Advanced Methods for Gas-Prechamber Combustion Research and Model Development

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Abstract

Lean-burn gas engines aiming at low NOx emissions require large ignition energy and distributed ignition sources in order to ignite and consume the lean premixed main charge, aiming to maximize efficiency and reduce unburned hydrocarbon emissions. A widely used technology in these engines is prechamber ignition systems, where the ignition source is located in a separate small volume, connected to the main chamber via small orifices. Research in the field of prechamber combustion has been extensive in the past years, with work done both in experimental and numerical investigations. In the design of prechamber ignition systems, commercial as well as research computational fluid dynamics codes are often used. Nevertheless, detailed understanding of heat transfer and turbulent jet ignition and combustion phenomena are still not well understood. The development of combustion and heat transfer models to be applied in such codes is often hampered by unavailability of reliable and detailed data. Recent advances in numerical modeling and increases in computational power and availability have allowed the use of direct numerical simulations (DNS) for the retrieval of reliable and detailed data for the improvement of physical and chemical process understanding of such complex phenomena. This paper presents a hierarchical approach for combustion research and model development, with particular focus on prechamber combustion. This approach combines experimental and numerical work ranging from optical diagnostics in generic setups to metal engine measurements and from generic DNS calculations and real-geometry 3D-CFD, to phenomenological 0D models.

1. INTRODUCTION

Lean-burn natural gas engines offer significant advantages in terms of engine efficiency, CO_2 emissions and other legislated gaseous and particulate emissions compared to other gas or liquid-fueled equivalents. Engine efficiency can be superior compared to stoichiometric-operated gas engines due to the reduced heat losses during combustion, reduced exhaust enthalpy losses, higher compression specific heat ratio, reduced throttling losses (particularly in part-load operation) and the ability to increase the engine compression ratio due to the lower self-ignition propensity of lean mixtures (lower knocking propensity) [1-7]. In addition, the low C/H ratio of natural gas (with its main component being methane) compared to liquid hydrocarbons results in low specific CO_2 emissions. Nevertheless, lean-burn gas engines also present significant drawbacks, with the most important being the lean flammability limit, which results in high cyclic variations and high engine-out unburned hydrocarbon (UHC) emissions [4, 8-11]. In addition, compared to diesel engines, premixed gas engines show limitations in compression ratio and power density due to the occurrence of end-gas autoignition (knocking).

Many of the drawbacks of lean-burn gas engines can be traced back to the ignition system employed and the combustion speed/duration. High-energy ignition systems which offer a successful, repeatable ignition and result in lower cyclic variations and fast combustion have been described in the literature [8]. These include the use of multiple spark plugs in the cylinder, corona ignition systems and prechamber ignition systems amongst others. The major advantage of prechamber ignition systems is the introduction of higher ignition energy which is distributed within the main chamber through ignition/reaction/flame jets. These distributed ignition points increase the combustion speed, reducing UHC emissions and knocking, and allowing the combustion of leaner mixtures and higher power densities [1]. Within the prechamber, controlled turbulence generation in the prechamber resulting from the inflow-jets formed from the piston movement, as well as the protection of the spark location from the large scale turbulent flow in the main chamber, allow the reduction of the cyclic variations even at very lean conditions [4]. As a result of the above, engines operating with $\lambda>2$, and presenting very low NOx emissions and high efficiency using prechamber ignition systems can be found in the literature, both for automotive and power generation applications [1, 5, 6, 12]. A description of multiple high energy ignition systems and different designs and concepts of prechambers can be found in a two review papers by Dale et al. [8] and Toulson et al. [4].

In an effort to comprehend the individual, complex physico-chemical processes which are involved in a prechamber ignition system, multiple investigations have focused on optical diagnostics. Investigations in generic, simplified geometries over the past 40 years have allowed the identification of different combustion phenomena for jet ignition using prechambers. Gussak et al. [13, 14] studied the effect of prechamber volume-to-nozzle area ratio, as well as the effect of nozzle orientation on subsequent combustion. Yamaguchi et al. [15] carried out a similar study in a constant-volume divided combustion chamber, where different combustion regimes were identified depending on the structure of the exiting torch and the subsequence burning process. More recently, Biswas et al. [16] used optical diagnostics in a divided chamber, and identified two distinct combustion regimes which depend on mixture reactivity and flow characteristics of the exiting jet. Studies in optically accessible engines and engine-like geometries try to also capture the prechamber-internal turbulence and mixture generation, while achieving engine-relevant thermodynamic conditions. Investigations in a rapid compression machine using generic prechamber geometries have been conducted, which provide insight into the combustion and the effects on nozzle size [17]. Other investigators have used commercial prechamber geometries in generic, engine-like test-rigs or optically accessible engines in order to study the full effects of turbulence generation in the prechamber and subsequent effects on combustion [3, 18-20].

In numerous prechamber experimental studies, the researchers have also used Computational Fluid Dynamics (CFD) simulations in order to obtain complementary information [17, 21-24]. CFD simulations can provide detailed local information concerning thermochemical and turbulence conditions, which are unattainable using conventional measurement techniques or in measurements in realistic geometries. Despite the extensive use of CFD in many industrial and academic investigations, as well as in prechamber design optimization efforts, the predictive capabilities of current commercial CFD codes may be limited, in particular pertaining to turbulence (affecting mixing and combustion) and wall heat transfer modeling, as well as the description of the combustion. In particular concerning prechamber torch ignition, there still exist multiple unanswered questions, particularly pertaining to flame and jet-wall interactions, main chamber ignition and combustion fundamentals, as well as the ability of simplified combustion models used in commercial CFD software to adequately describe the processes involved. In addition, the description/modeling of wall heat transfer, which is particularly important in prechamber studies due to the high surface to volume ratio of the prechamber, is also a cause of concern for commercial CFD codes.

This paper presents the research activities conducted at the Aerothermochemistry and Combustion Systems Laboratory (LAV) in a concurrent fashion to try and tackle some of the unknowns of prechamber ignition systems. The paper starts with the description of the LAV hierarchical approach, followed by a more detailed overview of the activities currently conducted in the area of prechamber combustion. This is followed by the conclusions.

