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A Review of Remote-Control Strategies for Reactivity Controlled Compression Ignition Combustion

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ABSTRACT

Over the past years, the increasingly stringent emission regulations for Internal Combustion Engines (ICE) have led to the development of non-conventional combustion strategies like Low Temperature Combustions (LTC) characterized by high efficiency and low pollutant emissions. One of the most relevant LTC strategies is the Reactivity Controlled Compression Ignition (RCCI), characterized by the combustion of a lean mixture composed by air and a low reactivity fuel (LRF, gasoline in the case under study) ignited by a high reactivity fuel (HRF, Diesel in this study), directly injected in the combustion chamber, due to the high pressure and temperature in the cylinder.

The proper management of this combustion strategy results in high efficiency and low engine-out emissions, with the simultaneous mitigation of both nitrogen oxides (NO_x) and particulate matter (Soot). On the other hand, this combustion methodology is affected by high instability and high sensitivity to slight variations of the in-cylinder thermal conditions. Previous works demonstrate that combustion stability can be guaranteed through closed-loop control strategies that vary the injection parameters to keep the center of combustion (CA₅₀, i.e. the angular position when the 50% of fuel burned within the engine cycle) at a proper target value.

Although the center of combustion can be directly evaluated from in-cylinder pressure measurement, the on-board installation of in-cylinder sensors is still uncommon, mainly because they would increase the cost of the whole engine management system. Due to the above considerations, two different closed-loop control strategies have been developed by the authors of this paper to evaluate combustion characteristics using low-cost sensor, that are already present on-board for other management purposes. The current work summarizes these different strategies and demonstrate how a feed-forward estimation of the ignition delay, based on the estimation of the in-cylinder temperature, can improve the transient behavior of the control and how it is possible to replace all the information from in-cylinder pressure signal.

INTRODUCTION

Nowadays, Diesel engine can be considered the most efficient ICE technology for automotive applications.

In these engines, combustion of a high-reactivity fuel (Diesel) is obtained via compression-ignition, in a high temperature mixing-controlled process [1-13].

However, due to high pressure Diesel direct injection, the air-fuel mixture is characterized by a high heterogeneity. The compression-ignition of this kind of mixture produces both particulate matter (PM, in rich regions) and nitric oxides (NO_x, in stoichiometric and lean region) that are usually removed using expensive exhaust gas aftertreatment systems.

With the aim of respecting the increasingly stringent regulations on pollutants emissions, a large amount of research in the field of innovative combustion methodologies characterized by low emissions and high thermal efficiency has been carried out. These combustions, usually called Low Temperature Combustions (LTC), proved to be effective in the reduction of both PM and NO_x. The low level of pollutants emissions of these combustion processes is usually guaranteed by the auto-ignition of a homogeneous air-fuel mixture, obtained using high ignition delays and gasoline-like fuels.

As matter of fact to obtain a homogeneous mixture, it is necessary to inject fuel very early, during the compression stroke. Unfortunately, very long ignition delays result in low combustion stability, reduced engine operating range and high sensitivity to cylinder thermal conditions [1-4]. To overcome these critical aspects, it is necessary to use robust closed-loop control strategies which dynamically correct the injection parameters to keep stable the combustion process and to increase the range of use of the engine. In particular, many studies demonstrate that a proper closed loop control strategy can be based on a controller that varies the center of combustion (CA50) at a proper target value. The LTC combustion process taken into consideration in this work is reactivity-controlled compression ignition (RCCI), i.e. a chemically controlled dual fuel process. This combustion involves a nearly homogeneous mixture of air and low reactivity fuel (in this case gasoline) which is activated by the direct injection of high reactivity fuel (Diesel).

