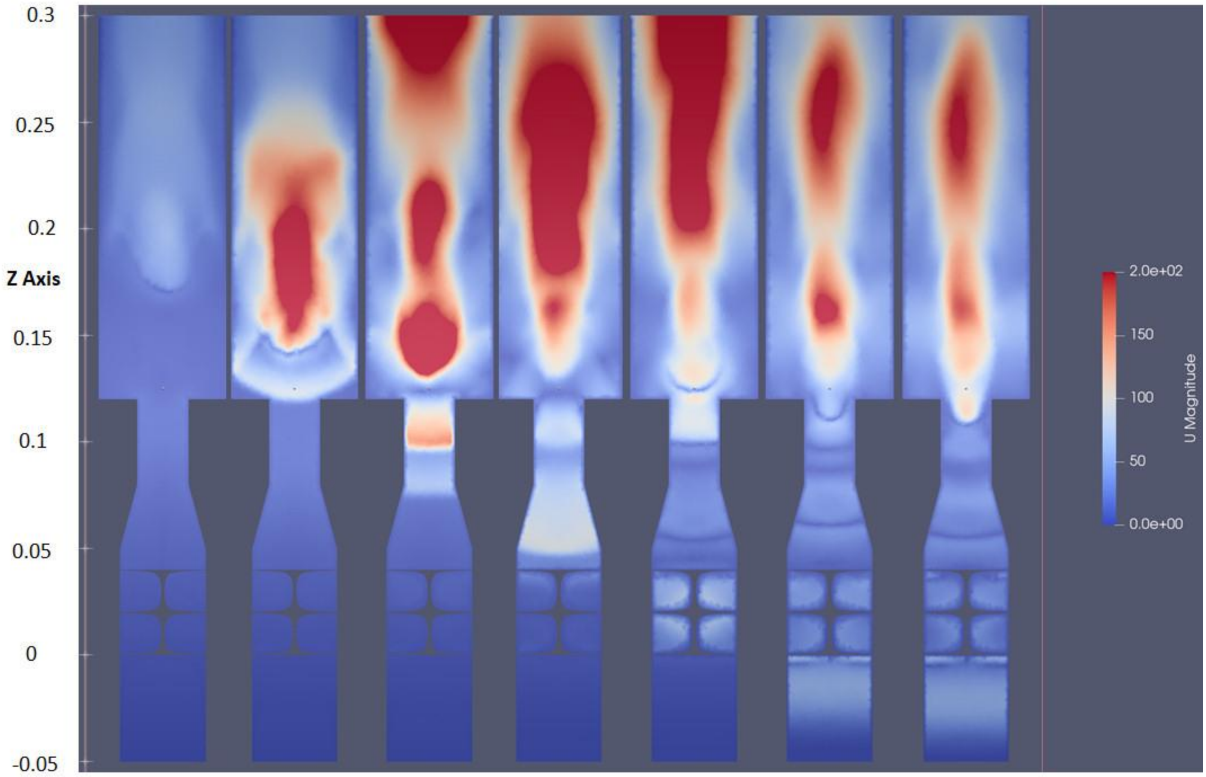


Figure 9: *Velocity profile of the flame performing a flashback over the time, computed with XiFoam for the case of premixed hydrogen at a thermal power of 5 kW and phi of 0.5.*

4.2 Experimental Setup

An early test campaign was carried out with premixed hydrogen. First, different hydrogen injection methods were tested resulting in a prioritised premixed variant. Then, experiments with thermo-acoustic excitation using Siren E were performed.

Hydrogen flames emit very little visible radiation and are essentially invisible in daylight. Besides the substantial IR radiation of a hydrogen flame, the radiation of excited OH* radicals dominates in the ultraviolet and visible range (around 310 nm) [9]. Due to this fact, a UV camera type ARTCAM-2020UV-USB3 was used for flame monitoring. Furthermore, CBOne's Emootion probe was applied as additional measurement to optically capture the effect of a thermo-acoustic excitation by using the fast-responding optical sensors. Figure 10 shows the optical response of the Emootion probe to a premixed hydrogen flame alternately turned off and on. The combustion was carried out open in daylight and the flame was limited only by the glass liner. The optical sensors of the Emootion probe are equipped with optical filters in the RGB range. The best response to the premixed hydrogen flame is provided by the sensor without optical filter, followed by the sensor in the red domain. The acoustic response was measured via a microphone, situated on the level of the air inlet.