2. THE LAV HIERARCHICAL APPROACH

The LAV approach is a concentrated effort from multiple research areas which try to identify and comprehend relevant processes using modern experimental and computational tools. The so-called “Hierarchical Approach” has on the one side the near-application experiments and 0-D simulations, which forms a connection to the commercial engine design and development. On the other side this approach extends to increasingly simplified and generic experiments and detailed simulations (including reactive Direct Numerical Simulations-DNS), which allow the accurate description of individual processes. The final aim of the hierarchical approach is to close the cycle from application to fundamentals back to application. This is effectively done through a dual approach:

- To provide phenomenological understanding of processes involved in order to assist in the empirical design and simplified/0D modeling for design and control purposes
- To provide high-fidelity data for combustion model development at near-engine conditions, which will be used at a later stage for engine design purposes

The approach as a whole is depicted graphically in Figure 1 below. From left to right, the approaches are ordered with decreasing relevance or proximity to the application, but with increasing data completeness.

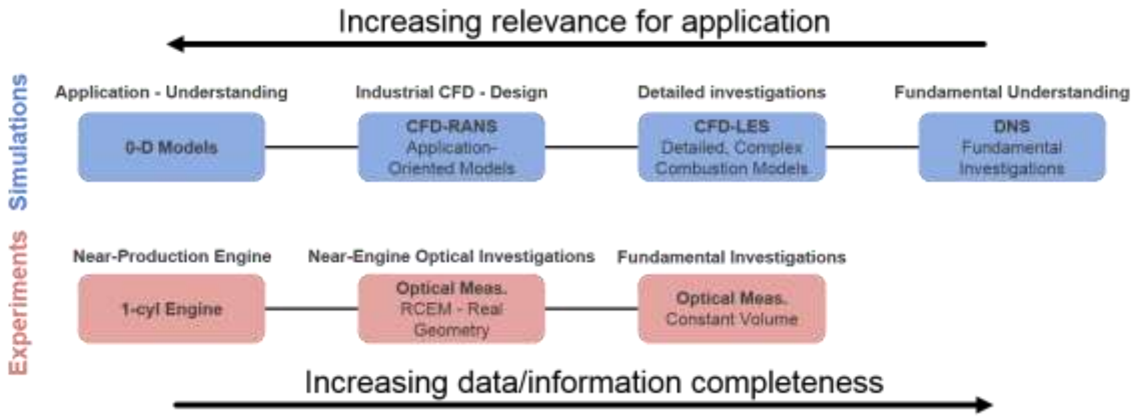

Figure 1: The LAV hierarchical approach

On the left of the figure lie approaches which are close to the application: On the simulation side we have the application-oriented 0D/1D phenomenological models which are used for engine thermodynamic design and engine parameter optimization purposes [25]. In cases where the models can be very much simplified, with reduction of the computational requirements (usually coming at the expense of model predictive capability and increase in tuning parameters), the models can also be used for on-line engine control purposes [26-29]. On the experimental side, multi-cylinder or 1-cylinder near production engines can be used, with 1-cylinder engines usually preferred due to the wider range of operation thanks mainly to external air-path control systems. The results from the engines in terms of spatial resolution are limited (only time-resolved pressure and usually cycle-averaged temperature and time-averaged emission concentration measurements are available), but in combination with the 0D/1D models, they can provide significant insights into the relevant conditions for engine combustion and the overall engine performance and emission production processes.

In order to extract spatial information from the engine flow and combustion processes, 3D CFD and optical diagnostics in engine-like test-rigs such as the Rapid-Compression-Expansion Machine (RCEM) are used, which are depicted in the second column in Figure 1. The 3-D CFD is usually in this case limited to Reynolds-Averaged Navier Stokes (RANS) calculations, where time-averaged equations of motion are used due to the limited computational resources available for the full geometry calculations. These calculations are often combined with a level-set approach for premixed combustion modelling – such as e.g. the G-equation model – where the flame front is tracked through a transport equation including a turbulent flame speed closure (e.g. [30]). Despite the significant advantages these approaches present in terms of computational resources and required resolution, significant limitations in terms of combustion predictions are present, in particular when dealing with the conditions found in turbulent jet ignition systems (broken reaction zones regime, possible local flame extinction and re-ignition, which are not accounted in the combustion modelling framework) [31]. The combination of CFD and engine experimental work has provided in the past significant insights into engine processes, which has been effectively translated into improved description of processes in phenomenological models for different applications [32-34]. Using optical diagnostics, spatial distributions of specific species can be tracked using passive or active optical methods, providing significant information in real or near-engine geometries (e.g. [3, 35-37]). This information can aid in the validation of combustion models as well as for the phenomenological understanding of the processes.

As mentioned previously, despite the insights provided using metal engine and optical measurements in combination with 0-D and 3-D RANS calculations, the significant limitations in flow and combustion modelling and available measurements often dictate the necessity for more detailed investigations. In the simulations, a more accurate description of turbulence can be attained using Large-Eddy Simulation (LES), where the large scales flow features are resolved and only the small scale turbulent motions need to be modelled.

For combustion modelling, LES still requires a model for the evaluation of the chemical reaction rate at the sub-grid scales in engine-relevant conditions (high pressures lead to very small flame thicknesses of the order of 10-50 μm), but the models used are typically more complex, with better description of the relevant processes. On the other end, DNS resolves all spatial and temporal scales of the flow and the flame and no model is required (apart from the common practice of employing increasingly mildly reduced chemical mechanisms for hydrocarbon fuels such as CH_4). Due to the flow and flame resolution constraints leading to high computational costs, DNS is typically limited to low to moderate Reynolds numbers and pressures. Thus DNS cannot be used for real turbulent combustion problems such as the ones encountered in engines. Nevertheless they have been used for investigations of flow in engine-like geometries (e.g. [38-40]) and can be used to provide data for simplified geometries and limited non-dimensional number ranges [41, 42]. Pitsch and Trisjono [41] in particular provide a detailed description of how data from simplified, tractable DNS calculations can be used for combustion model development in a systematic approach. In addition to detailed simulations, fundamental investigations of processes can also take place in generic, often constant-volume test rigs, which allow better optical access and often better control of boundary conditions compared to engine-like optical test-rigs.

