Performance of a conventional diesel aftertreatment system used in a medium-duty multi-cylinder dual-mode dual-fuel engine

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Abstract

Dual-mode dual-fuel combustion stands as one of the promising techniques to allow the dual-fuel operation along the whole engine map. This concept relies on using different combustion strategies as reactivity controlled compression ignition up to medium load, then migrating to diffusive dual-fuel combustion to reach full load. With this strategy, it is possible to obtain sensible reductions in NOx and soot while providing improvements in fuel consumption and CO_2 emissions. However, the excessive quantities of HC and CO together with the low exhaust temperature can compromise the diesel oxidation catalyst (DOC) efficiency. In addition, the diffusive dual-fuel combustion applied at high engine load produces considerable soot amounts that should be reduced within the diesel particulate filter (DPF).

Based on these facts, this work intends to evaluate the efficiency of a commercial aftertreatment system (DOC+DPF) while operating in dual-mode dual-fuel combustion. Additionally, fundamental studies where developed to understand the impact of the combination of fuels on the exhaust hydrocarbon species. First, the DOC performance was evaluated at steady-state and transient conditions under different operating conditions fulfilling the EUVI NOx and soot limits. In parallel, the different engine-out hydrocarbon species were measured by means of a Fourier-transform infrared spectroscopy (FTIR) gas analyzer. Finally, the passive and active regeneration processes were assessed by means of different methodologies aiming to evaluate the low NOx-low soot interaction and the capability of the active regeneration in dual-fuel dual-mode (DMDF) operating conditions. The DOC results showed an improper conversion efficiency at low load operating condition, where the exhaust temperature is low. By contrast, the thermal inertia at transient conditions allowed to improve the DOC behavior at low load, reaching DOC-out emissions one order of magnitude lower than those from the steady-state tests. Concerning the DPF, it was demonstrated that the low concentration of NOx and soot produced during the combustion does not lead to sensible changes in the NO_2/NOx ratio before and after the DPF, indicating a low level/absence of passive regeneration. In the case of the active regeneration, both conventional diesel combustion (CDC) and DMDF operating conditions can obtain satisfactory reduction in the total soot trapped, being the increase in the exhaust

temperature consequence of the HC and CO conversion the supporting mechanism for the active regeneration in the DMDF concept.

Keywords

Dual fuel combustion; aftertreatment; emissions; catalyst; speciation; particulate filter

1. Introduction

The internal combustion engines (ICEs) became fundamental devices in the daily life since the discovering of the Otto and Diesel cycles. Years after this event, the ICEs stand as the most used powertrain, representing 99.9% of the power used in the transport sector [1]. The light-duty vehicle market is shared by diesel and gasoline vehicles in similar proportion, while diesel engines are found to be dominant on medium and heavy-duty transportation [2]. This fact is mainly justified by its high efficiency with moderate engine-out emissions [3]. The engine-out emissions levels have been reduced almost 100% since the introduction of the EURO regulations in the early 90's [4]. The constraints imposed by these regulations forced the original equipment manufacturers (OEM) to develop auxiliary devices to reduce the pollutant levels to those specified by the normative [5]. Currently, the diesel powertrain requires a complex aftertreatment system (ATS) composed of different devices: diesel oxidation catalyst (DOC), diesel particulate filter (DPF) and selective catalyst reduction (SCR) [6][7]. Therefore, when the exhaust gas leave the combustion chamber, it is involved in different chemical and physical processes that allows to reduce the most hazarding substances. First, the hydrocarbon (HC) and carbon monoxide emissions (CO) are reduced in the DOC through the reaction of these compounds with the oxygen trapped in the device [8]. During this process, part of the NO present in the exhaust gas is converted to NO_2, a fundamental specie that is required to the passive DPF regeneration [9]. Leaving the DOC, the gas flow through the DPF where the particulates are trapped by the filter [10]. Finally, the NOx emissions are reduced in the SCR system by the reaction of this specie with the urea provided by an additional injector [11]. Nonetheless, the use of these devices has intrinsic drawbacks as the increased vehicle cost for the final consumer, the extra backpressure in the exhaust system, the additional maintenance, and the necessity to refill the urea reservoir periodically [12][13].

To overcome these issues, efforts on improving the combustion process are fundamental as it is the key to reduce the final pollutants concentration and consequently the aftertreatment needs. As extensively reported by the literature, the diesel combustion process cannot be optimized simultaneously for reducing both NOx and soot emissions as reducing one results in the increase of the other [14][15][16]. By this reason, new combustion strategies able to obtain similar efficiency of the diesel one with reduced emissions were investigated during the last years [17]. One of the most promising way to achieve it is by means of the low temperature combustion (LTC) concept. This nomenclature includes today several techniques as homogeneous charge compression ignition (HCCI), partially premixed compression ignition (PPCI), gasoline compression ignition (GCI), reactivity controlled compression ignition (RCCI), etc., and have as common denominator the use of high amounts of exhaust gas recirculation (EGR) with highly advanced injection strategies that improve the mixing process. This allows to reduce the emissions of both NOx and soot to virtually zero levels. Moreover, the thermodynamic efficiency of the engine cycle increases due to the heat transfer reduction and the lower combustion duration [18] - [23].

Among the different LTC concepts, RCCI strategy offers the traditional advantages from the LTC while providing better control over the combustion process by tailoring the mixture reactivity inside the combustion chamber [24]. This is done by using two fuels with different reactivity, defined as low reactivity fuel (LRF) and high reactivity fuel (HRF) [25]. Usually, the LRF is injected at low pressures with a port fuel injector (PFI) while the HRF is directly injected into the cylinder at high pressures [26]. Therefore, these independent systems can be managed to obtain different reactivity according to the operating condition. After the start of combustion (SOC), the combustion progression strongly depends on the in-cylinder reactivity stratification, mainly driven by the HRF injection conditions [27]. The reactivity gradient leads to a more sequential autoignition than other LTC concepts [28], reducing the maximum pressure rise rate (PRR) at high loads. To obtain a highly efficient operation, high portions of LRF should be used, reducing the HRF amounts to the minimum required to trigger the combustion [29][30].

