EXPERIMENTAL STUDIES AND NUMERICAL SIMULATION OF SI AND CAI COMBUSTION MODELS FOR BIOETHANOL-GASOLINE BLENDS IN SINGLE CYLINDER ENGINE

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Abstract: *Bioethanol offers the potential of a more efficient, less polluting fuel but limitations in current engine platforms prevent it from being fully exploited. The EC funded project BEAUTY – Bio-Ethanol engine for Advanced Urban Transport by light commercial & heavy duty captive fleets – brought together automotive manufacturers, universities and research centers in a two-years project under the Sustainable Surface Transport program. The project was aimed at developing dedicated solutions (engines, combustion technologies and fuels). The project examined three different combustion approaches – stoichiometric SI engine for Heavy Duty applications, surface ignition Diesel engines for Light Duty applications and Controlled Auto-Ignition SI engines for Light Duty applications.*

In the spark ignited platform the project has developed and optimized the CAI (Controlled Autoignition) approach on the SI engine with the blends containing up to 85% bioethanol, getting a reduction in fuel consumption up to 10% at partial load. Experimental studies were performed on (SCRE) single cylinder research engine for SI (Spark Ignition) and CAI combustion modes with pure gasoline, E20 (20% of bioethanol by volume) and E85 (85% of bioethanol). The mixture preparation was performed with a SGDI (Spray Guided Direct Injection) technology. The exhaust valve system of the specific engine is hydraulically operated which allows controlling the EGR composition in the combustion chamber. This approach is needed to control the auto-ignition process for CAI operation. The CAI mode in boosted engines shows slight improvement in comparison to SI engines which means that it is only reasonable to use CAI approach for naturally aspirated engine in which the combustion process is significantly improved in comparison to pure SI operation.

Numerical simulations of the combustion process were performed with the use of the ECFM-3Z combustion model in AVL FIRE® code. The ECFM-3Z combustion model is equipped with data tables containing the ethanol laminar flame speed and auto-ignition delay time data for different pressure, temperature and equivalence ratio conditions. Results of simulations show good agreement with experimental data for SI and CAI processes.

Keywords: CAI, SI, ECFM-3Z, gasoline, ethanol

MODELING APPROACH FOR MULTI-COMPONENT SPRAY EVAPORATION AND COMBUSTION

Spray Multi-Component Evaporation Model

The multi-component evaporation model (1) is based on the Abramzon-Sirignano (2) approach, which has been extended by Brenn et al. (3). The main difference to the single-component case is that mass transfer of every component is taken into account separately, whereas heat transfer remains a global mechanism.

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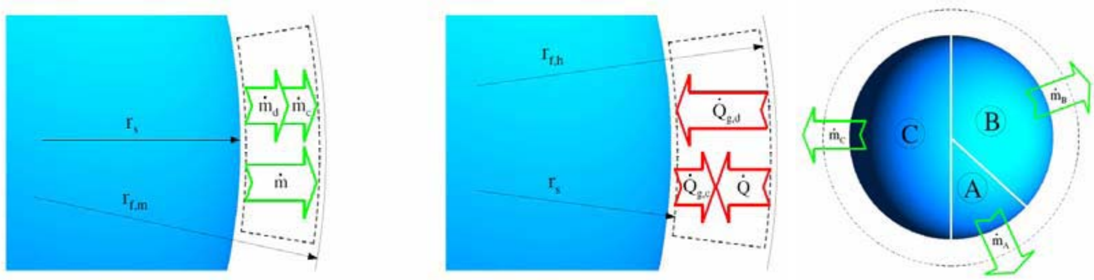


Figure 1. Mass and Heat Fluxes for Multi-component Droplet

The distribution of the components inside the droplet is assumed to be homogeneous. This assumption is justified for sufficiently high liquid mass diffusivities and moderate evaporation rates. That means, according to the "rapid mixing" approach the model is based on the assumption of a homogeneous liquid composition, which also reduces calculation time.