Overall, the hierarchical approach is used in LAV to provide detailed information concerning engine processes. The flow of information depicted in Figure 2 starts from the near-application side, where the approaches often employed by the industry but also in academia are used to understand the conditions of interest for engine applications. The detailed understanding and the precise spatially and temporally resolved data then flows in the opposite direction, stemming from the simplified, tractable simulations and experiments, providing detailed data for model development and process understanding. This latter part is usually restricted to academic work, due to the significant computational requirements and the difficulty of result interpretation. In this process the choice of problem simplification is of particular importance since it will dictate the applicability and relevance of the results in the real applications.

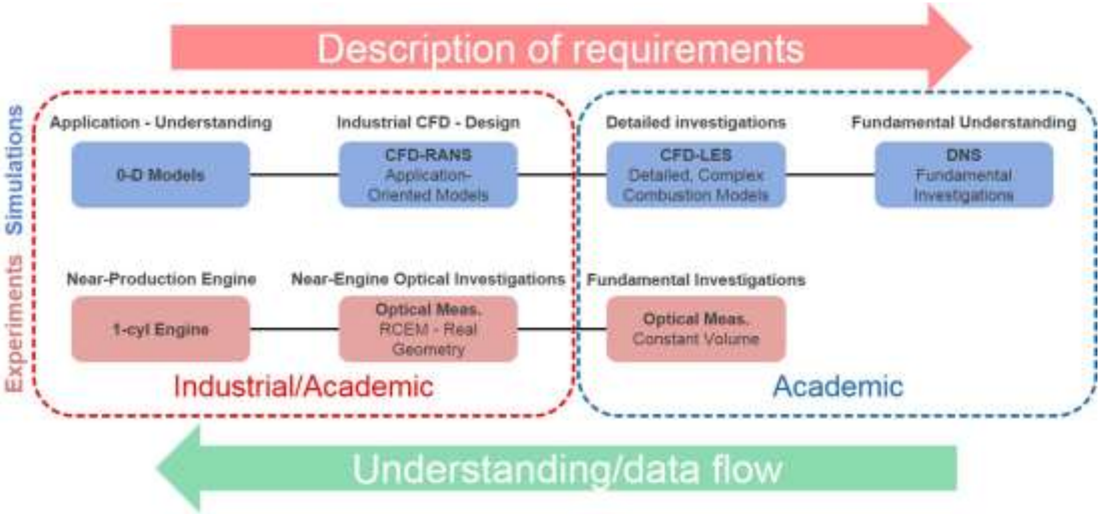

Figure 2: The LAV hierarchical approach: data flow

3. HIERARCHICAL APPROACH FOR PRECHAMBER COMBUSTION RESEARCH

As described in the introduction, prechamber engine combustion is of particular interest for modern, lean-burn gas engines. It also involves numerous processes which are not well understood, particularly pertaining to the turbulent jet ignition which results from the jets formed into the main combustion chamber. For this reason the hierarchical approach is currently used in order to develop more accurate models for future gas engines using prechamber ignition systems. This section will start by providing a brief description of the relevant prechamber combustion processes and presenting the most significant research questions. This will be followed by a description of the approaches used at LAV covering the whole chain of the hierarchical approach.

3.1. Description of Prechamber Combustion Processes

The sequence of the prechamber combustion is presented graphically in Figure 3. Following a combustion cycle, burned residual gases remain in the prechamber. In the case of a scavenged prechamber, sometime between the intake valve opening and the ignition during the compression stroke a small amount of fuel is injected into the prechamber which will displace some of these residual gases. This injection will create a richer mixture in the prechamber, which will ideally result in a more reactive mixture and higher energy content of the prechamber jets. The subsequent compression stroke introduces leaner mixture from the main chamber, which mix with the residuals and the additional fuel in the case of a scavenged prechamber. The incoming flow during compression, which is caused by the work done on the main chamber gases by the piston, will result in repeatable turbulence generation in the prechamber which is key for the high turbulent flame speed after ignition. During this process, turbulence, mixing and heat transfer are very important, since these will dictate the reactivity of the mixture and the flame propagation speed. The spatial distribution of the mixture at the timing of the spark is of particular importance, and is a main design parameter for engine prechambers.

Following the ignition of the mixture in the prechamber, the subsequent combustion is of particular importance since it leads to the pressure increase which will drive the creation of the prechamber jets. In the early stages of combustion the heat released will result in a pressure increase and cold, unburned jets will be formed into the main chamber. The jet velocity is a function of the heat release rate compared to the prechamber volume and the nozzle (effective) area. During this time, flame-wall interactions are of particular importance due to the small volume to area ratio of the prechamber. Relatively small errors in the estimation of the combustion rate in the prechamber will result in relatively large errors in the prediction of the jet velocity, since all thermochemical and combustion parameters are very important during this stage. Once the flame reaches the prechamber nozzles, reactive/burned gasses are forced into the main chamber, in the wake of the turbulence which is created by the cold jets. During the exit of the burned gases, the flame might be quenched because of heat transfer to the nozzle walls, flame straining upon exit and mixing with the cold unburned mixture. Ultimately, the hot burned/reactive gases will ignite the main chamber mixture, leading to a turbulent flame propagation which consumes all the main chamber charge.