In order to test the RCCI combustion, a common light-duty Diesel engine was modified. According to Reitz [3], the intake manifold was equipped with an extension of the runners able to house a gasoline injector for each cylinder. To manage the injection parameters, a Rapid Control Prototyping (RCP) system, based on National Instrument cRio 9082, was developed. This specifically designed software implemented in the RCP system, can calculate in real-time the injections parameters necessary to run the engine in RCCI mode. The injection parameters adjusted by the RCP system, i.e. amount of each fuel to be injected and Diesel Start of Injection (SOI_d), are calculated based on the information coming from the in-cylinder pressure sensor installed in engine (elaborated by an indicating system and communicated to the RCP via CAN bus). As mentioned above, RCCI combustion is very sensitive to cylinder thermal conditions, therefore slight temperature variations might generate significant variations of the ignition delay (with respect to reference thermal conditions) and consequentially of injection parameters selected by the controller to keep CA50 at the same value.

As already discussed in previous works [8], ignition delay shows a strongly correlation with the cylinder thermal conditions experienced by the fuel during the compression stroke, especially with the temperature in correspondence of Diesel SOI (T_{SOI} , i.e. the in-cylinder temperature in the angular position at which the HRF is injected).

As a result, a good estimation of in-cylinder temperature during compression can be used to accurately estimate the ignition delay of the mixture, which could be used in open-loop to correct the Diesel SOI characterized in reference thermal conditions. The goal being to achieve a stable and rapid control of the centre of combustion also when the engine runs during transients or far from the reference thermal conditions. As widely discussed in literature [9], the direct control of the center of combustion can be based on the real-time analysis of in-cylinder pressure. However, the on-board installation of in-cylinder pressure signal is not yet common, mainly due to problems related to sensor reliability and cost.

The approach proposed in this paper replaces the information coming from in-cylinder pressure signals with the ones coming from low-cost sensors already present on the engine in the exhaust manifold. This information will be used to develop an ignition delay mapping dependent on the engine thermal conditions. Furthermore, with the purpose of keeping stable the RCCI combustion when running far from the reference thermal conditions, the T_{SOI} mapping will be used in the control chain [9] to adjust in “feed-forward” diesel injection timing. This new closed loop combustion controller will be able to extend the stable RCCI operation conditions with high efficiency.

The first part of paper describes the experimental layout and all the components used to investigate RCCI combustion (especially RCP system developed to control the combustion process using in-cylinder pressure signal). Then, the results of several experimental tests run to study how the variation of the injection parameters affects the ignition delay in RCCI mode at different Diesel/gasoline ratios is reported. The last part of this work shows the correlation between ignition delay and T_{SOI} and how it is possible to replace the information from in-cylinder pressure with the signal coming from low-cost sensors.

EXPERIMENTAL SETUP

The analysis has been performed running a light-duty 1.3L Common-Rail Diesel engine mounted in a test cell. Table 1 summarizes the technical characteristics of the engine under investigation.

| | |
|--------------------------|--------------------------|
| Displaced Volume | 1248 cm ³ |
| Compression Ratio | 16.8 |
| Maximum Torque | 200 Nm @ 1500 rpm |
| Maximum Power | 70kW @ 3800 rpm |
| Number of valves | 4 per cylinder |
| Injection system | Common Rail Multi-Jet |
| Architecture | L4, firing order 1-3-4-2 |
| Bore | 69.9 mm |
| Stroke | 82 mm |

TABLE 1. Technical characteristics of the engine under study.

Compared to the standard layout, in order to investigate RCCI combustion, an additional fuel system for gasoline was designed. According to Del Vescovo et al. [5], the air and low reactivity fuel mixture can be achieved inside the intake manifold using PFI injectors. In this case, with the aim of accurately controlling the amount of gasoline introduced in each cylinder, 4 additional PFI injectors (IHP_043) were installed in a specifically designed support. Such custom component was mounted between the standard manifold and the intake runners. The additional injectors are connected to a rail filled with gasoline, kept at constant pressure (5.5 bar) through a rotary pump and a mechanical pressure regulator. Figure 1 shows the installation of the new gasoline injection system.

| | Gasoline | Diesel |
|-------------------------|-------------------------|---------------------------------------|
| Injection system | PFI (intake runners) | Common Rail (direct injection) |
| Injectors | Magneti Marelli IHP_043 | Bosch solenoid inj. (1600 bar system) |
| Fuel pressure | 5 bar | 500 bar |

TABLE 2. Main characteristics of the fuel systems for gasoline and diesel.