Combustion Of Multi-Component Fuels

ECFM-3Z General

The ECFM-3Z model (4) distinguishes between all three main regimes relevant in engine combustion, namely auto-ignition, premixed flame and non-premixed, i.e. diffusion combustion.
The auto-ignition pre-reactions are calculated within the premixed charge of fuel and air, with the ignition delay governed by the local temperature, pressure, fuel/air equivalence ratio and the amount of residual gas. Local auto-ignition is followed by premixed combustion in the fuel/air/residual gas mixture formed during the time period between start-of-injection and auto-ignition onset - within the ECFM-3Z modeled according to a flame propagation process. The third regime is the one of diffusion combustion where the reaction takes place in a thin zone which separates fuel and oxidizer. In the ECFM-3Z it is assumed that the chemical time in the reaction zone is much smaller than the time needed for the diffusion process. Therefore the rate of reaction during diffusion combustion is determined entirely by the intermixing of fuel and oxidizer. For the application under consideration the most important processes are the auto-ignition and the flame propagation.

Auto-Ignition Model

For the prediction of the auto-ignition process the model utilizes a so called precursor quantity which determines the progress of the auto-ignition event. The precursor quantity Y_P is solved applying the formation rate as shown in the equation below eq (1).

$$\frac{dY_P}{dt} = Y_{FM} \cdot F(t_{delay}) \qquad (1)$$

where Y_{FM} is the mixture fraction and F is a function of the delay time based on tabulated values. When the species Y_P reaches a certain threshold value (which is equal to the local mixture fraction), the auto-ignition event is triggered. Subsequently, the premixed fuel is consumed and an initial value of flame surface density is deposited locally.
The values for the delay time are stored in look-up tables for each fuel component. The so called cool-flame delay time is contained in the databases as well as the timing for the main 'hot' explosion. The range of the databases has been chosen in order to cover the usual range of engine applications (Temperature 600K – 1500K, pressure 10 bar – 80 bar, equivalence ratio 0.3 to 3 and residual gas content from 0 to 90%). In the figure below a graphical representation of the two applied databases for different ambient conditions are shown.

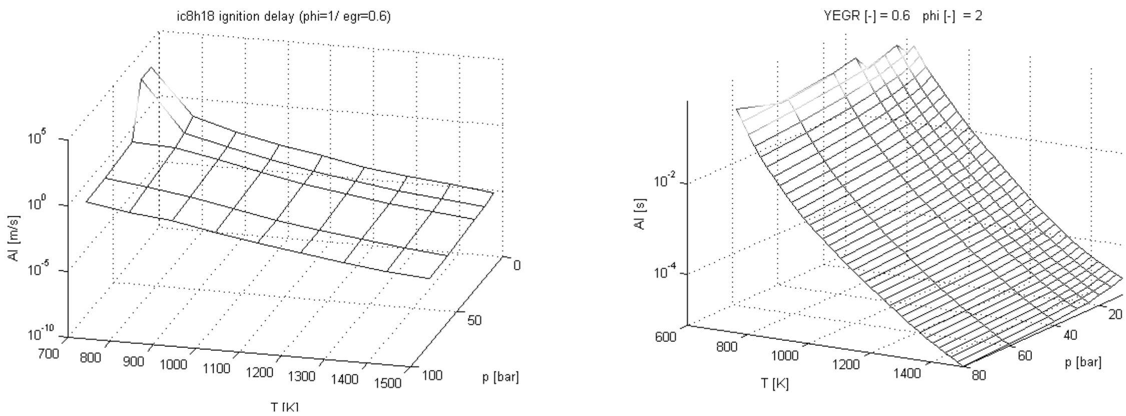


Figure 2. Graphical representation of the databases for i-octane and ethanol

Spark Ignition Model

The spark ignition is described by an Eulerian version (5) of the so called AKTIM (Arc and Kernel Tracking Ignition Model) model (6). The new model combines the advantages of the AKTIM model in respect of the accurate treatment of the electrical side of ignition process and the simplicity of an Eulerian treatment.
This new Eulerian multi-spark ignition model is based on the electrical circuit model of AKTIM as described in the references and which provides the spark length and duration and estimates the energy transferred to the gas and the amount of burnt gas mass deposited at the spark. At ignition timing an initial burned gas profile is created. After this initial phase, the reaction rate is directly controlled by the flame surface density (FSD) equation whose source terms are modified to correctly represent flame surface growth during ignition. The usage of the FSD equation naturally allows multi-spark description (i.e. modeling more than one spark plug at a time or multiple firings of a single spark, or combinations of both).