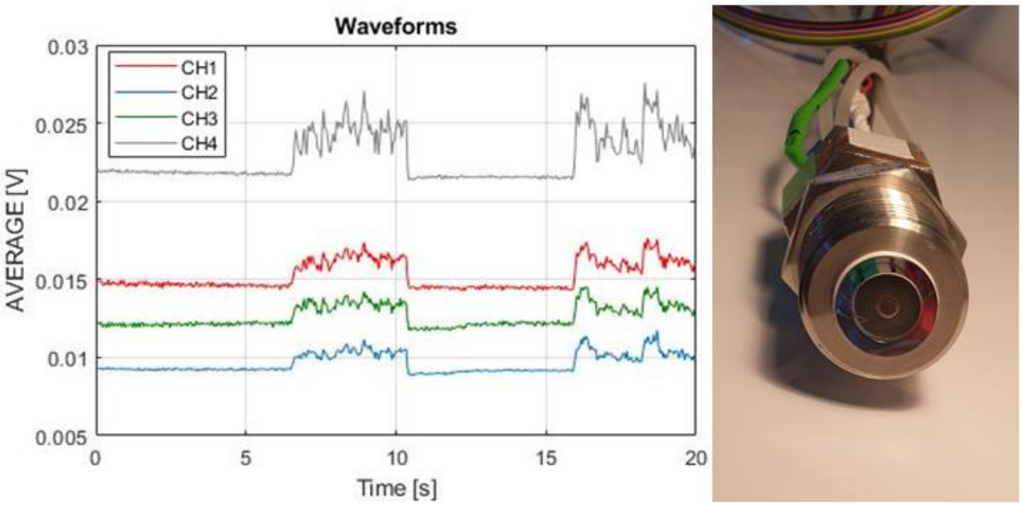
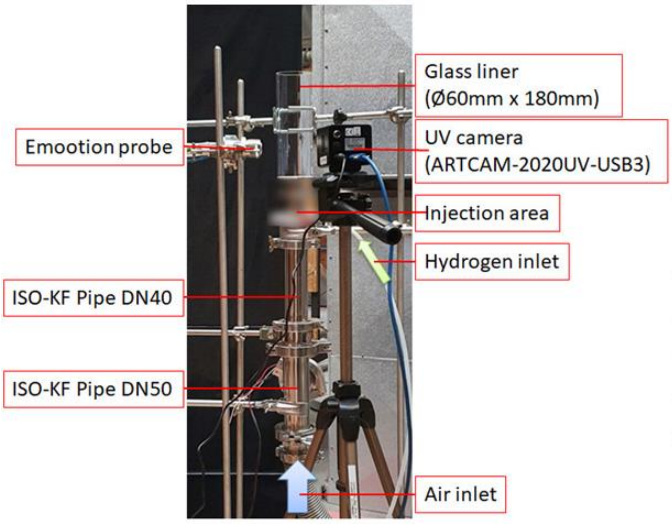


Figure 10: *Optical response of CBOne's Emootion probe (right), which combines optical and acoustic measurement techniques, to a premixed hydrogen flame alternately turned off and on without the impact of combustor walls.*

The combustion experiments were performed under atmospheric conditions on a modular design representing the pilot stage of the three-staged burner, visible in Figure 11 left. This design was chosen for the experiments to ensure a quick and easy exchange of the hydrogen injection modules and a quick and easy connection of the siren. The modular assembly consists mainly out of ISO-KF standard parts and is oriented upwards. A characterisation and experiments with a similar assembly can be found in [8]. The modular design was derived from this study. On the top, a glass liner with diameter 60 mm and length of 180 mm (optional 120 mm) is situated. Compressed air is fed into the modular system from below and is introduced with a swirl into the glass liner. The injection of hydrogen takes place in the last quarter of the assembly.

Different hydrogen injection methods were investigated for their ability to generate a detached, swirl-stabilised premixed flame, their tendency to flashback and the behaviour of the flame depending on them at thermo-acoustic excitation. In the table on the right side of Figure 11 the operating point domain, the mass flow ranges and the generated thermal power are displayed. The first injection configuration tested was a conventional hydrogen co-flow jet injector, which mainly results in a very loud, partially premixed flame. The flame appeared spherical with an expansion up to 20 mm in diameter. A high intensity of the flame radiation could be observed. This test session was performed at ϕ = 0.3 with hydrogen mass flow of 0.036 g/s and air mass flow of 4.2 g/s. The second configuration represented a basic multi point injection ring with an observed elevated tendency to flashback. Based on the observations of the conventional hydrogen injection types, a novel method especially designed for lean premixing of hydrogen was developed and tested. Due to a patent filing process, more specific details about the two resulting configurations out of the novel method cannot be disclosed at this moment. However, to be mentioned, Configuration 3 (novel) had the widest range in equivalence ratio from ϕ =0.15−0.4, while configuration 4 (novel) achieved the lowest equivalence ratio with stable combustion at ϕ =0.07. Initial combustion tests with thermo-acoustic excitation by a loudspeaker were carried out with all 4 configurations, with the best performance obtained by injection type 3 (novel). That’s why all following experiments were performed with this hydrogen injection module.