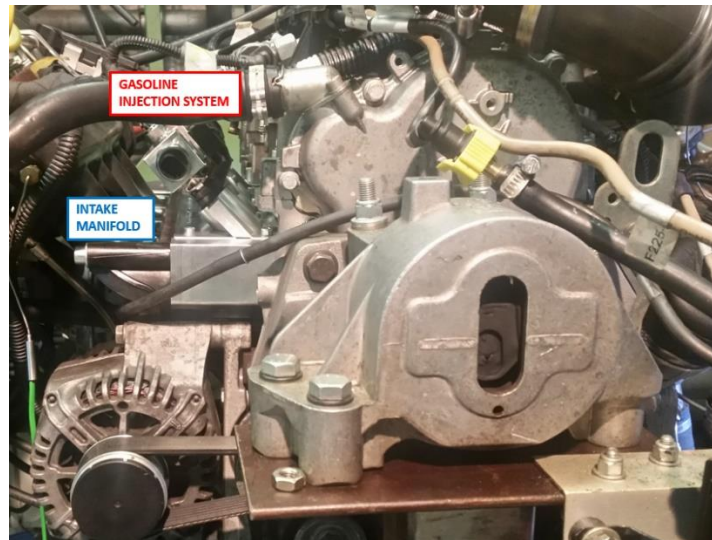


FIGURE 1. New gasoline injection system

Characteristics of PFI and GDI injection system are summarized in Table 2. To properly manage cycle by cycle phased injections, a Rapid Control Prototyping injection controller based on National Instruments cRio 9082 has been implemented. Sampling at high frequency the signal coming from crankshaft speed sensor, the RCP system can determine the instantaneous angular position within the engine cycle. Based on this information, the RCP generates the logical commands for the gasoline injector, i.e. Energizing Time (ET_g) and Start of Injection (SOI_g). These logical signals are communicated to a specific external ECU which converts the logical commands into the corresponding electrical commands. The RCP system also communicates with the standard ECU via CAN bus to read or overwrite the values of the Diesel injection parameters, i.e. Start of Injection (SOI_d) and Energizing Time (ET_d). This feature is necessary to implement the closed-loop control strategy that will ensure RCCI combustion stability.

The engine under study is equipped with one per cylinder piezoelectric pressure sensor (AVL GH14P). These signals are acquired and analysed using an indicating system (OBI by Alma Automotive) that real-time calculates all the main combustion indexes, such as indicated torque, CA50 and peak pressure rise rate (PPRR). In order to manage closed-loop RCCI combustion control, combustion feedbacks are sent from the indicating system to the RCP via CAN. Using the information coming from OBI, the RCP system real-time corrects Diesel SOI to keep CA50 close to its target value.

All the standard sensor, i.e. the ones already present on-board, are monitored and acquired using INCA software and ETAS hardware. Figure 2 shows the discussed experimental setup used to test RCCI combustion.