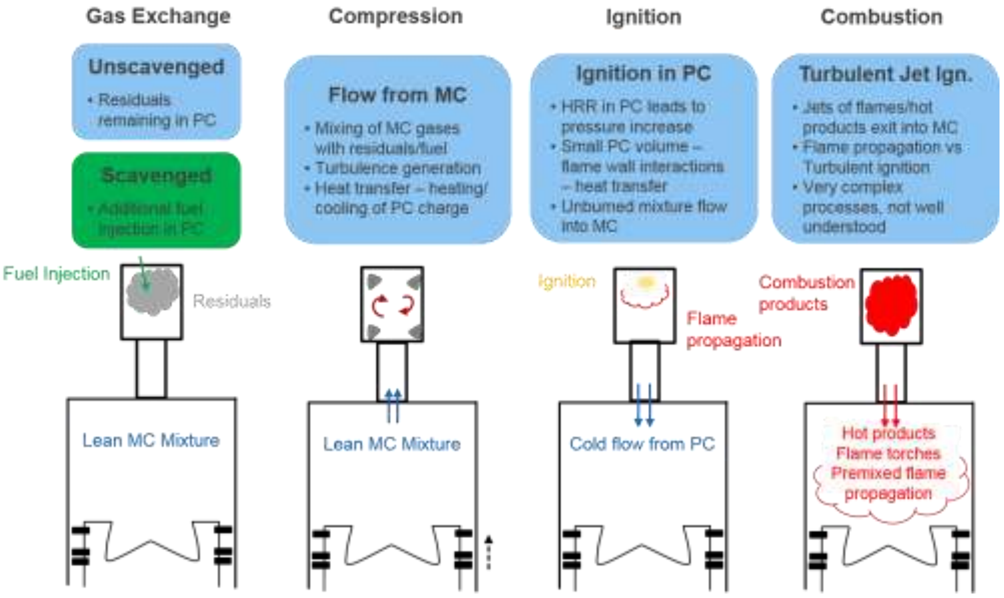

Figure 3: Prechamber combustion processes

Even though the processes leading to the jet creation and subsequent combustion have been studied extensively, there are numerous issues which are still not well understood. In particular, the main points are:

- Turbulence generation and dissipation in the PC before ignition, and its effects on cyclic variation of combustion
- Air-fuel mixing (scavenged prechamber) or mixture-residuals mixing (unscavenged prechamber), the resulting fuel spatial distribution and the effects on cyclic variation of combustion
- Wall heat transfer during the abovementioned processes, and the resulting thermodynamic conditions and temperature distribution of the prechamber mixture
- Ignition and flame propagation in the prechamber, and in particular flame-wall interactions
- Turbulent jet ignition of the main chamber charge, and in particular the nature of the jet ignition/flame propagation depending on the jet and mixture characteristics, under engine conditions

The abovementioned points are studied using the experimental and simulation tools at LAV.

3.2. Single Cylinder Engine Experiments and 0-D/1-D Simulations

A single-cylinder, heavy-duty lean burn gas engine is installed in the engine test laboratory at ETH Zurich. The engine was provided by Liebherr Machines Bulle (LMB) as part of a project co-funded by the Swiss Commission for Technology and Innovation (CTI-KTI) and Liebherr Machines Bulle SA (project No. 17565.1 PFEN-IW).

The test facility is equipped with intake and exhaust conditioning systems (intake temperature and pressure control, exhaust pressure control), in-cylinder and prechamber pressure measurement and exhaust gas analyzers. Fuels of different compositions can be tested at the facility, and a process chromatograph (Siemens MicroSAM Process Gas Chromatograph) which allows the measurement of the detailed gas composition in the fuel line. The 1-cyl engine specifications in its initial configuration are presented in Table 1. The engine configuration can be changed using different liners and piston/connecting rod, to change the engine bore and stroke. A view of the test facility is shown in Figure 4.

Table 1: Single cylinder LMB engine specifications

Displacement Volume	1.99 L/Cyl
No. of Cylinders	1
Stroke	150 mm
Bore	130 mm
Number of Valves	4
Rated Speed	1500 rpm (50Hz) / 1800 rpm (60Hz)

Figure 4: View of the LMB single cylinder engine test facility

The single-cylinder engine is used in order to identify the effects of different prechamber designs on combustion, engine performance and exhaust emissions (particularly NO_x and UHC). In combination with the 0-D models, it is possible to identify the operating conditions and output relevant quantities, including estimations of the local conditions in the prechamber as they change with changes in operating and design parameters, which help with the understanding of the observed performance and emissions trends. The pressure measurements in the pre- and main chambers are used for the calculation of the heat release rates in the respective chambers, which can provide insights into the effects of different operating and design parameters on combustion. The measurements and 0-D models are also used to provide the boundary conditions for the CFD-RANS investigations. Finally, the engine measurements provide the ideal platform for studies on cyclic variations and other statistical processes (e.g. knocking) which are important for engine design and control.

3.3. Optical Diagnostics and 3-D RANS Simulations

Optical diagnostics in the LAV Rapid Compression Expansion Machine are used to study the effects of different realistic prechamber geometries and mixture thermochemical conditions on the main chamber combustion. The RCEM allows optical access into the main chamber through multiple windows, where the OH* chemiluminescence and Schlieren imaging techniques are used.

A schematic of the RCEM can be found in Figure 5. The main optical access is parallel to the piston motion through the quartz piston insert and allows a view of a 52mm diameter window out of the 84mm cylinder bore. An additional optical access from the cylinder liner around the cylinder head surface allows Schlieren imaging of the exiting jets in parallel with the OH* Chemiluminescence, which enables the distinction between the cold jet exit and the exit of the hot combustion products and subsequent ignition of the main chamber charge. A exemplary sequence of OH* chemiluminescence images from the piston access during combustion using a scavenged prechamber can be seen in Figure 6 (taken from [43]).

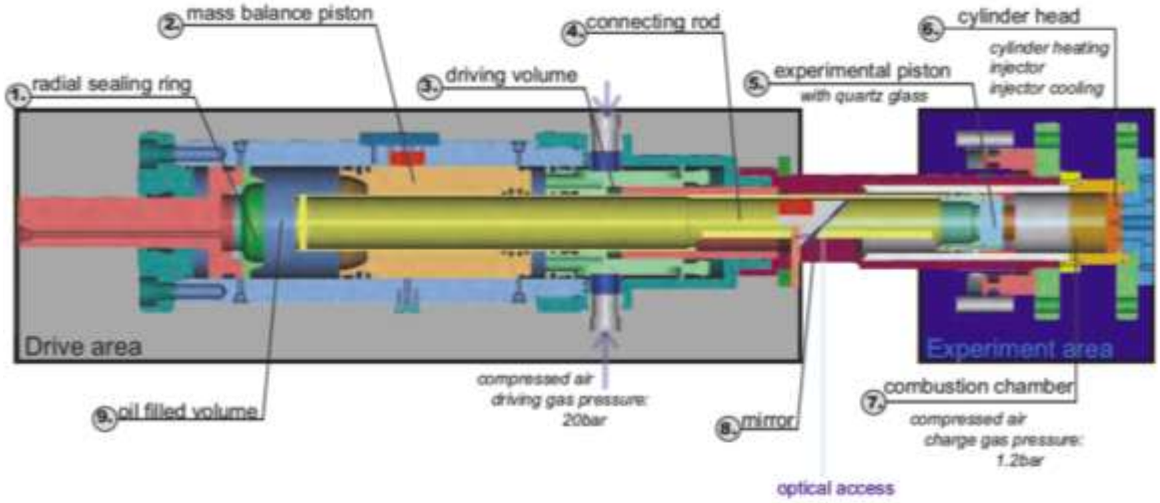

Figure 5: Schematic of the Rapid Compression Expansion Machine [43]