The potential of the RCCI concept to obtain NOx and soot emissions under the normative constraints are extensively addressed in the literature [31][32]. RCCI has been shown to be applicable on different engine platforms and use a diversity of LRF and HRF [33]. Nonetheless, important issues as the high EGR rates needed to suppress the pressure gradients at high load, and the excessive unburned species at low load prevent its practical application [34]- [39]. Recent works demonstrated that some of these issues can be overcome by combining different combustion strategies, migrating from a fully premixed combustion to a diffusive one at high loads [40]. A successful development and implementation of this methodology was addressed by Benajes et al. with the concept so-called dual-mode dual-fuel combustion (DMDF) [41]. The DMDF concept relies on three different injection strategies according to the engine load. The first one is defined by highly advanced injections that enables a fully premixed combustion strategy at low load. As the load increases, the injection is delayed promoting a partially premixed combustion to reduce the pressure gradients. Finally, at the high load conditions, the injection settings are adjusted to obtain a dual fuel diffusive combustion. The boundary of each one of this strategy is not fixed and is directed impacted by the fuel and compression ratio [43][44].

Despite of allowing the operation in all the engine operating, the DMDF strategy still presents high amounts of HC and CO emissions at low engine load due to the fully premixed combustion [41]. Additionally, at these conditions the exhaust temperature values are lower. Both facts can compromise the proper DOC operation, resulting in excessive ATS-out emissions as compared to the normative requirements. Moreover, the gasoline to diesel ratio varies across the DMDF engine map, and therefore the chemical composition of the unburned compounds in the exhaust stream also changes. The relation between this ratio and the exhaust composition is still unclear, requiring detailed studies to determine it. On the other side, the diffusive combustion used at high loads produces considerable amounts of soot, requiring the regeneration of the DPF, by passive or active methods. However, it is not clear if the low amounts of NOx at the exhaust gases are able to react with the trapped soot in a reaction rate higher enough to reduce the soot mass. In addition, the low temperatures at the exhaust can be a problem to obtain a proper active regeneration condition.

The objective of this work is to evaluate the implications of using a DMDF strategy on the DOC and DPF devices, as a continuation of the previous work developed by the authors [42]. The novelties of this work are the analysis for all operating conditions up to medium load, the investigation of the hydrocarbon speciation at the DOC inlet and a detailed investigation of the passive and active regeneration of the DPF under different conditions. In order to do this, the same platform of the previous work was used, i.e., medium-duty multi-cylinder diesel engine equipped with its original aftertreatment system. Firstly, the DOC performance was evaluated at steady state conditions, followed by an analysis using transients to emulate the thermal inertia on the device. In sequence, the hydrocarbon speciation was assessed before the DOC to quantify the amount of the low and high reactivity hydrocarbons that are originated during the combustion process as function of the different initial conditions. Finally, a detailed analysis was performed to assess the impact of using a DMDF mode on the DPF operation.

2. Materials and methods

2.1. Engine characteristics

The investigation was performed on a medium-duty, four stroke, serial production 8L multi-cylinder diesel engine (MCE). A dedicated piston with a bathtub bowl shape optimized in a previous work was used [32]. The geometric compression ratio was reduced to 12.75:1 to allow high load operation with acceptable levels of pressure gradient. Table 1 summarizes the main characteristics of the engine.

Table 1. Engine characteristics.

Engine Type	4 stroke, 4 valves, direct injection
Number of cylinders [-]	6
Displaced volume [cm^3]	7700
Stroke [mm]	135
Bore [mm]	110
Piston bowl geometry [-]	Bathtub
Compression ratio [-]	12.75:1
Rated power [kW]	235 @ 2100 rpm
Rated torque [Nm]	1200 @ 1050-1600 rpm

2.2. Test cell description

The bench tests required different measurement devices in order to allow the simultaneous measurement of pressures, temperatures, exhaust emissions and hydrocarbons species. The details of the test cell in which the multi-cylinder engine was installed is shown in Figure 1. An AVL active dynamometer was used to control the speed and load during the tests using the AVL Puma interface. This software was also used to acquire low frequency values. During each operating condition, the values of pressure and temperature of the intake charge were monitored before and after the high-pressure exhaust gas recirculation (EGR) line. The six cylinders were instrumented with piezoelectric pressure transducers to acquire cycle-to-cycle information about the combustion process. The pressure signals were crank angle related by a digital encoder with a resolution of 0.2 CAD and acquired by a NI PXIe 1071. This information was used to perform an online heat release (HR) analysis of each cylinder by a routine developed in LabView. The same routine was used to acquire high frequency signals and to control the injection settings of the LRF and HRF and the low pressure EGR system. This last one was developed due to the high EGR demand. For this, the original exhaust line was modified to include a cooler, filters and dryers for particulates and water. Additionally, an electric backpressure valve in the exhaust line, in conjunction with regulators valve near to the intake, were installed to allow the control of the EGR rate.

The exhaust pressure and temperature were monitored at the exhaust manifold as well as at different points of the exhaust line. The original aftertreatment system (ATS), composed of a DOC, DPF and SCR (this last deactivated for all conditions), was installed after the backpressure valve, 1300 mm far from the exhaust manifold. This distance was selected to be representative of the OEM configuration. The ATS was fully instrumented to obtain information for each place of interest (before and after the DOC, and after the DPF). Pressure and temperature transducers were instrumented for each one of the measurement location. A five-gas Horiba MEXA-7100 DEGR analyzer was used to measure the gaseous engine-out emissions upwards and downwards the DOC and after the DPF. In conjunction a Fourier-transform infrared spectroscopy (FTIR) HORIBA MEXA-6000FT was used to assess the hydrocarbon composition. The measurements in the three locations were done alternatively. In this case, each operating point was measured three times along a period of 60 seconds with the emissions test probe located upwards the DOC. Later, the same procedure was done with the emissions test probe located downwards the DOC. Finally, the emissions values were measured after the DPF. Smoke emissions were measured in filter smoke number (FSN) units using an AVL 415S smoke meter. Three consecutive measurements of 1 liter volume each with paper-saving mode off were took at each engine operating point [45]. The geometrical parameters of the DOC and the DPF used in this investigation are listed in Table 2 whilst the accuracy of the main elements of the test cell is presented in Table 3.