DESIGNATION	UNIT	VALUE
Thermal power range	[kW]	1.3 - 7.5
Equivalence ratio range	[-]	0.07 - 0.5
Air mass flow range	[g/s]	3 - 6.6
Hydrogen mass flow range	[g/s]	0.011 - 0.06
Standard operating point - air	[g/s]	4.46
Standard operating point - hydrogen	[g/s]	0.0266
Standard equivalence ratio	[-]	0.2

Figure 11: *Left: The modular test setup monitored via UV-camera and Emootion probe. Right: Operating point ranges of the premixed hydrogen experiments in the very lean domain.*

For investigating the thermo-acoustic effect on the lean premixed hydrogen flame, the whole combustion air was led over the Siren E. The method for detecting eigenfrequencies presented above was carried out on the modular assembly. A dominant frequency peak was observed at 687 Hz. This frequency was closer investigated and the resulting data is discussed in the following section.

5 Early Results

5.1 Experiments

A more detailed analysis of the thermo-acoustic flame behaviour at 687 Hz was carried using Siren E. In Figure 12 a lean premixed hydrogen flame at standard operating point (defined in Figure 11 right) without excitation (left) and the same hydrogen flame excited with 687 Hz (right) are compared. The flame shape and the radiation intensity are represented via the recorded data of the UV camera on the top. An unfiltered spectral analysis was performed with the optical gathered data from the Emootion probe and is displayed below the UV camera data.