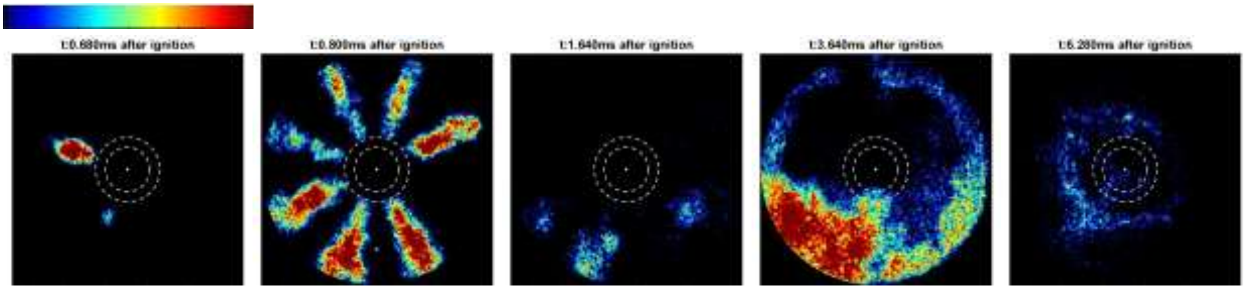

Figure 6: Sequence of OH* chemiluminescence images at different moments after the ignition signal for a scavenged prechamber, showing the flame- / radicals- jets exiting from the prechamber nozzles and the combustion inside the main chamber. The scale of the OH* signal is given on the top-left of the figure, showing increasing intensity from left to right [43].

The advantage of the optical data in comparison with the pressure-only data available from a metal engine is the additional validation opportunities for model development. The optical data in the main chamber allows the direct comparison of the optical images with the results from 3-D CFD, as is shown in Figure 7. The two images show the prechamber reactive jets from the experiment (OH* Chemiluminescence) and the simulation (integrated reaction rate in the line of sight, equivalent to the OH* concentration) exiting and propagating into the main chamber, at similar points in time. In addition, a comparison of characteristic data such as jet exit timing, jet penetration velocity and cyclic variations can be used to validate the simulations and provide additional understanding of the phenomena observed in the engine, under similar conditions.

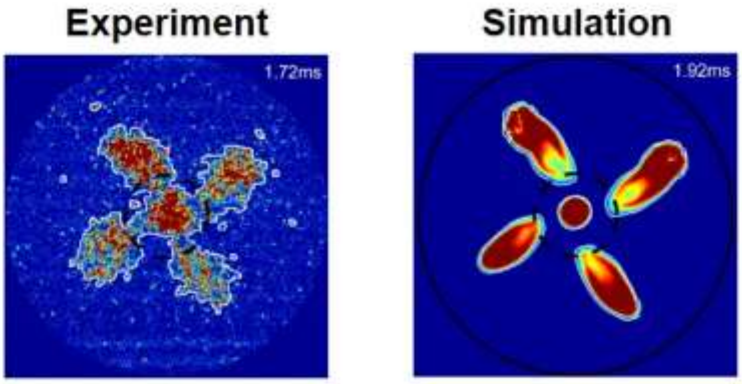

Figure 7: Comparison of the measured OH* chemiluminescence signal with the simulated integrated reaction rate in the line of sight (G. Xu)

3.4. Questions Arising from Near-Application Experiments and Simulations

Despite the significant information which can be drawn from the combination of engine and near-engine optical experiments and simulations, there still exist limitations in the approaches as has been highlighted in section 2. The uncertainties for the particular application of prechamber combustion can be grouped in two overarching areas, which are described in the points below:

- Major uncertainties from the optical investigations and the corresponding RANS simulations:
  - What are the local thermochemical conditions in the prechamber at spark timing, and how are these influenced by the turbulence and heat transfer models used? Are the models used accurate and how does their accuracy vary depending on the conditions?
  - How will the uncertainties and cyclic variations in turbulence/mixture affect the resulting combustion in the prechamber and the main chamber?
- Major uncertainties in combustion modeling:
  - How valid is the level-set flame front tracking model for turbulent jet ignition? Under which conditions does it underperform/fail?
  - What is the composition of the gases exiting the prechamber and how does this composition affect main chamber combustion?
  - How much does flame quenching due to wall heat transfer in the nozzle/flame stretch/turbulent mixing play a role in the combustion regime?

The abovementioned uncertainties are attempted to be resolved in LAV using a purpose-built generic test-rig and more detailed simulations under simplified conditions in order to isolate and quantify some of the phenomena involved.

3.5. Generic Optical Prechamber Experiments

In order to gain more insight into the in-prechamber processes and the resulting main chamber turbulent jet ignition, a purpose-built test rig will be used. This is constructed around an optically-accessible prechamber (OPC, shown in Figure 8), which has additional accesses for pressure measurement and fuel/mixture injection. The prechamber is designed so that it can be mounted onto a heated constant volume high pressure and temperature combustion chamber, as well as on the RCEM. The former will allow the study of prechamber and main chamber combustion under various pressures, temperatures and prechamber/main chamber mixtures, while under quiescent, well-controlled conditions. The variability in pressure is of particular importance, since the flame thickness and the ratio of flame thickness to nozzle diameter is important for flame quenching considerations. The nozzle which connects the prechamber with the main chamber has been designed to be interchangeable, allowing diameters up to 4 mm. The prechamber has four optical accesses, two of which are into the whole prechamber volume, to allow passive and active optical diagnostics using a laser sheet. Investigations in the RCEM will allow the study of the effects of the piston motion on the mixture distribution and turbulence generation in the prechamber.