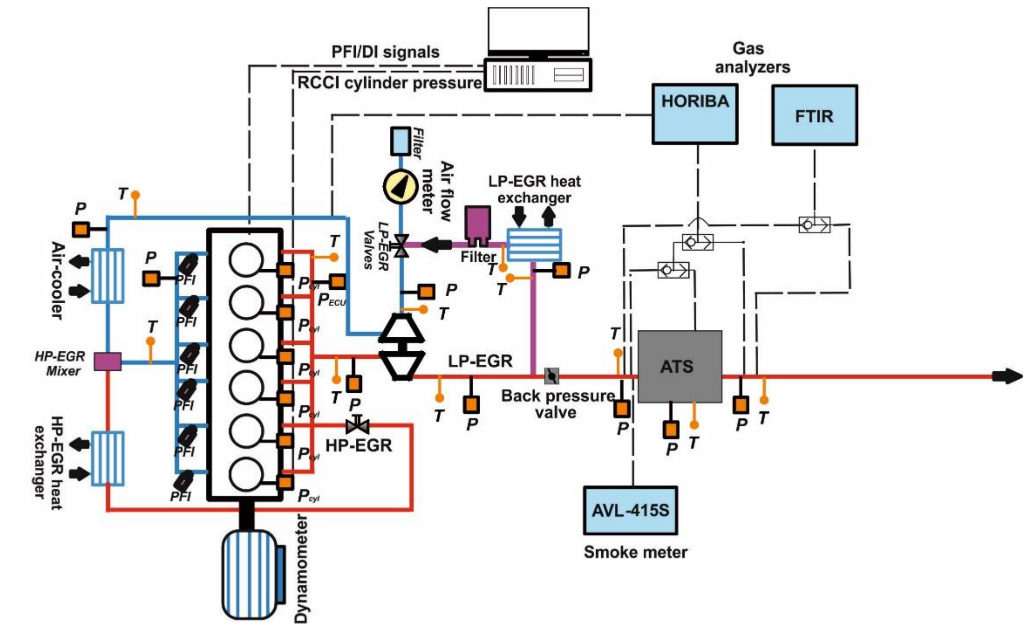

Figure 1. Test cell scheme.

Table 2. Characteristics of the diesel oxidation catalyst and Diesel particulate filter used in this work.

DOC	
Diameter [m]	0.266
Length [m]	0.102
Cell density [cpsi]	400
Total volume [dm^3]	5.7
DPF	
Substrate	Cordierite NGK
Diameter [m]	0.266
Length [m]	0.254
Cell density [cpsi]	200
Volume[dm^3]	14.2

Table 3. Accuracy of the instrumentation used in this work.

Variable measured	Device	Manufacturer / model	Accuracy
In-cylinder pressure	Piezoelectric transducer	Kistler / 6125C	±1.25 bar
Intake/exhaust pressure	Piezoresistive transducers	Kistler / 4045A	±25 mbar
Temperature in settling chambers and manifolds	Thermocouple	TC direct / type K	±2.5 °C
Crank angle, engine speed	Encoder	AVL / 364	±0.02 CAD
NOx, CO, HC, O_2, CO_2	Gas analyzer	HORIBA / MEXA 7100 DEGR	4%
C_3H_6, C_2H_4, C_2H_6, 1,3-C_4H_6, C_6H_6 and C_7H_8	Gas analyzer	Horiba Mexa - 6000FT	4%
FSN	Smoke meter	AVL / 415	±0.025 FSN
Gasoline/diesel fuel mass flow	Fuel balances	AVL / 733S	±0.2%
Air mass flow	Air flow meter	Elster / RVG G100	±0.1%

2.3. Fuels and injection systems characteristics

The DMDF concept requires using two fuels with different reactivity to obtain proper control over the combustion process. In this research, the DMDF operation was promoted using EN 590 diesel as high reactivity fuel and EN 228 gasoline with research octane number (RON) 95 and sensitivity 9.9 as low reactivity fuel. Additional fuel characteristics are presented in table 4.

Table 4. Physical and chemical properties of the fuels.

	EN 590 diesel	EN 228 gasoline
Density [kg/m^3] (T= 15 °C)	842	720
Viscosity [mm^2/s] (T= 40 °C)	2.929	0.545
RON [-]	-	95.6
MON [-]	-	85.7
Cetane number [-]	51	-
Lower heating value [MJ/kg]	42.50	42.4

The HRF (diesel) was injected into the cylinder using the stock common-rail fuel injection system, with a centrally located solenoid injector. The gasoline was port fuel injected by means of PFI located at the intake manifolds. All the injectors were handled through a DRIVVEN control system [40]. The direct injected (DI) and PFI fuel mass flows were measured using dedicated AVL 733S fuel balances. The main characteristics of the DI and PFI are depicted in Table 5.

Table 5. Characteristics of the direct and port fuel injectors.

Direct injector		Port fuel injector	
Actuation Type [-]	Solenoid	Injector Style [-]	Saturated
Steady flow rate @ 100 bar [cm^3/min]	1300	Steady flow rate @ 3 bar [cm^3/min]	980
Included spray angle [°]	150	Included Spray Angle [°]	30
Number of holes [-]	7	Injection Strategy [-]	single
Hole diameter [µm]	177	Start of Injection [CAD ATDC]	340
Maximum injection pressure [bar]	2500	Maximum injection pressure [bar]	5.5

2.4. Combustion strategy description

The major claim of the RCCI combustion is the ability to obtain engine-out values for NOx and soot bellow the normative standards while maintaining diesel-like efficiencies. Nonetheless, the excessive pressure gradients at high load conditions in conjunction with the low combustion efficiencies at low engine loads are constraints that restricts the operation of the concept. To overcome this issue, developments were made aiming to operate with different injection strategies, relaxing the final constraints regarding emissions. One promising concept was presented by Benajes et al. [43], so-called dual-mode dual-fuel strategy. Figure 2 presents the fundamentals of the injection process to each one of the zones inside the operating map, as well as their characteristic heat release profiles.

As it can be seen, a fully premixed combustion strategy (i.e., RCCI) is used for the low load conditions, achieving indicated mean effective pressure (IMEP) values up to 9 bar. In this zone, a highly advanced diesel injection strategy is used obtaining premixed conditions before the combustion start. As result, the combustion products contain low concentrations of both NOx and Soot with lower fuel consumption values [43]. However, the exhaust temperature values are lower with increase HC and CO emissions. As the engine load is increased, the second diesel pulse is shifted towards TDC. This allows to avoid excessive pressure gradients. In this strategy, the NOx emissions are still under the EURO VI levels, but soot emissions start to be penalized due to the lower mixing time for the second diesel injection. At high load, a diffusive dual-fuel strategy must be implemented to avoid excessive PRR. In this area, the peak NOx and soot values are around 1.5 g/kWh, as those found during CDC.

From this brief description it is possible to note that the DMDF products can be challenging to deal with in the aftertreatment system. The lower temperatures with the excessive amounts of HC and CO from the RCCI operation can compromise the DOC operation. In addition to this, the soot production from medium to high load can increase the soot load on the DPF, requiring frequent regenerations. However, the low NOx amounts produced together with the low temperature values changes the dynamic of both passive and active regeneration. Therefore, it is clear the interest to investigate the performance of these devices on a multi-cylinder engine with its original ATS.