THE SINGLE CYLINDER RESEARCH ENGINE (SCRE)

To investigate the potential of the controlled auto-ignition (CAI) combustion initiation at partial load on a spark ignited engine platform in deep relationship to ethanol blend properties engine dyno tests have been carried out at AVL. For this task the AVL single cylinder research engine FM540 was selected.

Type	GDI NA
Displacement	500 cm³
Bore	86 mm
Stroke	86 mm
Compression Ratio	11.5 (up to 14 possible)
Injector	Side mounted GDI injector, double injection capability
Other	Intake and exhaust cam-phasers (dual VVT)

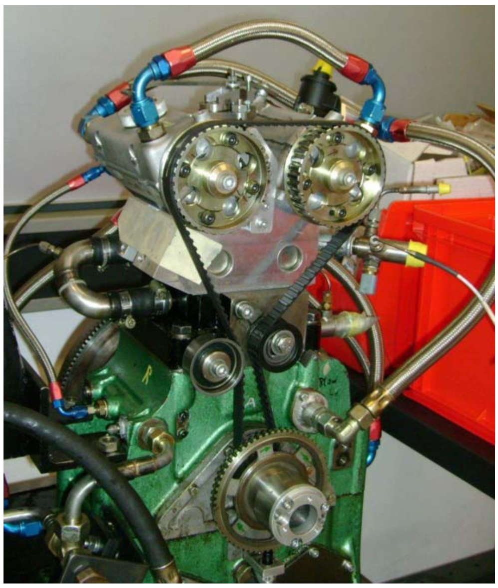


Figure 3. AVL Single cylinder engine FM540

This engine has been equipped with a specific electro-hydraulic system on the exhaust valve to realize a second opening of the valve (the so called “re-breathing”) during the intake stroke so as to provide high rate of residual gas in the combustion chamber for auto-ignition operation (Fig. 4).

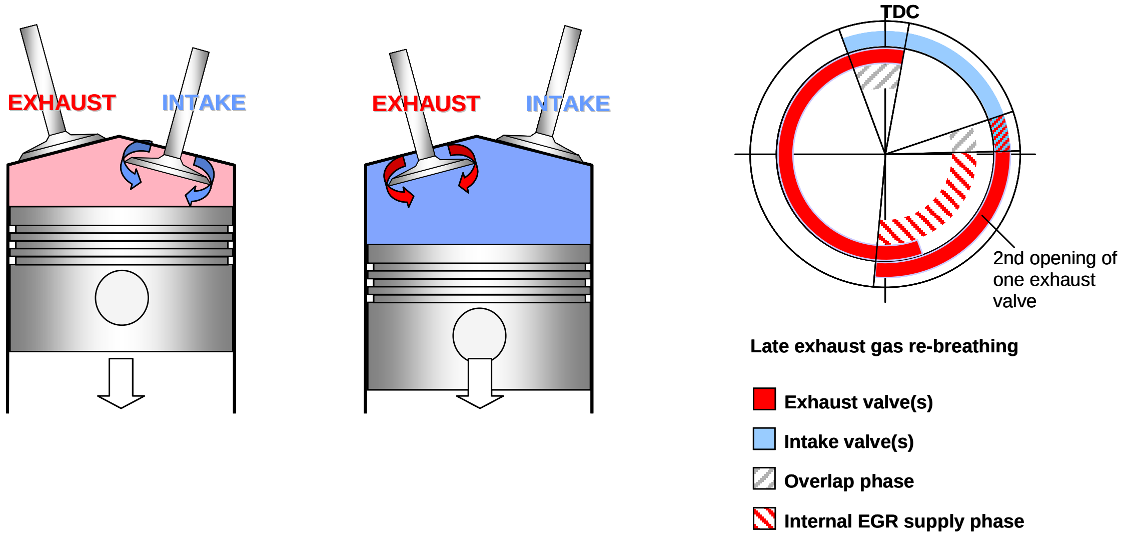


Figure 4. Control of Residual Gas Content for CAI Operation

On Fig. 5 it is shown how the cylinder charge and residual gas content is controlled in the auto ignition combustion mode, which is feasible only at lower part load:

- Standard cam actuation of exhaust valves
- Additional lifting of one exhaust valve during the intake stroke by means of an electro-hydraulic valve actuator (EHVA)
- Cam actuation of intake valves with low lift and cam phase shifting possibility

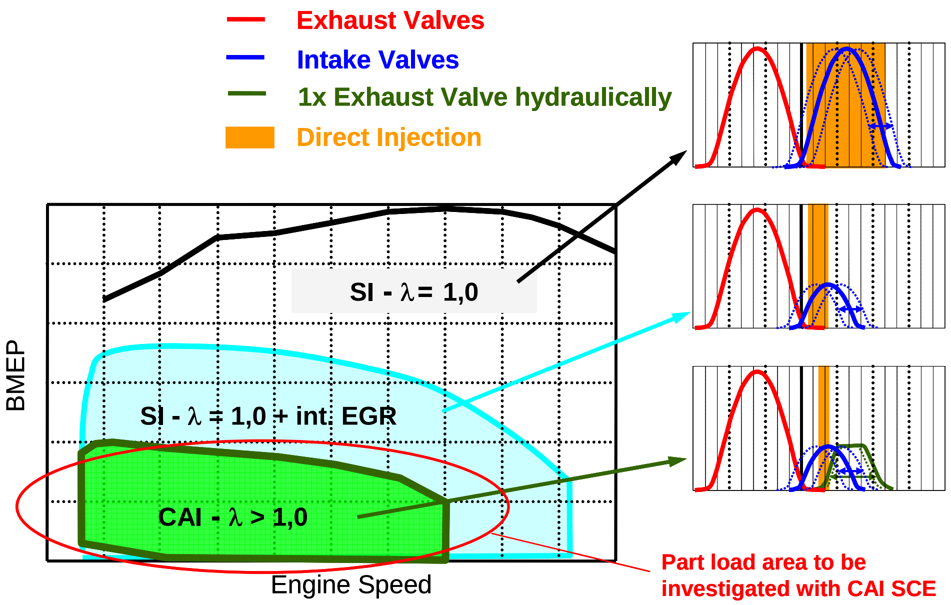


Figure 5. Operation strategy for CAI single cylinder engine

The single cylinder engine will be used to investigate the CAI combustion having the opportunity to check different combinations of lambda value and EGR rates at different ignition / injection timing, depending also on the fuel properties.
For the BEAUTY project the following adaptations of the AVL single cylinder engine had to be made:

- valve train variability system design and integration for CAI operation
- 100% ethanol capability of fuel supply system

NUMERICAL MODEL OF SCRE

For the purpose of the numerical calculation the 3D models of the SCRE engine has been prepared. In figure 6. the model is presented for a crank angle position (CA) in which intake and outlet valves are open simultaneously. Additionally there was a need to prepare separate files describing the movement of the valves respectively to the operating point and used fuel. The moving meshes were prepared in the 'Fame Engine plus' meshing tool included in the FIRE Software.