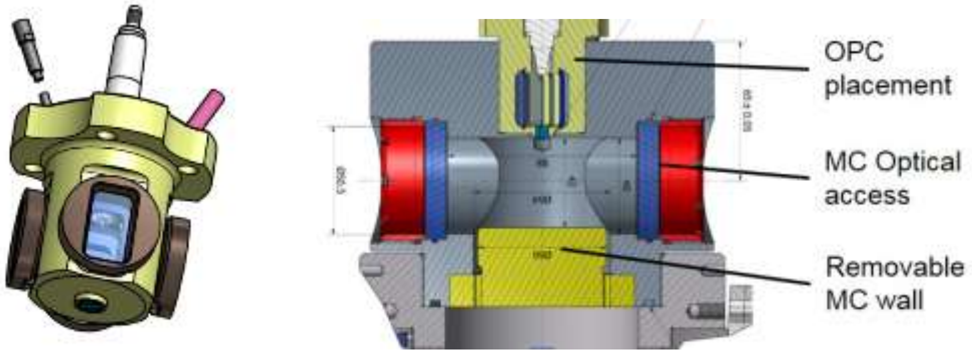

Figure 8: View of the generic optically accessible prechamber, with additional gas injection and variable nozzle geometry (left). OPC placement in the constant volume chamber, showing the main chamber optical access and the removable main chamber wall (right).

The variability of operating conditions which the optical prechamber allows is expected to provide, despite the simplicity and generic shape, significant insights into different turbulent jet ignition regimes. Nevertheless, careful considerations concerning the combination of the design and thermochemical settings to resemble engine operating conditions must be made.

3.6. Large Eddy Simulations

LES is used in order to provide more understanding into fuel-air mixing effects, as well as to provide insights into different combustion regimes through more detailed combustion modeling. For the mixture distribution, multiple LES realizations with slight, random perturbation of the boundary conditions can be used to study the effects of such perturbations on cyclic variations. Figure 9 portrays the fuel mass fraction distribution at spark timing for 20 single LES realizations in a scavenged prechamber with an imposed slight perturbation in the fuel injection rate, demonstrating the variability of the flow structures between runs. The contour of the spark plug is shown in the top-right of each figure, and one of the nozzles which connect to the main chamber can be seen in the bottom. Note that the same colour scale has been applied for every sub-figure. Investigations such as this one can be used to asses the observed cyclic variability of the combustion, which might be caused by such variations in mixture composition at spark timing. The data can also be used for validation of RANS simulations for the same imposed boundary conditions.

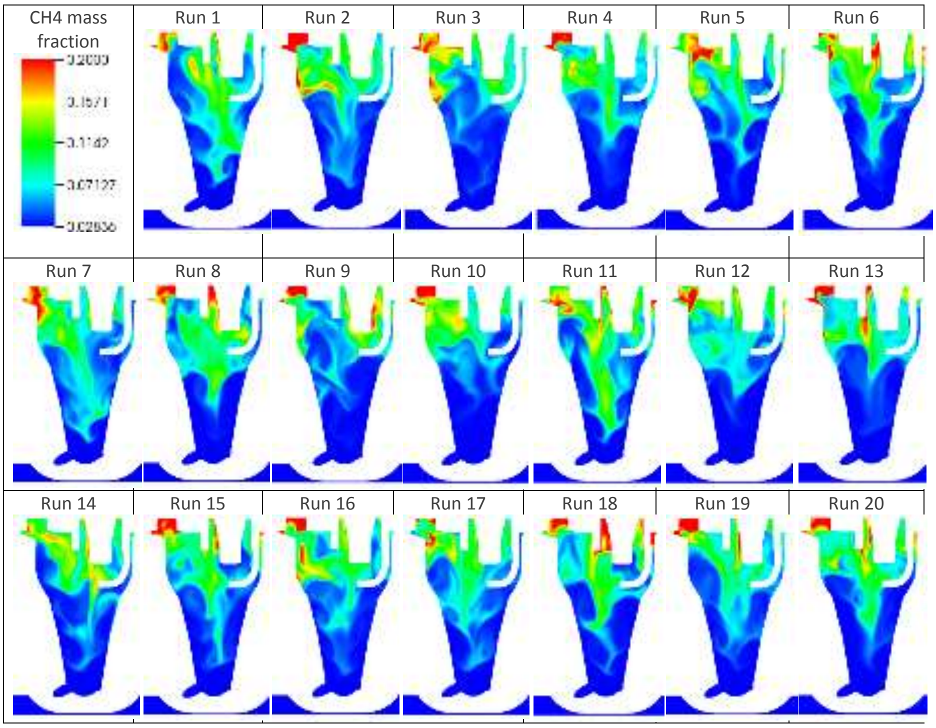

Figure 9: 20 single LES realizations depicting the fuel distribution at spark timing for a scavenged prechamber using a slight perturbation of the injection (M. Bolla)

In addition to cold-flow calculations, LES simulations coupled to detailed combustion models can be used to study combustion phenomena. Figure 10 shows the temperature distribution for the main chamber ignition through a turbulent jet resulting from the generic prechamber geometry with two different prechamber compositions and the same main chamber composition. From the figure it is apparent that, as expected, the exit of the burned gases is significantly delayed for the less reactive prechamber case (right). In addition, in the less reactive case the ignition takes place near the tip of the jet near the imposed main chamber wall. This effect is expected to be a combination of ignition and flame propagation and this transition is poorly understood in the literature. On the other hand, the jet of the more reactive case ignites the main chamber earlier before impinging the lower wall and ignition takes place more volumetrically.

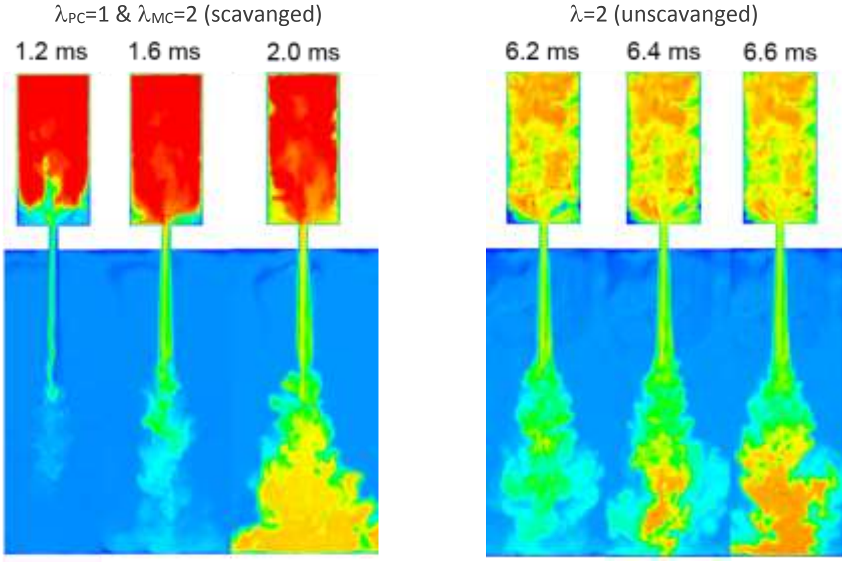

Figure 10: Prechamber jet ignition in the optically accessible prechamber geometry for two different prechamber mixtures and a constant main chamber mixture (M. Bolla)