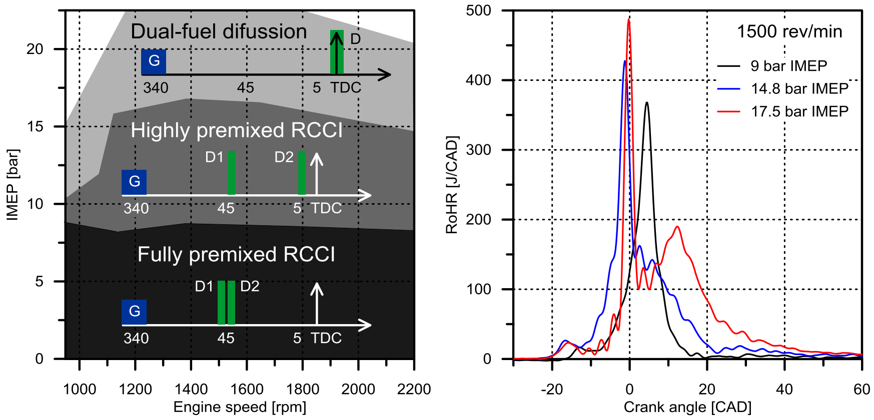

Figure 2. Characteristics zones and heat release rates of the DMDF combustion strategy [43].

3. Results and discussion

The results are divided into two subsections. The first one addresses the performance of the Diesel oxidation catalyst on steady state and transient conditions as well as the speciation of the hydrocarbons for the different operating conditions that were tested. Finally, the results for the DPF are presented, illustrating its response regarding passive and active regeneration for different operating conditions under DMDF regime.

3.1. Performance of the Diesel oxidation catalyst

3.1.1. DOC performance in steady conditions

First of all, the DOC performance was assessed in steady-state conditions in order to verify the DOC behavior and the critic conditions in which the DOC does not work properly. To guarantee steady-state operation, a temperature-based criterion was defined, imposing a maximum DOC outlet temperature variation of 1°C in a time interval of 120 s. The measurements were started from the time were this condition was accomplished. The DOC outlet temperature evolution profile is illustrated in Figure 3 followed by its variation.

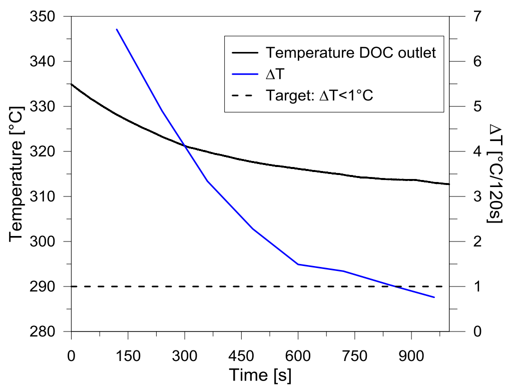

Figure 3. Definition of steady-state condition based on the temperature difference

It is possible to verify that the temperature profile presents an asymptotic behavior. This implies that the required time to reach a fully stabilized condition tends to infinite. Nonetheless, it is also clear that the chosen criterion is able to guarantee a quasi-steady state operation. Therefore, the same strategy was employed for all operating conditions tested during this work. Additionally, a cleaning step between each operating condition was included in the methodology in order to avoid HC and CO residuals from the previous measured condition, thus reestablishing the same initial condition for all cases. The methodology is summarized in the diagram shown in Figure 4.

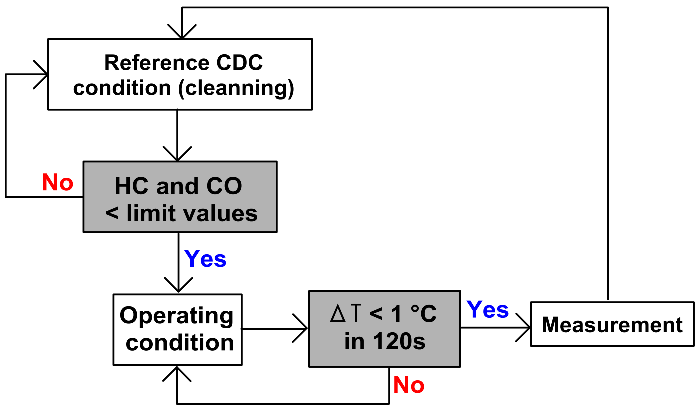

Figure 4. Measurement methodology employed to the steady state measurements for DOC evaluation.

Following the methodology described above, several operating conditions were tested addressing different engine speeds and loads. The results obtained for both HC and CO emissions at the DOC outlet are presented in Figure 5. The region above the white dashed line satisfies the EUVI limits. In the region between the white and red dashed lines, the emissions levels are up to two times the levels imposed by the EUVI regulation. Below the red dashed line, the emissions exceed the EUVI limits by far. As it can be seen, the major issues regarding the DOC operation are found at low load conditions. At these conditions, the exhaust flow temperature/energy is not high enough to achieve the light-off condition in the DOC. Therefore, the DOC-out emissions are similar to those at the inlet. Nonetheless, as the load increases, the temperature values at the exhaust reach levels that allow the proper operation of the DOC. Then, the resultant values start to be close to the normative ones. It is interesting to note that the CO emissions have a narrower range in the EUVI>emission>2xEUVI condition. In the case of this specie, once the light-off temperature is reached, it is fully converted. Controversially, the HC has a broad range where the condition EUVI>emission>2xEUVI is fulfilled. It can be concluded from this that the required energy to convert the HC is considerable higher compared to the CO. This can also indicate that the exhaust emissions are composed by hydrocarbons with low reactivity that requires higher amounts of energy to be fully converted.

Therefore, it is clear that strategies to improve the operation at low engine loads should be investigated to guarantee a proper operation of the DOC that results in emissions values lower than the normative ones.

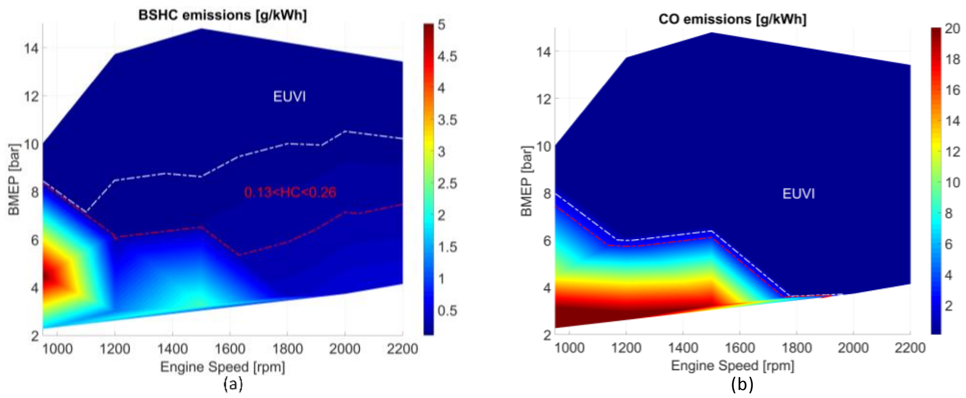

Figure 5. DOC conversion efficiency for (a) unburned hydrocarbons and (b) carbon monoxide for steady state conditions.

