Final scientific report

Prechamber autoignition of gaseous mixtures: numerical simulation with detailed chemistry and testing on engine test bench

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a) Summary of results obtained

The work accomplished during the second period of the project mainly focused on the experimental evaluation of the prechamber system comparing its performance regarding emissions and efficiency to standard spark ignition mode. Further instrumentation of the engine made it possible to verify that ignition actually takes places inside the prechamber.
A system to start up the engine without spark plug was installed and successfully tested. In order to achieve the necessary further improvement of the engine performance, a reduction of the cycle to cycle variations observed during the experimental test runs is absolutely necessary. Two pathways to achieve a more stable operation of the engine were pursued: on the one hand, static mixers were introduced into the intake manifold in order to render the mixture preparation more homogeneous, but did not show the expected improvements. On the other hand, a modification of the prechamber geometry and its influence on the temperature and mixture distribution was investigated via numerical fluid dynamic simulations. These results show an important variation between different geometries and might be used to determine an optimal geometry for optimal mixture preparation for homogeneous ignition conditions inside the prechamber.
This numerical model also was used to test a simplified combustion model and its validity in the range of operation of the prechamber system. Scaling was necessary to properly reproduce the experiments but once the main parameters adjusted, the model can be used to investigate the variations in different operation parameters and the prechamber geometry to further improve the system. The modelling with detailed chemistry was continued but problems with convergence issues still persist. The methodology for the development of a natural gas mechanism suitable for low temperature elaborated during this project was finalized. The resulting mechanism gave good results on other experimental data in the same temperature regime. Three papers summarising this work have been submitted for publication to the scientific journal “Fuel”.

Experimental

As announced in the intermediate report a database comparing the operation of the single cylinder engine test bench was established comparing the performance of the prechamber system with standard spark ignition mode. Test runs were done at two different engine speeds (1150 and 1500 rpm), varying compression ratio (8.5,10,13 and 14) and the whole range of air-to-fuel ratio λ with stable operation conditions at each experimental point (λ_{max}=1.6). The results showed that the feasible range of operation of the prechamber system is more limited than in spark ignition mode. The highest air-to-fuel ratio for stable operation of the prechamber system was λ =1.4 to 1.5 depending on the other operation parameters. At conditions close to stoichiometry the spark ignition system is performing much better than the prechamber system both considering emissions and efficiency. This was to be expected as prechamber systems are mainly used for lean-burn conditions. At higher dilutions the gap in efficiency is clearly decreasing and the trend indicates a higher efficiency for the prechamber system at more elevated λ-values. The main drawback of the prechamber system resides in the fact that, in order to ensure stable operation, ignition has to occur very early during the cycle (at around 20°CA before top dead centre) and therefore most of the heat release still occurs during the compression cycle, strongly deteriorating the efficiency and emission values. The high NO_x emissions also can be explained by the early

ignition timing as the peak combustion temperatures in consequence are a lot higher therefore creating a lot more thermal NO_x. The ignition timing is mainly determined by the prechamber wall temperature that was chosen as low as possible while still maintaining stable operation of the engine. When further lowering the prechamber temperature the engine died off. A cycle-to-cycle analysis of the prechamber operation revealed a high fluctuation of the ignition timing from one cycle to another. This broad distribution is the reason why it is not possible to shift the ignition closer to the top dead centre what would drastically improve the engine performance. The late ignition in fact is the major advantage of the prechamber system as had been shown by former studies at the laboratory with prechambers equipped with spark plugs. This operation mode though is not achievable with the unstable operation of the system in its current state. As possible reasons for the high cycle-to-cycle fluctuations the following elements were identified: the injection system using two small injectors for the gas supply in the intake manifold causing mixture stratification and cycle-to-cycle fluctuations; the admission valves that might not work exactly the same way each cycle admitting different amounts of fresh mixture into the cylinder each cycle; the flow field inside the engine causing differences in the local mixture composition and temperature from one cycle to another; and finally the prechamber heating element causing changes in the prechamber wall temperature when fluctuations in the heat flux occur. The mixture preparation in the intake manifold being the most obvious and probable reason for the fluctuations, it was tested to increase the distance of the injectors from the inlet valves and to introduce to static mixtures in order to improve the mixture homogeneity at the engine inlet. A change in the injection mode also was tested to create a more continuous flow of natural gas in order to improve the performance of the static mixers. A comparison between prechamber test runs with and without the static mixers showed very little improvement of the cycle-to-cycle variations though. The problem may also be due to a change in the amount of gas injected per cycle by the injectors, a problem that cannot be solved by installation of static mixers, of course. A crucial measurement of the air and gas flow in the admission section of the engine and probably a modification of the system of mixture preparation (e.g. change to a carburettor) therefore would be essential to test the system under optimal conditions.
In addition to the establishment of the database, tests have been run with a prechamber specially designed to incorporate a pressure sensor, in order to enable the detection of the ignition location based on differences in the prechamber and main chamber pressure signal. This technique proved that the system is operating as expected with the ignition starting inside the prechamber, indicated by a small peak in the pressure trace, and propagating into the main chamber.
Another aspect treated in the experimental work is the start-up of the engine. As the system is designed to operate without a spark plug, the start-up of the engine turns out to be a delicate operation with natural gas only. Tests had shown that the prechamber heating is not sufficient to trigger auto-ignition for a cold start of the engine. So far, the engine had to be heated in spark plug mode before shifting to prechamber operation. By installing a controlled injection of a second fuel – dimethyl ether (DME) – it was possible to start up the engine completely without a spark plug. Limitations in the accuracy of the mass flow control led to slight knock due to the high reactivity of DME during the start-up phase. This though only represents a control issue and is not a serious problem. The only critical aspect that can be mentioned is that the installation of a dual fuel injection system again increases the complexity of the system and might level out the advantage of not needing spark plugs any more. It though is a part that – once installed – does not need any maintenance besides refilling the DME reservoir.