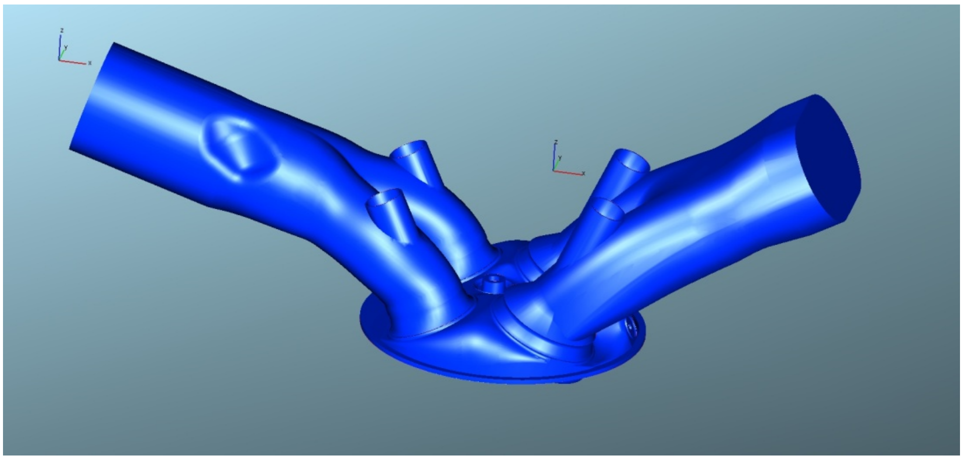


Figure 6. 3D geometrical model of the SCRE engine.

After this work the set off moving meshes were prepared. Correspondingly one mesh was covering only one operating point CAI/SI mode. The reason for that was Internal EGR, which was control by reopening the outlet valve, different for every tested case. Average number of cells varied from 500 000 (Fig. 7 left) to 2 500 000 (Fig 7. right).

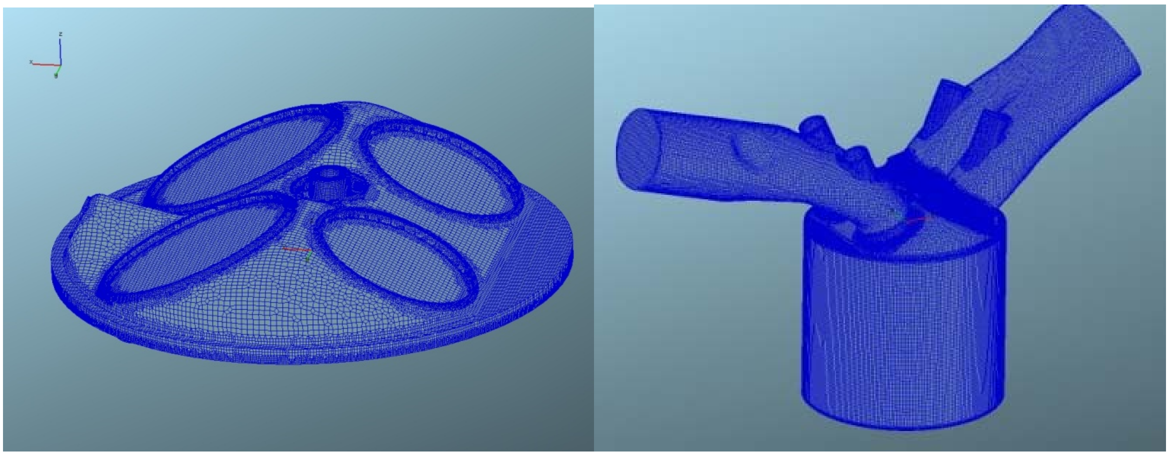


Figure 7. Mesh model of the SCRE Engine.

RESULTS

The targets of the project experimental part was to extend the knowledge about:
- The possibility of use the bio-ethanol/gasoline fuels for SI and CAI engines
- The influence of the used fuel on the engines parts which are designed for gasoline fuels
- The improvement in combustion processes and emission

For numerical investigation the targets were:

- Improvement of the numerical models for multi-fuels injection, vaporization, ignition and combustion
- Test if presented models are capable to represent the experimental results

Experimental studies were performed on (SCRE) single cylinder research engine for SI (Spark Ignition) and CAI combustion modes with pure gasoline, E20 (20% of bioethanol by volume) and E85 (85% of bioethanol). In presented paper only results for pure gasoline SI and E85 CAI will be presented.