3.1.2. DOC performance in transient conditions

Generally, different strategies are used to overcome the issues at low load discussed in section 3.1.1. The use of post injections to heat up the DOC as well as the use of the thermal inertia during decelerations are frequently employed [46]. Whilst the first one can be done during the engine start up, the second can only be used when the aftertreatment system is already hot. Despite of this, the use of thermal inertia can be interesting in low load conditions and decelerations to obtain values closer to those imposed by the normative. Therefore, the potential of the thermal inertia to improve the conversion efficiency values at low load was evaluated. For this, the engine was set to a reference condition at 50% of engine load @ 1800 rpm and subsequently taken to the operating condition to be tested. Then, the thermal inertia from the baseline condition (1800 rpm/50% load) could be used to improve the oxidation process.

Figure 6 illustrates the results achieved for the experiments. It can be seen that a sensible improvement was verified for both emissions. In the case of the HC, the maximum values were reduced by a factor of 10, allowing to obtain a broader range inside the condition EUVI>emission>2xEUVI. Additionally, the larger zone inside the EUVI limits can also support to obtain driving cycle results inside the normative values. The CO emissions presented an effective conversion over all the conditions tested fulfilling the normative restrictions showing that this emission can be dealt with in during driving conditions.

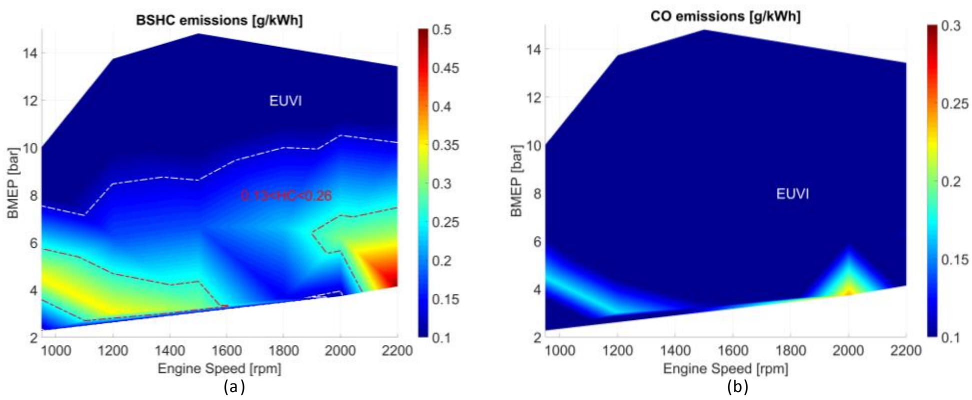

Figure 6. DOC conversion efficiency for (a) unburned hydrocarbons and (b) carbon monoxide for transient conditions.

3.1.3. Hydrocarbon speciation

The DOC conversion efficiency is strongly related to the species in the exhaust flow, mainly to the hydrocarbon compounds. The understanding of the catalytic process and the design of an effective DOC relies on the knowledge of the species that will be dealt with in this device, allowing to select the best coverage compound. Several studies addressed this subject in diesel and gasoline engines being the basis to determine the proportions of the different reactive compounds for simplified modelling of catalyst devices [47][48]. Despite of this, the use of dual-fuel combustion has implications on the hydrocarbon composition due to the different fractions of low and high reactivity fuels used in the different operating conditions. Therefore, it was carried an auxiliary study to investigate the effects of using dual fuel combustion on the hydrocarbon compositions for different engine loads and engine speeds as illustrated in Table 6. The operating conditions have its peculiarities according to the calibration, as different gasoline fraction (GF) and EGR fractions.

Table 6. Operating conditions evaluated during the speciation tests.

Load [%]	Engine speed [rpm]	O_2 [%]	GF [%]	EGR [%]
10	950	13.45	0	50
10	1200	12.08	0	48
10	1800	12.87	0	52
10	2200	10.87	0	54
25	950	10.46	49	43
25	1200	8.61	49	36
25	1800	9.11	44	43
25	2200	10.08	43	48
50	950	3.91	68	41
50	1200	2.88	81	41
50	1800	2.83	80	45
50	2200	6.76	84	38
60	950	3.82	61	37
60	1200	3.88	70	32
60	1800	4.33	57	30
60	2200	4.78	56	35

For each operating condition, the concentration of C_3H_6, C_2H_4, C_2H_6, 1,3-C_4H_6, C_6H_6 and C_7H_8 were measured, and the contribution of each specie in the total hydrocarbon was calculated by reducing all hydrocarbons to a C_1 basis. The results of this analysis are presented in Figure 7. The conditions at 10% engine load presented considerably lower values of GF. For these conditions, the quantity of high reactivity hydrocarbons or short chain hydrocarbons is higher. As the GF values are increased, there is a trend towards the increase of hydrocarbon with longer chains. Generally, the engine loads of 50% and 60% presents the higher amounts of C_7H_8 as these conditions have the higher GF levels. In this sense, it is clear that the GF plays a fundamental role on the hydrocarbon spectrum at the exhaust.