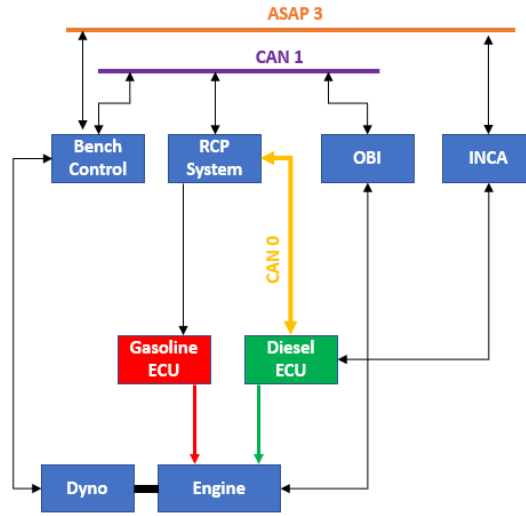


FIGURE 2. Experimental setup

T_{SOI} THERMAL MODEL

Many studies demonstrate that RCCI combustion is strongly affected by in-cylinder thermal conditions. Previous researches [8] showed how the ignition delay can be related to the thermal state of the cylinder calculating a synthetic parameter called temperature at SOI_d (T_{SOI}). When in-cylinder pressure measurement is available, this quantity can be calculated as reported in the following.

First, cylinder pressure signal can be used to measure the P_{EVO} (pressure corresponding at exhaust valve opening) and to calculate the temperature at the same angular value T_{EVO} through Equation 1.

$$T_{EVO} = \frac{P_{EVO} V_{EVO}}{R m_{tot}} \quad (1)$$

The measurement of P_{EXH} , average cylinder pressure during exhaust stroke, is helpful to calculate with Equation 2 the volumetric fraction of residual gases trapped inside the cylinder, where V_C is the displaced volume and V_{CC} is the volume of combustion chamber.

$$V_{\%EGR} = \frac{V_{CC} \left(\frac{P_{EXH}}{P_{MAN}} \right)^{\frac{1}{\gamma}}}{V_{CC} + V_C} \quad (2)$$

Using the parameters coming from Eq.1 and Eq.2, it is possible to evaluate the average charge temperature in correspondence of intake valve closing T_{IVC} :

$$T_{IVC} = \frac{T_{MAN}m_{AIRQ} + T_{EVO}V_{\%EGR}m_{TOT}}{m_{AIRQ} + V_{\%EGR}m_{TOT}} \quad (3)$$

Finally, assuming the compression process as polytropic the temperature in correspondence of the SOI_d is:

$$T_{SOI} = T_{IVC} \left(\frac{V_{IVC}}{V_{SOI}} \right)^{\gamma-1} \quad (4)$$

The correlation between ignition delay and T_{SOI} has been used to set-up a feed-forward correction for the base calibration of SOI_d . The goal being to compensate in open-loop the deviations between the current operating conditions and the thermal conditions in which the reference engine base calibration has been performed. Figure 3 shows a scheme of how the correlation between the ignition delay and temperature (that will be discussed in the following session) can be used in a closed-loop controller of the centre of combustion.

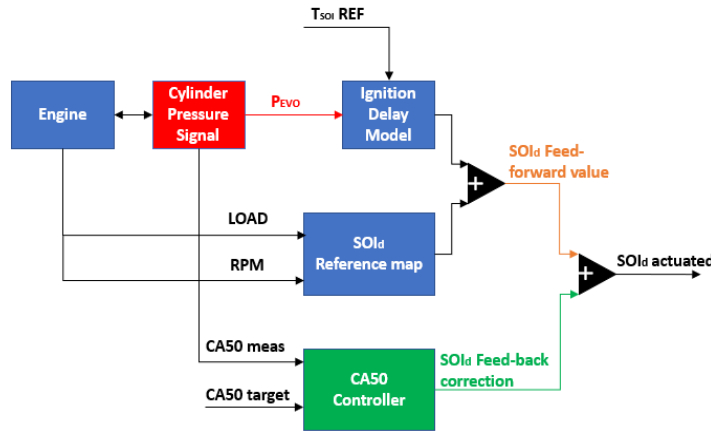


FIGURE 3. Scheme of the base CA50 closed-loop controller

In this work, the base mapping has been carried out running the engine with 3 cylinders in conventional Diesel combustion (CDC) and only one cylinder in RCCI mode. Using that approach, the engine stability has been guaranteed to 3 CDC cylinders and the fourth can operate at any load and any gasoline/Diesel target ratio (DF). The main critical aspect of this operating mode is that the sensors installed in the exhaust path, such as exhaust pressure and temperature sensors, are influenced mainly by the cylinders operating in CDC mode.