Simulation and Experimental Results Comparison for Gasoline SI

Below in Figure 8 the mean cylinder pressure and the rate of heat release for a load point utilizing spark ignition can be seen. It is obvious that the applied modeling approaches are able to describe the physical and chemical processes of this kind of engine operation. The development of the flame front over the time, which is shown in Figure 9, clearly reveals the standard operating mode with SI. The radius of the flame front propagate uniformly and it reaches the cylinder wall in the same time. This results in fast and smooth combustion processes. The SCRE combustion chamber is well designed for SI processes and there is a need to test it for CAI.

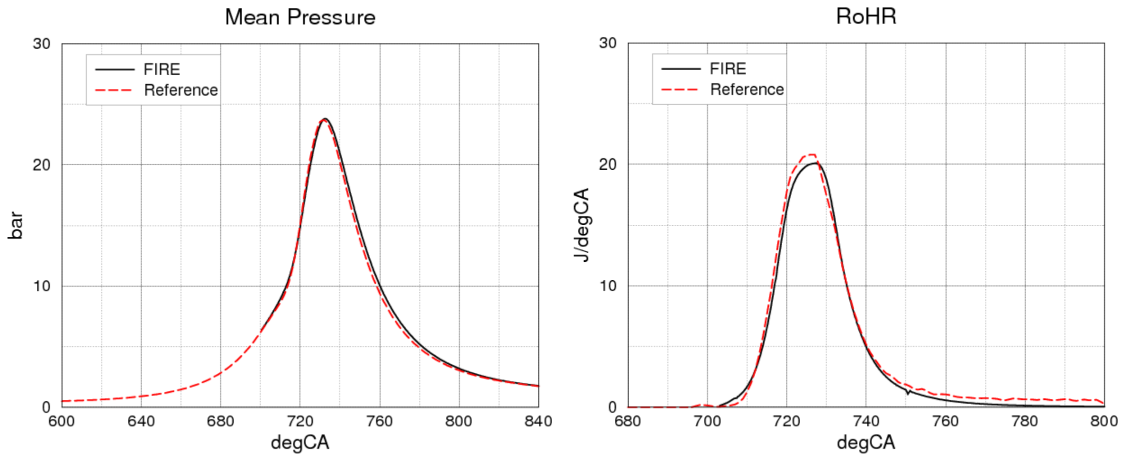
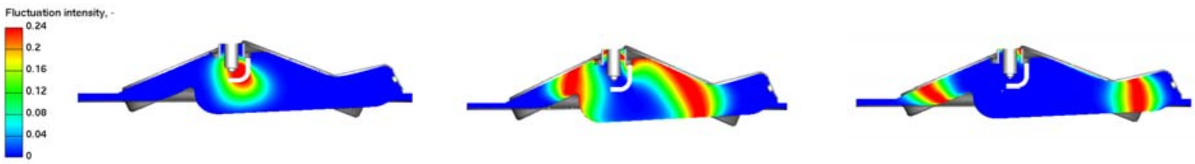


Figure 8. SCRE SI – Pressure and Rate of Heat Release – 2000 rpm / 3 bar, Gasoline



710 deg CA 720 deg CA 730 deg CA

Figure 9. Flame front represented by the 'fluctuation intensity' - 2000 rpm / 3 bar, Gasoline

Simulation and Experimental Results Comparison for E85 CAI

In Figure 10 the results from experimental and numerical investigation are presented. On the left the mean pressure value in combustion chamber, on the right the rate of heat release in the combustion chamber. The numerical results fit to the experimental ones with good agreement. There can be seen only slight deviation on the ignition point, for simulation results the rapid hot ignition is starting 5 deg CA later which still is good for the auto-ignition model. In Figure 11 the so-called AI precursor is presented from simulation investigation. It shows that the source of the AI phenomenon is located in the main part of the combustion chamber in the center of the vortex obtained by the shape of the piston and injection direction.