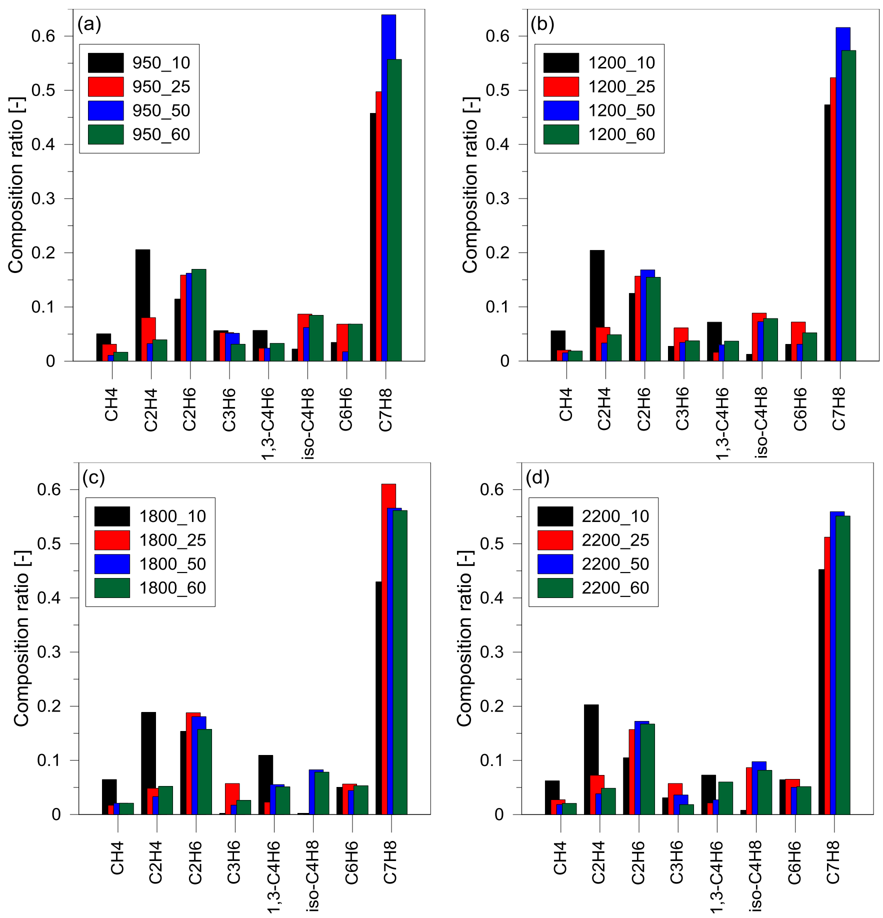

Figure 7. Different hydrocarbon species measured at the exhaust line before the DOC for 950rpm (a), 1200rpm (b), 1800rpm (c) and 2200 (d) at different engine loads.

In order to account the influence of the GF on the hydrocarbon split, the conditions previously discussed were grouped into two different groups. This approach is commonly used in modelling of DOC [49][50]. The first one, called low reactivity hydrocarbons (LRH) comprehends the hydrocarbon chains ranging from C_4 to C_7 whilst the second, named high reactivity hydrocarbons (HRH) regards the chains from C_1 to C_3. The result of this analysis is presented in Figure 8. As it can be seen, the GF values have a direct impact on the quantity of LRH and HRH. Using a second order polynomial regression is possible to obtain two different equations that allow the proper determination of the hydrocarbon split for different GF values. Therefore, the authors suggest that a proper correction over the amount of HRH and LRH should be done based on the GF of each operating condition, demonstrating that the split is scaled directly with the values of this property.

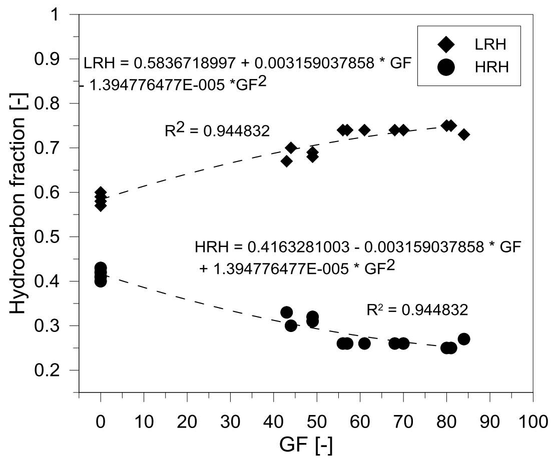

Figure 8. LRH and HRH split as function of the GF levels.

3.2. Diesel particulate filter

3.2.1. Passive regeneration- NO screening

The passive regeneration process relies on the reaction of the soot trapped in the DPF with the NO_2 from the exhaust gases. This phenomenon plays a fundamental role in assisting the cleaning of the DPF without requiring any additional fuel consumption. The process can be summarized by the global reactions as follows [51]:

$$C+2NO_2 \rightarrow CO_2 + 2NO \quad (1)$$

$$C+ NO_2 \rightarrow CO+NO \quad (2)$$

Therefore, an effective way to evaluate the passive regeneration is to assess the rate of NO_2/NO_x before and after the DPF. As it can be realized from Equations 1 and 2, the consumption of carbon inside the DPF will result in changes of the total NO_2 and NO concentrations through the DPF. In general, the total NOx emissions from Diesel combustion is composed of NO_2 in a range of 5-30% [52]. Nonetheless, the kinetic mechanisms and characteristic times that govern the RCCI combustion, and consequently the NO_2 formation, are different from the CDC combustion. Therefore, the composition of the total NO_X emitted during the combustion could be also different. Additionally, it is not clear if the low NOx concentration provided by the RCCI combustion is high enough to result in reaction rates able to reduce the black carbon to sensible levels. In this sense, the NO_2, NO and NO_x concentrations were measured in different places of the aftertreatment system: DOC inlet, DOC outlet (DPF inlet) and DPF outlet. In this way, the overall trend considering the NO_2/NO_x ratio along the aftertreatment system can be drawn. During the tests, the exhaust temperature was steeply increased by means of engine load increment. Additionally, a cleaning operating condition was used to guarantee that no previous soot was stored in the DPF. Figure 9 illustrates the results of the NO_2/NO_x ratio found at each aforementioned location.

As it can be seen, the first notable difference regards the NO_x composition right before the DOC. Differently from the Diesel combustion, the NO_x emissions are mainly composed of NO_2, being higher as lower is the exhaust temperature. As the exhaust gas flows through the DOC, exothermic reactions take place during the conversion of HC and CO, changing the final composition of the NOx emissions. This can be verified in Figure

9b, that represents the NOx composition after the DOC. It can be concluded that there is an inversion on the NO_2/NO ratio for temperatures below 200°C. Previous studies demonstrate that the NO_2 can be reduced to NO in the first period, where the HC and CO conversion is improper, allowing the NO_2 be reduced to NO through reductants present on the exhaust flow as the HC [53].

Finally, the results after the DPF are presented in Figure 9c. As it can be seen, the curves profiles as well as their magnitude remained unaltered for all conditions. This implies that all the NO_2 from the exhaust gases flows through the DPF without reacting with the soot present. It is worth to mention that in this test, there is no previous storage operating condition. Therefore, the soot present in the DPF will be as high as the one produced in the operating conditions that are tested. In this sense, it can be concluded that the low NOx emissions in conjunction with the reduced soot mass produced during the DMDF combustion does not react inside the DPF to the conditions tested. Therefore, alternative strategies as active regeneration should be used to avoid excessive soot inside the DPF.

