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Gas Prechamber Combustion – Joint Experimental and Numerical Investigations

Natural gas (NG) is a low-carbon fuel which can be used in the mobility sector to reduce combustion-produced CO_2 emissions. This project aims to enhance the understanding of NG prechamber (PC) combustion through experimental and numerical investigations. On the experimental side investigations range from efficiency and emission measurements on near-production engines employing near-production prechambers, to optical investigations in a generic, constant-volume combustion chamber. On the numerical side, Direct Numerical Simulations (DNS) are used to develop understanding of the underlying processes which control PC combustion. These results are used for the development of 3D CFD and 0D-1D phenomenological combustion models [1], which can be used for the design and optimization of lean-burn gas engine combustion systems.

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Natural gas (NG) can be used in existing internal combustion engines, but due to its favorable characteristics – namely high resistance to self-ignition (knock) – it can be utilized best in high-compression-ratio, high-efficiency, lean-burn engines. Lean-burn gas engines possess the advantage of lower fuel consumption, and as a result also emit less CO_2 compared to stoichiometric engines. Nevertheless, they suffer from increased cycle-to-cycle variations and unburned hydro-carbon emissions. Prechambers are used to increase the ignition energy and stabilize combustion under increasingly lean conditions by creating optimal conditions near the spark plug for the early flame development and distributed ignition points in the main combustion chamber. This increases combustion speed and reduces unburned hydrocarbon emissions.

Engine Investigations – CTI, LMB

Single-cylinder research engine experiments are performed to evaluate different prechamber designs in terms of combustion characteristics, performance, as well as emissions (mainly NO_x and CH_4 slip). The main aim of the investigations is to test new designs of prechambers which will extend the operating range to higher loads and leaner mixtures, in order to reach very low engine-out NO_x values while increasing efficiency.

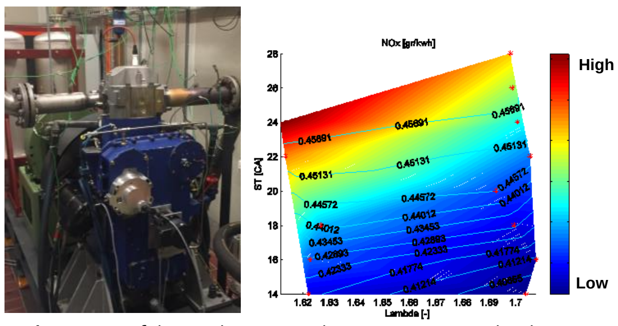

Fig.1: View of the 1-cyl engine and measurement results showing NOx emissions (color scale) with varying lambda and spark timing.

RCEM Investigations - CTI,LMB & EU,GasOn

Optical data is obtained from prechamber combustion systems under near-engine conditions, using an optically accessible rapid compression-expansion machine (RCEM). The pressure and optical data is used for validation of simulation codes, as well as in order to increase the understanding of in-prechamber and main chamber combustion processes.

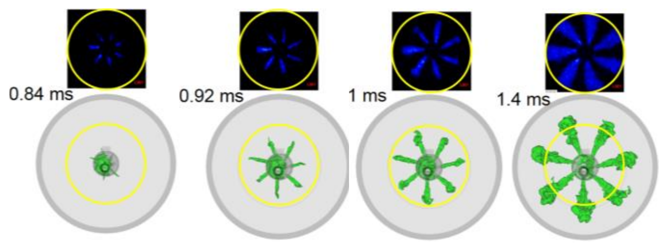

Fig.2: Comparison of OH* chemiluminescence (top) and flame temperature iso-surface obtained using reactive LES simulation (bottom) at different time instants after spark time. The yellow circles represents the experimentally visible region. [2]

Generic Investigations – SFOE & CTI,LMB

To enable the detailed study of turbulent jet ignition processes, a generic, constant volume divided combustion chamber with optical access into both chambers has been constructed. The two chambers are connected through a single hole of variable diameter, allowing a range of conditions to be studied.

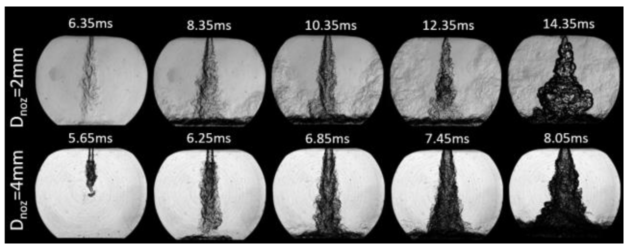

Fig.3: Schlieren imaging from the optical prechamber test rig showing single jet penetration into the main chamber for two different nozzle diameters. Time t=0 is at ignition. The sequence shows the hot jet from exit up to main chamber ignition, indicating slower ignition with a smaller nozzle. Initial conditions: T=350K, P=5bar, Φ_{PC}=1, Φ_{MC}=0.75

Reactive DNS Simulations – SFOE

Reactive Direct Numerical Simulations are used for the in-depth understanding of the early flame propagation within the prechamber, the flame stability at the prechamber exit, the resulting combustion in the main chamber and the influence of the walls on the turbulent flame. A range of 2D and 3D calculations have been completed and are being processed.

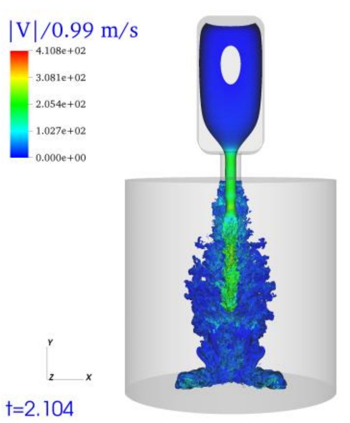

Fig.4: 3D reactive DNS simulation of the generic single-hole prechamber geometry. The plotted surface depicts the iso-contour of stoichiometric mixture, showing the mixture pushed out of the prechamber (main chamber) and the flame surface where the fuel is consumed (prechamber and main chamber). Color scale shows velocity magnitude. Initial conditions: T=500K, P=1bar, Φ_{PC}=1, Φ_{MC}=0.75

Expected Impact

The knowledge generated within these projects is expected to contribute significantly to the future design and development of internal combustion engines using prechamber combustion systems. Such engines will allow the widespread use of natural gas as a fuel, which in itself will lead to a 20% reduction of greenhouse gas (GHG) emissions compared to other traditional fossil fuels. In addition, the increase in efficiency due to expansion of the lean limit operating window, the increase in power density as well as the increases in compression ratio will result in a further reduction of fuel consumption and GHG emissions. The optimal design of prechambers should allow the minimization of the CH_4 slip, a potent GHG, further decreasing the environmental footprint of such engines. Finally, future use of alternative fuels from power-to-gas processes in prechamber gas engines will allow the complete removal of GHG emissions from power generation using gas engines.

References

[1] K. Bardis, G. Xu, P. Kyrtatos, Y.M. Wright, K. Boulouchos, A Zero Dimensional Turbulence and Heat Transfer Phenomenological Model for Pre-Chamber Gas Engines, SAE 2018-01-1453, 2018
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[3] Benekos et al., 2017, Direct Numerical Simulation and experimental validation of ignition/early flame propagation and flame-wall interactions in future gas engines, Annual report, 2017

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