Numerical simulations

The numerical simulations done on the engine system were presented during the 3rd European Combustion Meeting 2007 in an article and during a poster session. The results mainly showed the efficiency of the prechamber heating in triggering ignition inside the prechamber and indicated the risk of independent ignition inside the main chamber – what actually is not the case as shown by the experimental investigations. The coupled CFD simulations including detailed chemistry showed some difficulties in convergence questioning their reliability. This issue was further investigated but problems still persist.

The fluid dynamics simulations therefore mainly were used to investigate modifications of the prechamber geometry and its influence on the conditions into the prechamber. Using the commercial code FLUENT, a simplified combustion model was applied in order to reduce the requirements in calculation time to be able to complete the simulations in a reasonable amount of time. A simple cylindrical geometry of the prechamber was tested in comparison to the original one. Due to restrictions linked to the cylinder head dimensions of the experimental engine the volume of the second prechamber was considerably smaller than that of the original one. The mixture formation taking into account the different gas composition in the prechamber and main chamber at the beginning of the compression cycle, the temperature evolution, as well as the combustion process, were investigated for both geometries. The new geometry resulted in higher temperatures and earlier ignition in the test case simulated but showed little difference concerning the homogeneity of temperature and mixture inside the prechamber. The optimal case would be a homogeneous temperature distribution as well as the smallest mixture inhomogeneities as possible inside the prechamber to trigger a homogeneous ignition and speed up the combustion process inside the main chamber as well. The new cylindrical geometry though was not able to ignite the whole mixture in the main chamber, leading to undesired knock like ignition simply due to compression heating. Limited by the real engine geometry there is little margin for improvements. Baffle-like flow obstacles to increase the turbulence and hence the heat transfer and turbulent mixing inside the prechamber might be an option to overcome this problem. More flexibility for the size and form of the prechamber would be given on the experimental six cylinder engine with a displacement volume of 10 l at the laboratory, but the increased complexity of this system on the other hand renders the analysis of results more demanding.
The combustion model used for the simulations has been scaled on the combustion duration of the experiment and now might be used to investigate the performance of the system in different operation regimes. The calculation effort though still is quite high for doing a parametric study.

Reaction mechanism development
The development work of the reaction mechanism based on experimental data from a rapid compression machine (RCM) at Lille university has been documented in an article that currently is submitted for publication in the scientific journal "Fuel". In this article the optimised mechanism obtained was also tested on experimental shock tube data giving good results in the same temperature regime showing the efficiency of the optimisation technique applied. The collaboration with Lille university will be continued as there is a great interest to further use the optimisation technique as well as the heat transfer model that has been elaborated for the RCM for mechanism development and optimisation.
The reduction of the reaction mechanism that was intended has not yet been accomplished, as the numerical problems with the coupled fluid dynamics simulation including detailed chemistry need to be solved in the first place making these calculations reliable. The reduction of the calculation time by using a reduced mechanism is a consecutive step in the development.

b) Publications resulting from the ongoing research

Numerical Flow Simulation of a Natural Gas Engine Equipped with an Unscavanged Auto-Ignition Prechamber, Poster presentation with article at the "3rd European Combustion Meeting 2007", Chania/Greece, 11-13 April 2007

c) Publications in print

Heyne S., Roubaud A, Ribaucour M,Vanhove G, Minetti R, Favrat D. Development of a natural gas reaction mechanism for engine simulations based on rapid compression machine experiments using a multi-objective optimisation strategy, Paper in collaboration with Lille University, submitted to "Fuel" ,July 2007.
Heyne S, Meier M, Imbert B, Favrat D. Prechamber autoignition in a natural gas engine for cogeneration. Part I: Experimental. Paper submitted to "Fuel", Sept. 2007.
Heyne S, Millot G, Favrat D. Prechamber autoignition in a natural gas engine for cogeneration. Part II: Numerical simulations. Paper submitted to "Fuel", Sept 2007.

d) Other publications planned

No

e) Patents

No patents will be submitted so far.