In cases like the ones presented above, the value of the LES and detailed combustion modeling to accompany and extend the RANS approach with very simplified combustion models is clear. Nevertheless, there still exist uncertainties in the phenomenology of the combustion as well as the validity of the sub-grid turbulence and combustion modeling, in particular for multi-mode combustion. These can be addressed through well-designed pointed DNS numerical experiments, which are described in the following section.

3.7. Direct Numerical Simulations of Prechamber Combustion

Due to the significant limitations of DNS arising from the high computational cost, the calculations are limited in terms of non-dimensional number ranges which are practically possible. This in principle allows two different, complementary directions for the calculations.

On the one hand, laboratory-scale DNS can be used synergistically with targeted experiments to provide more spatial resolved quantities and insights into the phenomenology of prechamber combustion without the use of models. For this purpose the calculations are generally limited to low pressures, since the size of the computational domain and the required resolution of the flame for the validity of the combustion simulation required large flame thicknesses to make the calculations practically possible. The DNS code Nek5000 uses a scalable, open source, spectral element incompressible flow solver with the LAV plugin, implementing a low-Mach number reactive flow solver and high-order splitting for thermochemistry and flow equations.

Preliminary 2-D simulations using the Nek5000 code have shown already interesting results for the phenomenology of prechamber jet ignition in the optically-accessible prechamber volume. A parametric study consisting of ten different conditions (see Figures 11 and 12) has been carried out, where the following quantities have been varied: orifice diameter (d_j), unburned temperature (T_u), equivalence ratio in the main chamber (ϕ_{MC}), shape of orifice corners (sharp or smooth), initial velocity field (laminar and turbulent initial conditions). A detailed description of the conditions illustrated in the figures is provided in the respective captures. The figures illustrate the temperature distribution for the ten different test cases at selected times. The particular simulations revealed that the nozzle geometry is very important for the jet velocity and the turbulence and vorticity generation in the main chamber, while the main chamber ignition depends very much on the flow structure in the jet.

Further 2-D and eventually 3-D investigations will be performed in the near future for comparison with the optical prechamber experiments under the same boundary conditions. In addition to the lab-scale experiment, targeted higher-pressure DNS will be used for pointed 3-D CFD combustion model development and validation. The required flow and flame resolution as well as the respective importance of the main governing processes (e.g. mixing and chemical time and length scales), in addition to the limitation in Reynolds number and resulting separation of scales are of particular importance for these types of calculations so that they can be used for combustion model development. It is important to note that for an effective model validation the combustion model needs to be challenged by resolved DNS data. For example, this naturally leads to the requirement for higher simulation initial pressures in order to approach the flame thickness vs nozzle diameter ratios of realistic engine conditions. The detailed information which can be made available from such direct numerical simulations is instrumental for further model development.