With the aim of replacing the information coming from in-cylinder pressure sensor with other transducers, it is necessary to test the engine performing RCCI combustion in all the cylinders. In this way, the in-cylinder condition during the exhaust stroke will be similar to the thermal conditions measured in the exhaust manifold.

This new information can be used to modify the thermal model introducing T_{EXH} and P_{EXH} instead of T_{EVO} and P_{EVO} . Then, Eq. 1 and Eq. 2 will change into Equation 5:

$$T_{IVC} = \frac{T_{MAN}m_{AIRQ} + T_{EXH}V_{\%EGR}m_{TOT}}{m_{AIRQ} + V_{\%EGR}m_{TOT}} \quad (5)$$

INVESTIGATION OF RCCI COMBUSTION

As mentioned above, ignition delay map has been developed using in-cylinder pressure signal. However, the on-board installation of this kind of transducers is not common because of high cost and low reliability. In order to obtain the same T_{SOI} map using low-cost sensors, experimental tests were carried out running the engine in RCCI mode.

According to Reitz et al. [3], dual-fuel combustion is strongly affected by variation of the gasoline/Diesel ratio and thermal conditions. According to [1-4], different DF values require SOI_d adjustment to keep CA50 at the same value. To investigate the effect of DF and SOI_d on the ignition delay, a CA50 sweep has been performed (covering the entire range of combustion stability, from 2° after top dead centre (aTDC) to 8° aTDC every 2 degrees).

Furthermore, with the purpose of extending the ignition delay correlation at different thermal conditions, two air temperature levels have been analysed (T_{HOT} represents the tests with manifold temperature equal to 33°C, while T_{COLD} represents the tests run at 15°C).

As discussed in literature, in the RCCI combustion the use of external EGR causes a lot of changes in the chemistry of the mixture and it changes the combustion behaviour, especially the ignition delay. In order to avoid these effects, the external EGR has been closed during all the experimental investigation.

Table 3 reports the experimental tests run on the engine under study. The tests were carried out at IMEP nearly equal to 5 bar with fix amount of fuel injection (ET_g and ET_d were kept constant).

| DF | CA50 Sweep | Intake Manifold Air Temperature |
|------|------------------|---------------------------------|
| 0.4 | 2: 2 :8 deg aTDC | T_{HOT} 33° C |
| 0.3 | 2: 2 :8 deg aTDC | T_{HOT} 33° C |
| 0.25 | 2: 2 :8 deg aTDC | T_{HOT} 33° C |
| 0.2 | 2: 2 :8 deg aTDC | T_{HOT} 33° C |
| 0.4 | 2: 2 :8 deg aTDC | T_{COLD} 15 °C |
| 0.3 | 2: 2 :8 deg aTDC | T_{COLD} 15 °C |
| 0.25 | 2: 2 :8 deg aTDC | T_{COLD} 15 °C |
| 0.2 | 2: 2 :8 deg aTDC | T_{COLD} 15 °C |

TABLE 3. Experimental test

Figure 4 shows the SOI_d values at the same DF 0.2 during CA50 sweep with closed-loop control strategy enabled. As can be observed in Figure 4, the correlation between SOI_d and CA50 is inverted with respect to CDC combustion, i.e. retarding CA50 target the SOI_d must be increased. As discussed in literature [8], the SOI_d -CA50 trend shown in Figure 4 seems to be mainly related to the local air-fuel ratio in the region where the Diesel ignites. When high SOI_d are chosen (as usual happens running in RCCI mode) the Diesel ignition delay increases due to the local air-fuel ratio “over-lean” might become dominant with respect to the effect of injection phasing.