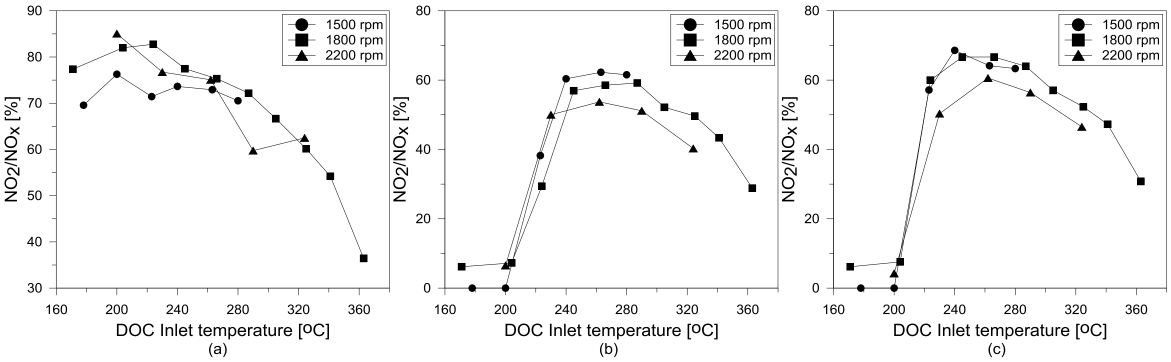

Figure 9. NO_2/NO_x profiles for different temperature and engine speeds: (a) before DOC, (b) after DOC and (c) after DPF.

3.2.2. Active regeneration

Another alternative to oxidize the soot trapped in the DPF is using high temperatures that allow to burn away the soot mass, regenerating the DPF. This method is widely used in diesel engines. However, it requires the injection of extra fuel quantity in the exhaust system with an additional injector. The injected fuel after the turbine outlet will oxidize at the exhaust system and the DOC, increasing the temperature levels up to those required to regenerate the DPF. Despite of its effectiveness, this method has an intrinsically drawback that is the increase in the fuel consumption.

An additional way to regenerate the DPF is running the engine at high load conditions, where the temperature levels are high enough to provide the required energy to oxidize the trapped soot. Regarding dual-fuel combustion, this second option is not easily achieved due to the low temperature levels obtained during the combustion process. Nonetheless, the exhaust gas contains high amounts of unburned hydrocarbons and CO from the incomplete combustion process. Once these species are converted in the DOC, they release massive quantities of energy, increasing the temperature of the exhaust flow in a process similar to the extra fuel injection at the exhaust. This temperature increase could reach levels up to those required for oxidizing the soot in the DPF.

To evaluate the suitability of this strategy to regenerate the DPF, two studies were performed. First, a dual-fuel calibrated condition (low soot) was used to increase the soot mass in the DPF with a subsequent DPF regeneration using a high temperature CDC condition. Second, the DPF was filled again. However, in this time, an operating condition producing high amount of soot was used to increase the DPF soot mas in a shorter period of time. After that, a dual-fuel condition from the calibrated map was used to verify if the temperature increase from CO and HC conversion at the DOC will be enough to regenerate the DPF properly.

In the first test, the engine was run in the operating condition from the calibration map that has the highest soot emissions for 15 hours. Measurements were made each 5 hours to evaluate the filling rate of the DPF. The results of the measurements are presented in Figure 10. As it can be seen in Figure 10a, even after 15 h, the increase of the total DPF mass was only 10 grams due to the low amount of soot produced in DMDF operation. After that, a CDC operating condition with temperatures an temperature o 390 °C was adjusted and the active regeneration was performed. Measurements were done each 20 min to evaluate the evolution of the regeneration process (Figure 10b). The soot oxidation was more preeminent during the first 20 min, decreasing the soot mas from 10 to 3 grams. From this point, the regeneration efficiency decreased due to the low reaction area. This brief analysis allowed to prove that the DMDF generates low amount of soot during its operation. Additionally, this amount of soot can be easily reduced to almost zero levels in short periods of time.

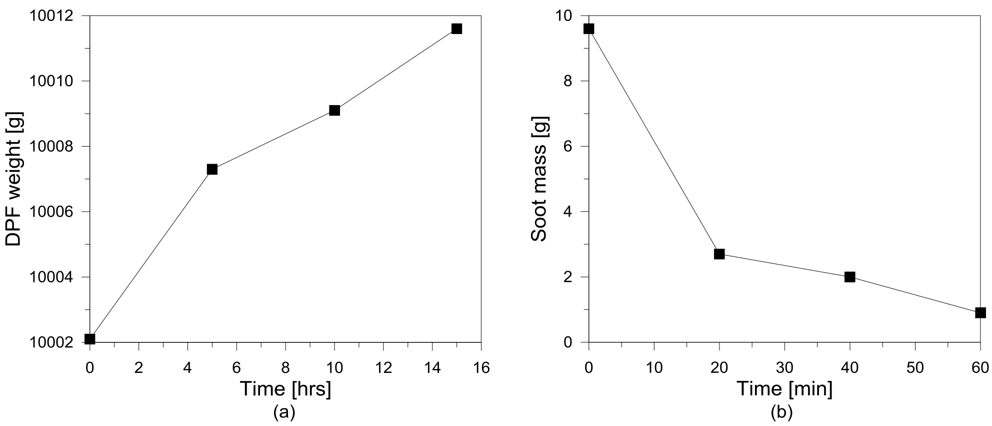

Figure 10. (a) Total mass of the DPF as function of time and (b) soot mass decrease for the active regeneration condition using CDC combustion.

Operating under DMDF combustion, temperature values over the regeneration limit (>450°C) are found only in high load conditions. However, the HC and CO oxidation in the DOC can help to increase the exhaust temperature up to levels where the DPF regeneration is possible. Therefore, this phenomenon was explored by measuring the temperature values before and after the DOC, aiming to quantify the temperature increase due to the catalysis process. Figure 11 presents the changes in the temperature values due to the conversion in the DOC for the operating conditions tested in section 3.1.3 for 50% of engine load, with two additional points at 1500 rpm and 2000 rpm. As it can be seen, the temperature values can increase up to 40^{o}C, reaching similar levels than those from CDC operating condition used in the first test. Nonetheless, it is expected a decrease in the regeneration efficiency due to the lower exhaust mass flow caused by the higher EGR rates used during the engine operation.