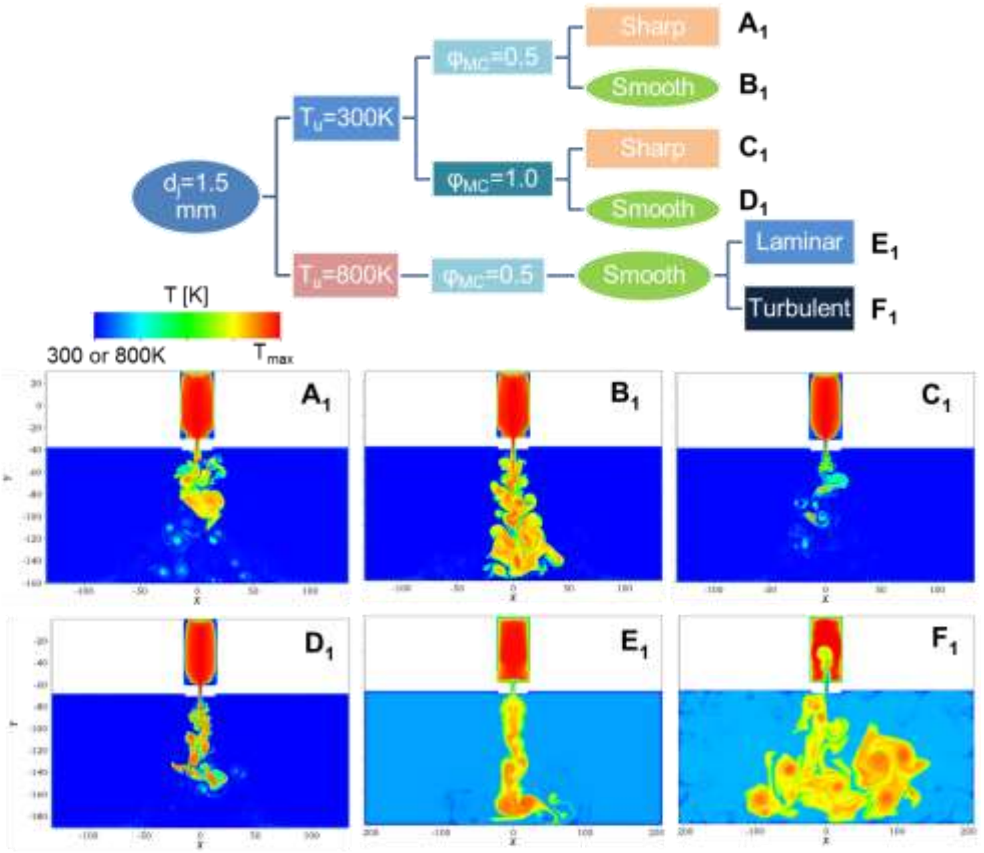

Figure 11: Narrow nozzle (d_j=1.5 mm): effect of unburned mixture temperature T_u (same in both chamber), equivalence ratio in the main chamber phi$_{MC}$, nozzle geometry (sharp vs. smooth corners) and turbulence (u'_{PC}=1.5S_L, $l_I=0.5\delta_f$, $u'_{MC}=3S_L$, $l_I=4\delta_f$) on the temperature distribution. The mixture in the prechamber is stoichiometric. (images at A1 and B1: t=4.9 ms, C1 and D1: 4.1 ms, E1 and F1: 2.6 ms times after spark with corresponding T_{max}: 2280 K, 2220 K, 2520 K). Ignition by distributed hot kernels was observed in cases B1, D1, E1 and F1 and slow consumption in the main chamber in cases A1, E1. Dimensions scaled by the corresponding laminar flame thickness of the stoichiometric mixture at p=1 atm and T_u=300 or 800 K (0.41 and 0.03 cm) (C. E. Frouzakis, S. Benekos).

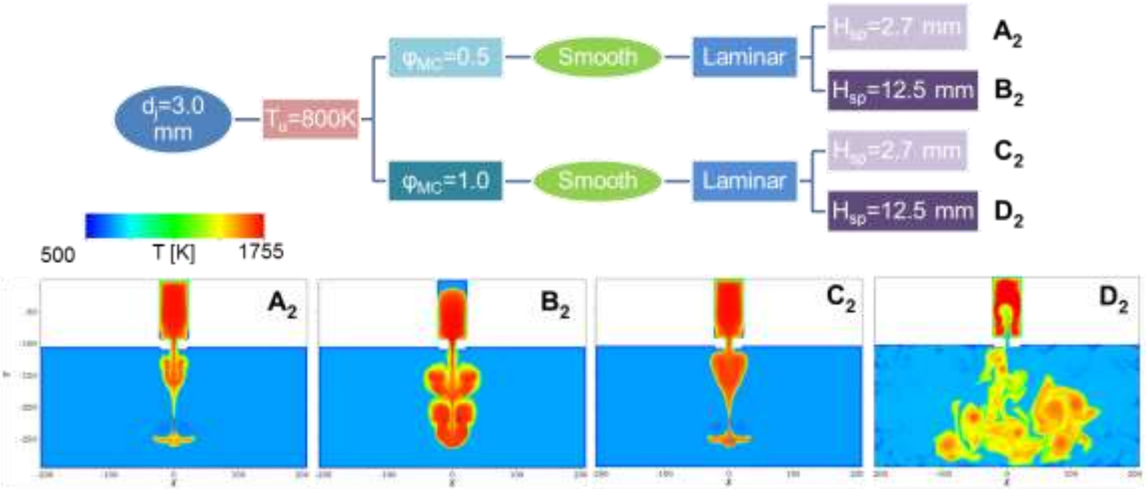

Figure 12: Wide nozzle (d_j=1.5 mm): equivalence ratio in the main chamber phi$_{MC}$, and spark location H_{sp} at 2.7 and 12.5 mm from the top. The mixture in the prechamber is stoichiometric. Torch ignition in all cases with faster flame propagation in the phi$_{MC}$=1 case (all images at t=2.1 ms after spark) (C. E. Frouzakis, S. Benekos).

3.8. General Considerations

As a first overall consideration, it is useful to provide some general orders of magnitude for the computational cost for the different CFD calculations. For similar (but not identical) geometries and operating conditions, the RANS calculation requires around 72 CPU hours per ms of simulated time, which is tractable for current industrial design optimization purposes. For a similar calculation, the computational cost of the LES would be 6’700 CPU hours per ms, around 2 orders of magnitude more expensive, and marginally outside what is currently used for industrial CFD (although expected to be manageable in the near future). Finally, the DNS requirements would be 57’000 and 1.7e6 CPU hours per ms for 2-D and 3-D calculations respectively. This is 3 and 5 orders of magnitude more than the RANS calculations, which makes such calculations prohibitive for industry, without even considering the additional cost and effort for data storage and analysis.

Finally to close the cycle of knowledge transfer from application to fundamentals and back to the application, one should consider the necessity for the transfer of the understanding back to the application. This is mainly done through the novel model development which can be used for future engine design and optimization. Novel combustion models in particular should be computationally efficient while accurately describing the relevant processes. In addition, the phenomenological understanding which arises from the detailed calculations and the optical investigations can aid in the development of simplified 0-D models, which can be used for engine thermodynamic and layout design, as well as real-time control purposes, in particular under changing operating conditions and with different fuels.

4. CONCLUSIONS

This paper presents the Hierarchical Approach followed at LAV for research in combustion systems, and a particular application on prechamber ignition systems for lean-burn gas engines. The hierarchical approach aims to provide phenomenological understanding of combustion processes and high-fidelity data for combustion model development through a combination of computational and experimental tools of different accuracy, complexity and scale. The hierarchical approach starts from the application with near-application engine experiments and 0-D calculations which provide the boundary conditions for the more detailed investigations. The next level includes 3-D CFD and optical diagnostics in engine-like optically accessible rigs, which provide spatial resolution but still offer limitations due to modeling uncertainties and limited optical access and measurement capabilities. At the end of the hierarchical approach lie the fundamental investigations using LES coupled to advanced combustion models, optical investigations in highly accessible generic test-rigs and direct numerical simulations. These offer the fundamental understanding of underlying processes, providing the information which is necessary for model development and validation.

For the prechamber combustion in particular, we use a combination of a single-cylinder research engine, an optically accessible rapid compression machine and a purpose-built optically accessible constant volume chamber and prechamber for the experimental investigations into prechamber combustion. On the simulation side, the tools include 0D models for turbulence generation/dissipation, heat transfer and combustion, 3-D RANS calculations with level-set combustion models for industrial CFD and design optimization, LES calculations with detailed combustion models for further understanding of mixing and combustion phenomena and 2-D/3-D DNS calculations for fundamental investigations into the phenomenology and provision of unprecedented high-fidelity data for model development.

Overall, the hierarchical approach offers a great opportunity for the advancement of combustion research, taking into account the limitations and advantages of each individual tool which is available in an academic combustion research environment.

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