In order to highlight all phenomena during combustion of very small Diesel quantities, the apparent rate of heat release (ROHR) has been calculated from the in-cylinder pressure through Equation 6:

$$ROHR = \frac{\gamma}{\gamma-1} \cdot P \cdot \frac{dV}{d\theta} + \frac{1}{\gamma-1} \cdot V \cdot \frac{dP}{d\theta} \quad (6)$$

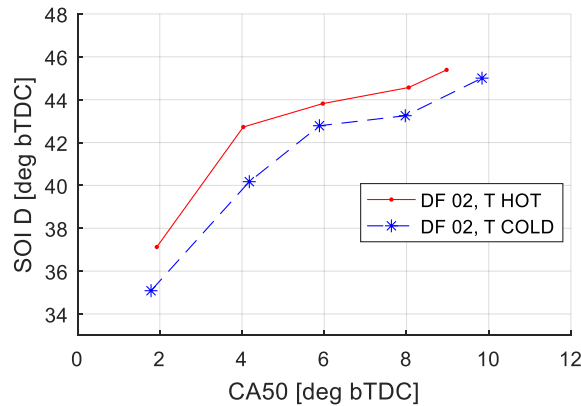
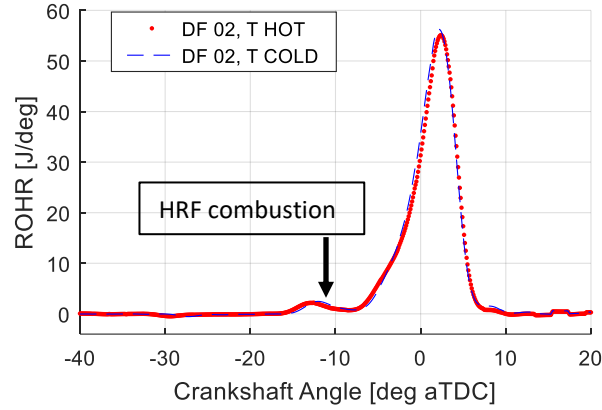
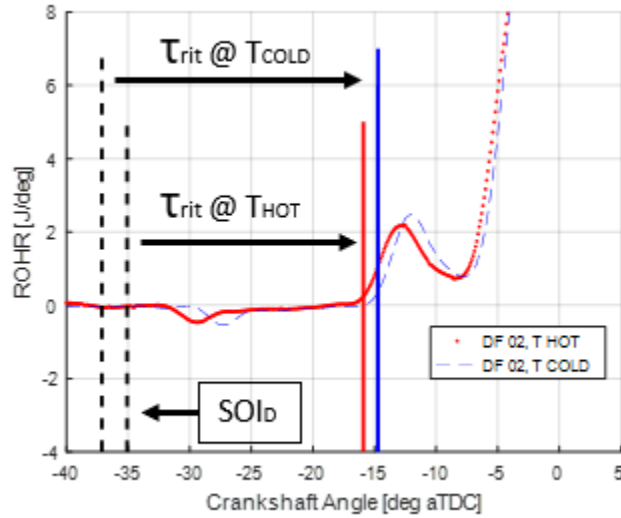


FIGURE 4. Injection parameters (SOI_d) difference running with different engine thermal conditions



(a)



(b)

FIGURE 5. Ignition delay analysis running RCCI at different intake air manifold temperature: combustions with same CA50 (a) but with different ignition delay (b).

The combustion behaviour observed in Figure 5a and 5b is common to all analysed DF values.

Using the information coming from the ignition delay analysis for all the investigated operating points, a correlation between DF, T_{SOI} and ignition delay (τ_{rit}) can be obtained.

Figure 5a and 5b report the ROHR at different intake air temperature with same CA50 and DF. Comparing the two different combustions at same CA50, it is interesting to observe differences mainly during the HRF ignition phase, Figure 4. As a result, the higher air temperature level reduces Diesel ignition delay. In order to account for this reduction, the CA50 controller will increase SOI_d which will produce the required increment of the ignition delay to keep a constant centre of combustion. Figure 4 shows also two different angular positions of HRF vaporisation in line with different SOI_d actuated.