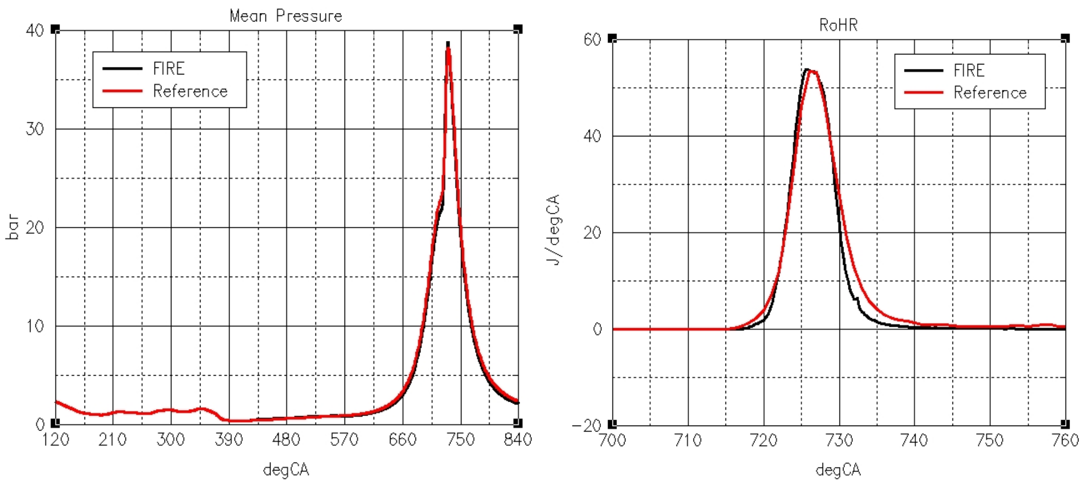


Figure 10. SCRE CAI – Pressure and Rate of Heat Release – 2000 rpm / 3 bar, E85

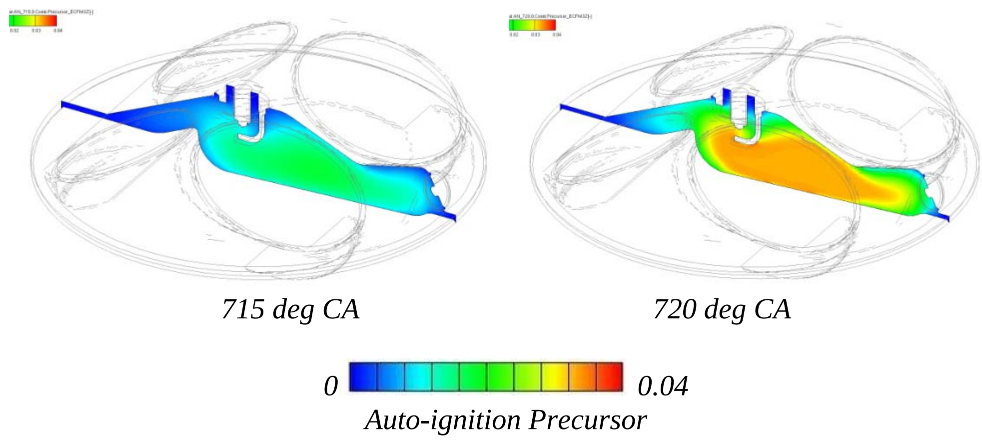


Figure 11. SCRE CAI – Auto-ignition Precursor – 2000 rpm / 3 bar, E85

DISCUSSION

With use of the spark ignited platform the project has developed and optimized the CAI (Controlled Autoignition) approach on the SI engine with the blends containing up to 85% bioethanol, getting a reduction in fuel consumption up to 10% at partial load. During the project experimental and numerical investigation the below conclusions were conducted.

- The exhaust valve system of the specific engine is hydraulically operated which allows controlling the EGR composition in the combustion chamber and works perfectly on SCRE for SI/CAI.
- The CAI mode in boosted engines shows slight improvement in comparison to SI engines which means that it is only reasonable to use CAI approach for naturally aspirated engine in which the combustion process is significantly improved in comparison to pure SI operation.
- Improvement in injection and combustion models extend the range of Fire simulation capability to multi-fuels purpose.
- Results of simulations are in good agreement with experimental data for SI and CAI processes.

ACKNOWLEDGMENTS

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