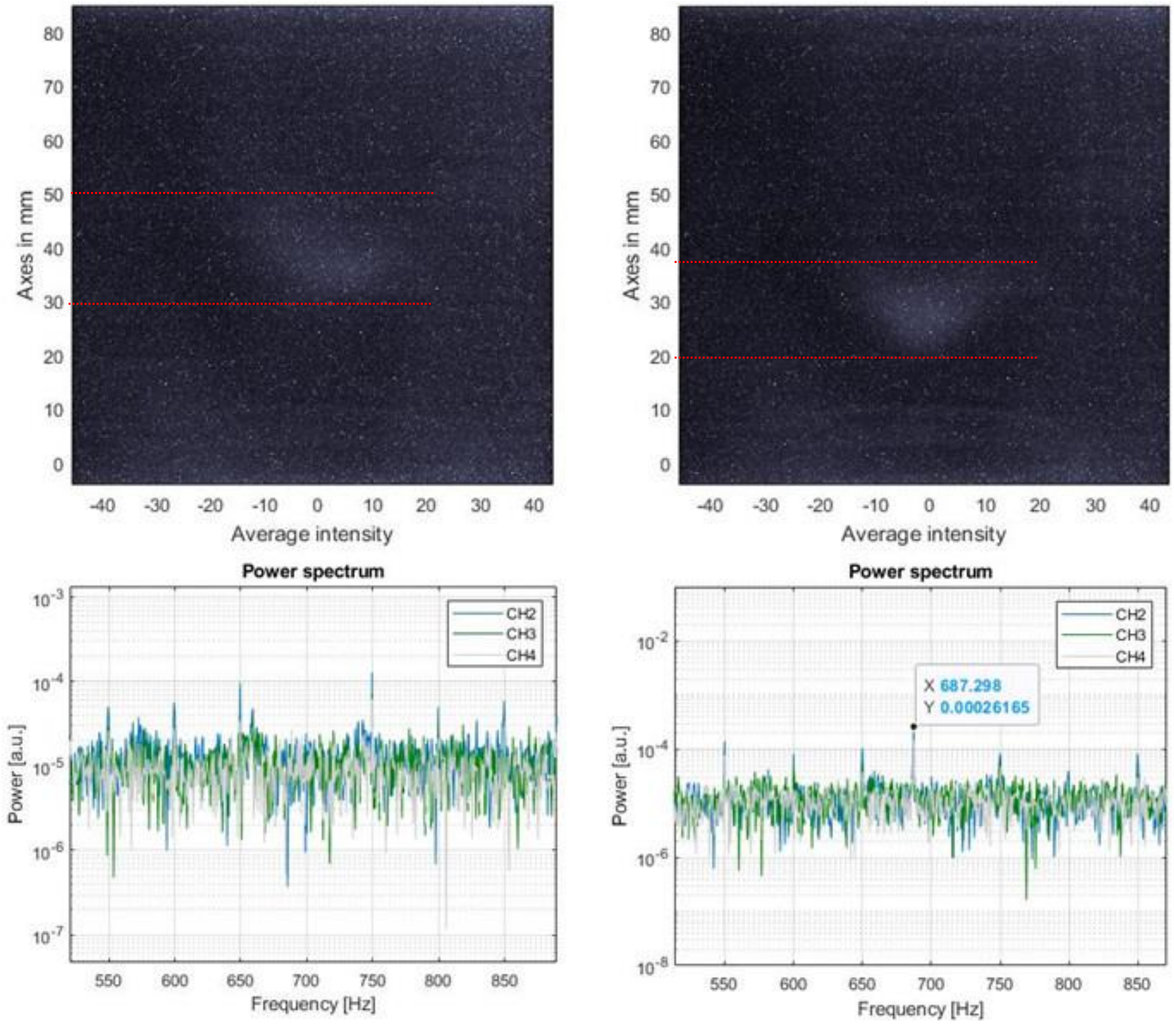


Figure 12: *Left: Reference premixed hydrogen flame at a certain operating point without excitation (nearly visible). Right: Premixed hydrogen flame at the same operating point excited at 687 Hz using the siren. Top: Recorded data of the UV camera. Bottom: Measured data of the optical sensors of the Emootion probe with corresponding spectral analysis.*

The unexcited flame on the left side is barely visible in the UV domain and is located in the region between 30 mm to 50 mm away from the top plate (Position 0 mm). On the right side, the radiation intensity of the flame increased leading to a clearly visible flame at UV domain. Compared to the unexcited case, a clear downward shift of the flame position on the right side is observed. The excited flame is situated in the region between 20 mm to 35 mm.

Furthermore, the flame shape changed by having a V-shaped, compact flame, when thermo-acoustically excited. The spectral analysis of the optical sensor data shows that the flame pulsates in time with the thermo-acoustic excitation, revealing a distinct peak in the spectrum.

6 Conclusion and Perspectives

This paper introduces an innovative combustion concept, intended for the complete and low-NO_x combustion of non-carbon eco-fuels based on a thermo-acoustically excited, forced flame behaviour. A novel method for premixing hydrogen including two different types of settings was mentioned and tested successfully. These premixing modules have to operate safely under ultra-lean conditions ($\phi \leq 0.5$) and have to provide the desired auto-ignition temperature of the eco-fuels. The injection method proved to be effectively, resulting in a premixed, detached, swirl-stabilised flame.

The latest version of the Emootion probe was actually designed for the use with conventional fuels. The integrated photodiodes are especially suitable for applications from 380 nm to 1100 nm. The dominant radiation in the UV range at 310 nm is outside the detectable range of the probe. However, the enormous IR radiation is measured by the probe, which gave good results. Considering further experiments with combustor, the response of the probe needs to be investigated in more detail, as results can be distorted by thermal radiation (IR-radiation) from the combustor walls. Subsequently, when needed, the Emootion probe will be equipped with optical sensors sensitive to the UV range.

Early results with the novel premixing module showed a significant effect on a detached, swirl-stabilised hydrogen flame when excited with a determined eigenfrequency. There, a clear change in flame shape from crescent-shaped to V-shaped at simultaneously increased radiation intensity was observed, implying an augmentation of the flame’s energy density. In addition, the flame position was shifted downwards towards the top plate.

By now knowing that there is an impact on a premixed hydrogen flame when performing thermo-acoustic pulsation, the next step is to investigate in more detail what effect pulsation has on combustion stability and combustion quality. Future works will report on correlation between pulsation and combustion temperature, NO_x formation and combustion range extension. In the near future initial combustion tests performed with premixed ammonia and hydrogen-powered pilot stage will be carried out with additional safety measures. An isolated work area with integrated air extraction for combustion experiments with toxic reactants has already been produced. The air extraction will be directly connected to the flue gas treatment sectors. Prior to that, further numerical computations will be performed with reacting flows including hydrogen and ammonia. The results will be used to determine optimum operating points for hydrogen and ammonia combustion and to make an initial statement about the amount of nitrogen oxide emissions.

7 Acknowledgment

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