IGNITION DELAY MAPPING

As mentioned above, in order to improve the CA50 controller behavior far from the reference mapping conditions in RCCI mode, an ignition delay map can be obtained using the estimated T_{SOI} .

First, the mapping has been carried out using the information from in-cylinder pressure. Figure 6 shows the correlation between DF, T_{SOI} and τ_{rit} .

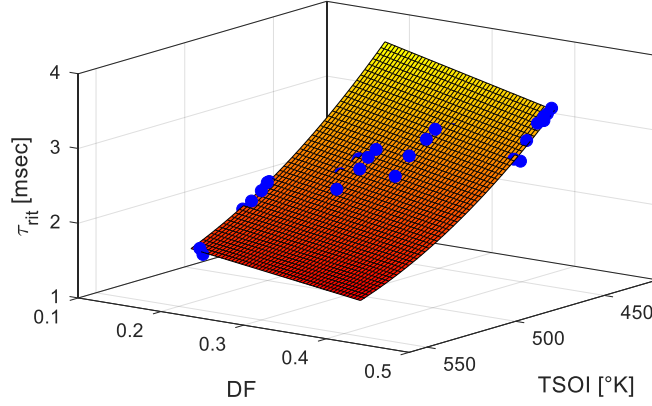


FIGURE 6. Correlation between DF, T_{SOI} and τ_{rit} calculated using thermal model

According to previous investigations, in LTC combustion there are multiple factors that strongly influence the ignition delay. Increasing the amount of gasoline changes the chemistry and the way in which heat is released modifying the thermodynamics conditions at the end of combustion. For these reasons, T_{SOI} evaluation is useful to take into account all these phenomena.

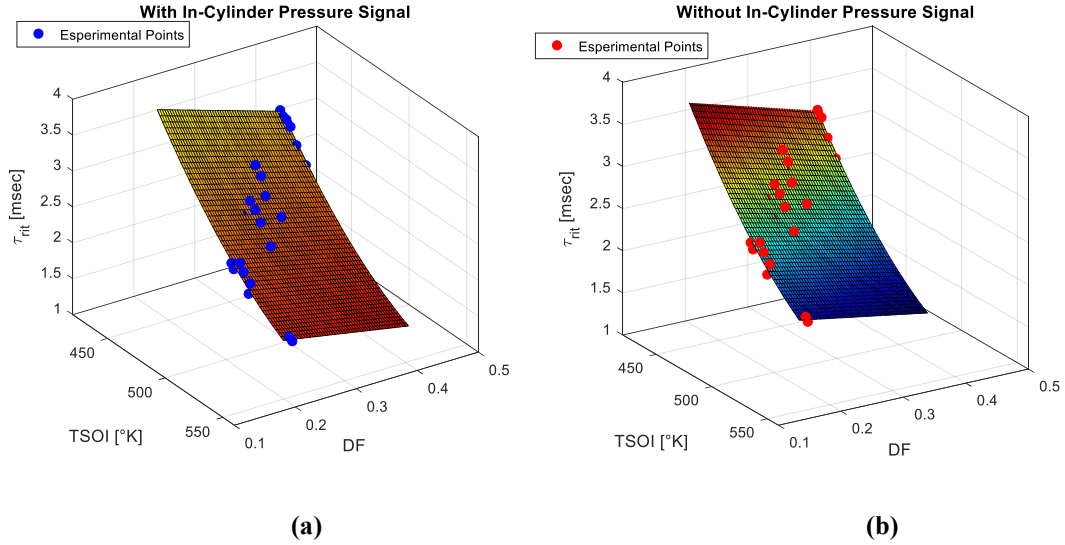


FIGURE 7. Comparison between T_{SOI} mapping carried out using in-cylinder pressure signal (a), and temperature and pressure transducers in the exhaust manifold(b)

With the aim of evaluating T_{SOI} without the quantity coming from in-cylinder pressure signal, the new mapping has been obtained using Eq. 5. Figure 7 shows a comparison between the new mapping and the old one.