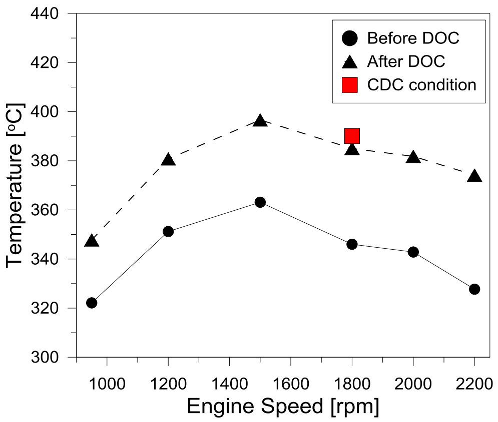

Figure 11. Temperature values before and after the DOC for the DMDF condition and the value of DOC out temperature for an equivalent CDC condition.

To evaluate the effectiveness of the DMDF concept in regenerating the DPF, the DPF was firstly filled with appreciable soot. To do this, the engine was run in a condition outside the calibration map that generates high amount of soot. After 1 hour, the total amount trapped in the DPF was 25 grams. Subsequently, the engine was run under a DMDF condition with the same load and engine speed that was previously used to assess the CDC active regeneration (1800 rpm and 50% load), measuring the DPF weight each 20 minutes. The evolution of the soot reduction obtained with this condition is depicted in Figure 12. As it can be seen, the DMDF operating condition is able to regenerate the DPF, reducing the total soot mas in 72 %. Nonetheless, the behavior is gradual compared to the CDC, where the reduction is more evident in the first 20 min.

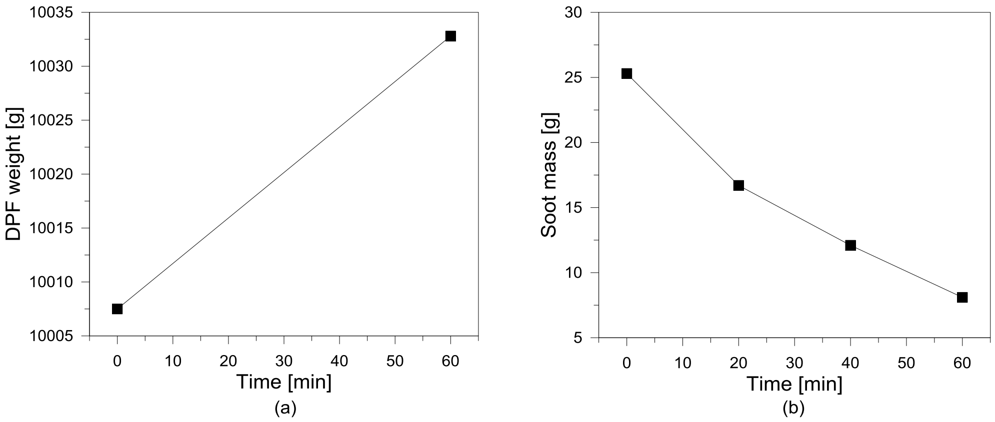

Figure 12. (a) Total mass of the DPF as function of time and (b) soot mass decrease for the active regeneration condition using a DMDF operating condition.

4. Conclusions

This paper evaluated the response of the DOC and DPF systems when operating under DMDF combustion conditions. Additionally, a hydrocarbon speciation study was performed to understand the effect of the GF values on the HC species present at the exhaust emissions.

In the first step, the CO and HC conversion efficiency in the DOC at steady state operation was evaluated for different operating conditions. For this, a dedicated methodology was developed and applied for each measurement point. The findings of this study allowed to elucidate the problems faced at low load conditions, where both

CO and HC conversion efficiencies are low. By this reason, alternative techniques should be developed to improve the DOC performance at this condition.

The results from the hydrocarbon speciation allowed to identify that the increased values of low reactivity hydrocarbons found at medium load conditions contribute to the improper performance of the DOC. Aiming to improve the DOC performance, the use of the thermal inertia of the ATS system was investigated. This method was found to be useful at transient conditions, helping to overcome the low temperature conditions found at the device during decelerations and idling. Even with the improvements found, the HC emissions were not able to fulfill the EUVI constraints. This suggests that additional improvements, as different coverages best suited to the exhaust products of this combustion concept, are needed.

The DPF investigations allowed to draw important conclusions about its behavior to be used under DMDF operation:

From the passive regeneration study, it could be concluded that the low amounts of NOx produced by the combustion concept are not enough to obtain consistent reaction rates to produce soot removal.

By contrast, different operating conditions of active regeneration have been found to be suitable to remove the soot trapped in the DPF. CDC operation show high efficiency to burn away the soot. It was also found that the use of a DMDF operating condition can be enough to produce the same temperature as the one obtained by the CDC operating condition. However, the high temperature is only achieved at the DOC outlet due to the exothermic oxidation reactions of the unburned products. It is important to mention that the difference of the total exhaust flow between CDC and DMDF can play an important role on the total transported energy. Nevertheless, the results from the active regeneration using DMDF shows that a sensible reduction can be obtained by using it.

As a summary, the present study allowed to assess the possible drawbacks resulted from the DMDF combustion concept use regarding the aftertreatment system and their possible solutions. It can be concluded that the strategies that are already employed in the diesel commercial vehicles can be extended to the DMDF concept. The only exception that was found regards the passive regeneration by the NO_2 due to the raw emissions under the normative constraints. Additionally, the speciation results can serve as a guide to select the proper coverage to deal with the HC species from the combustion.

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Abbreviations

ATDC: After Top Dead Center

ATS: Aftertreatment System

CAD: Crank Angle Degree

CO: Carbon Monoxide

DI: Direct Injection

DOC: Diesel Oxidation Catalyst

DPF: Diesel Particulate Filter

DMDF: Dual Mode Dual Fuel

EGR: Exhaust Gas Recirculation

FSN: Filter Smoke Number

GCI: Gasoline Compression Ignition

GF: Gasoline Fraction

HC: Hydro Carbons

HCCI: Homogeneous Charge Compression Ignition

HR: Heat Release

HRF: High Reactivity Fuel

ICE: Internal Combustion Engine

IMEP: Indicated Mean Effective Pressure

LRF: Low Reactivity Fuel

LTC: Low Temperature Combustion

MCE: Multi Cylinder Engine

NOx: Nitrogen Oxides

OEM: Original Equipment Manufacturer

PFI: Port Fuel Injection

PPCI: Partially Premixed Compression Ignition

PRR: Pressure Rise Rate

RCCI: Reactivity Controlled Compression Ignition

RON: Research Octane Number

MON: Motor Octane Number

SCR: Selective Catalytic Reduction