As can be observed, the maps present the same shape despite the differences in term of absolute temperature values.

For these reasons, T_{EVO} computed in Eq. 1 by means of in-cylinder pressure signal can be replaced using T_{EXH} without losing information in terms of the engine thermal conditions.

As discussed, temperature model can be used to improve the behavior of the closed-loop combustion controller. Furthermore, the T_{SOI} calculation can be performed using measures coming from sensors placed in the exhaust manifold.

For these reasons, the new T_{SOI} map can replace the ignition delay map obtained using in-cylinder pressure information.

The thermal model was implemented together with a lookup table (function of speed and load) containing the information of the ignition delay of the mixture during reference operating conditions obtained using low-cost sensors.

The simultaneous knowledge of both current ignition delay (predicted using T_{SOI} model) and reference ignition delay can be used to calculate the deviation due to the different engine thermal conditions. This deviation is converted into a SOI_d offset that can be used as a feed-forward SOI_d correction of the base SOI_d map. The scheme of the closed-loop CA50 controller, modified adding the ignition delay map and T_{SOIref} is summarized in Figure 8.

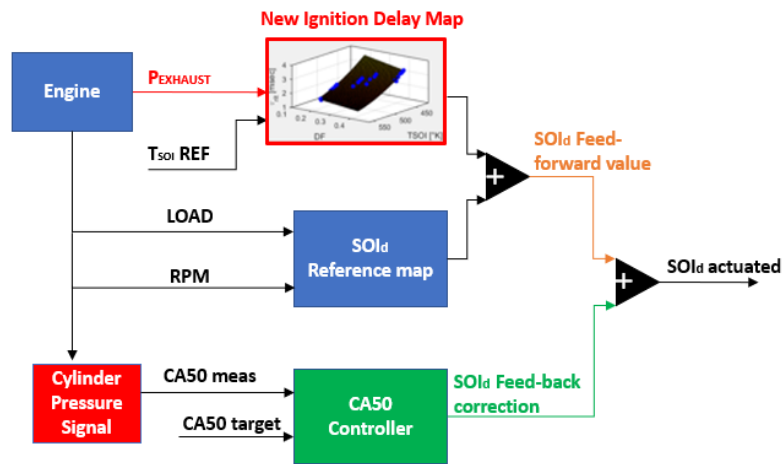


FIGURE 8. Scheme of the modified CA50 closed-loop controller with new ignition delay map

CONCLUSIONS

This work presents an experimental study of RCCI combustion, performed running a light-duty 1.3L Diesel engine modified with the installation of an additional gasoline injection system.

As widely discussed in literature, the ignition mechanisms of dual-fuel combustion are very sensitive to cylinder thermal conditions, which results in combustion instability and very high cycles-to-cycles variability.

As mentioned above, to control this LTC combustion a real-time closed-loop CA50 controller has been implemented.

The combustion analysis demonstrated that the injection parameters strongly depends on cylinder thermal conditions, that need to be compensated to avoid excessive closed-loop corrections.

To properly compensate the difference between reference mapping conditions and operation conditions an ignition delay map using thermal model has been developed and implemented in the RCP system for ignition control.

In order to reduce the cost of the control system, the data required to estimate T_{SOI} coming from in-cylinder pressure has been replaced using low-cost sensors, such as thermocouples and pressure transducers, placed in the exhaust manifold.

Using the ignition delay calculation based on the estimated T_{SOI} , the combustion controller can keep stable the RCCI combustion running the engine far from the thermal reference conditions. Furthermore, with the purpose of reducing the cost of the control system, the new T_{SOI} mapping has been performed using the information coming from low cost sensors placed inside the intake and the exhaust manifold.

Further investigations to verify the CA50 controller behavior using the new T_{SOI} mapping is currently being performed. In addition, to further improve the performance of the controller during transients, the effects of other deviations, such as lambda, are being studied.

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