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Dossier
Development and Control of Combustion Systems
Évolutions et contrôle des systèmes de combustion

New HCCI/CAI Combustion Process Development: Methodology for Determination of Relevant Fuel Parameters

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Résumé — Développement des nouveaux procédés de combustion CAI/HCCI : méthodologie de détermination des propriétés critiques du carburant — Atteindre des niveaux d'émissions de polluants de plus en plus faibles tout en limitant les émissions de CO_2 sont les 2 principaux challenges de l'industrie automobile. De nombreuses recherches sont actuellement menées sur les nouveaux modes de combustion tels que la CAI *(Controlled Auto-Ignition)* pour les moteurs à allumage commandé ou le HCCI (Homogeneous Charge Compression Ignition) pour les moteurs diesel. Ces nouveaux procédés ont en effet le potentiel de réduire d'un facteur de 10 à 100 les émissions de NOx et de particules par rapport à des moteurs à allumage commandé ou diesel « classiques ». La principale difficulté freinant le développement de ces nouveaux moteurs reste leur zone de fonctionnement limitée en termes de régime/charge en raison des limitations en émissions de NOx et en bruit. Une des voies les plus prometteuses permettant d'augmenter la zone de fonctionnement CAI réside dans une formulation du carburant optimisée afin d'améliorer l'initiation de la combustion en modifiant et contrôlant les propriétés d'auto-inflammation et/ou les propriétés physiques et chimiques.

Afin de sélectionner les carburants, une nouvelle procédure permettant une meilleure caractérisation de l'impact du carburant sur le fonctionnement moteur pour un grand nombre de points de fonctionnement a été mise en place. L'utilisation de cette méthode pour une large gamme de carburants, formulés en fonction de leurs propriétés d'auto-inflammation, leur volatilité et leur composition chimique a permis de souligner la complexité de l'impact carburant et a permis de mettre en avant les principales caractéristiques permettant d'optimiser la formulation de ceux-ci.

Abstract* — *New HCCI/CAI Combustion Process Development: Methodology for Determination of Relevant Fuel Parameters — *To pass the simultaneous emission requirements for near zero pollutant and for low CO_2, which are the challenges of future powertrains many research studies are currently carried out over the world on new engine combustion processes, such as the Controlled Auto-Ignition (CAI^{TM}) for gasoline engines and the Homogeneous Charge Compression Ignition (HCCI) for diesel engines. These new processes have the potential to reduce, by a factor from 10 to 100, the NOx and articulate emissions (PM) in comparison with a typical gasoline or diesel engine. The main issue in the development of such combustion modes remains the limited range of engine speed and load that enable good engine running, according to required levels for NOx and noise emissions. One of the most promising ways to increase the CAI combustion range lies in the formulation of dedicated fuels, optimised to enhance combustion initiation by modifying and controlling the auto-ignition characteristics and/or the fuel physical and chemical properties.*

To select the fuels, a new procedure has been set-up that allows a better characterization of the fuel impact on engine running in CAI, for various conditions of speed and load. The use of this methodology for a large set of fuels, formulated according to their auto-ignition characteristics, volatility and chemical composition has underlined the complexity of the action of fuel and has enabled one to point out the most influent fuel characteristics to over as large as possible requirements.

INTRODUCTION

Fuels and engines used in road transportation have to face two main challenges in a highly competitive economy:

– To reduce pollutant emission levels to such values that air quality in the cities complies with World Health Organization standards;
– To reduce carbon dioxide emissions (CO_2) which is regarded as the major greenhouse gas contributing to global warming and climate change.

In order to face these two challenges, new combustion mode such as CAI (Controlled Auto-ignition) or HCCI (Homogeneous Charge Compression Ignition) can have an important potential, by strongly reducing the NOx emissions and consequently being able to pass emission levels without important post-treatment systems, which often induce a high cost in terms of CO_2 emissions ([1] to [12]).

1 DEVELOPMENT OF A FUEL CHARACTERIZATION METHODOLOGY

Among the parameters affecting the CAI range, one of the key issues for the CAI combustion process based on the use of a high rate of internal EGR is the precise control of the switch from the CAI mode to the classical SI one necessary at very low load (for combustion stability reasons) and at high load (to avoid knock). For that purpose, several companies have developed variable valve trains able to change valve timing from cycle-to-cycle [13, 14]. These systems could help to make more flexible the cycle to cycle combustion control and to extend the CAI application range, which is the other key issue of the concept. But they remain, for the moment, rather complex, expensive and they induce a significant increase of engine parameter to control.

Another parameter which could significantly affect the performance of new CAI & HCCI combustion processes is the fuel composition as shown by Foster [15]. To use specific fuels or additives could be an interesting way of obtaining more benefit from the CAI combustion process by extending its application range [16-19]. The IFP background and know-how already pointed out this significant influence of fuel composition and physical properties on CAI combustion (especially in terms of operating range, pollutant emissions and noise, etc.). In previous work on 2-stroke CAI engines, IFP showed that the benefits of such new combustion processes could be greatly enhanced with more appropriate fuel (and/or additives) formulations which have to be studied and developed. To start such kind of study, it was necessary to define a testing procedure allowing one to evaluate the fuel effect on the CAI.

1.1 Method Description Basic Principle

The method that has been developed has been described in previous publications [20, 21]. Only the most important points are consequently summarized in this paper.

The method is based on an index, called "CAI Number" or CAN. This index was initially developed for 2-strokes engines [9]. It has then been adapted for 4 strokes engines [20].

The principle of this method is basically:

– definition of engine running limitations (intake air pressure, combustion noise, NOx emissions, engine stability;
– evaluation of the CAI running zone for each fuel with these parameters;
– comparison of this CAI running zone with the one measured with a reference fuel;
– calculation of a CAI Number defined by the ratio between the surface covered by each CAI zone on a speed/load representation (see *Figs.1* and *2*).

This method is summarized in Figure 1.

The CAI range is limited at low speed/low load by engine stability: the temperature is too low to ensure a correct auto-ignition of the air/fuel mix and consequently the IMEP becomes highly unstable (misfiring). At high load, several cumulative phenomena tend to limit the operating range. The combustion noise can reach the 90 dB limitation and in some cases, the maximum acceptable NOx level can be reached limiting also the level of load. Another high load limiting factor could be with some particular «low noise/low NOx/CAI» fuels, the intake air flow itself. As explained before, when the maximum intake pressure is used, the maximum volumetric efficiency becomes limited by the «negative valve overlap» configuration used in this study to get CAI part load operation. Therefore, it must be pointed out that in the results presented here, the two first criteria (noise and NOx) are really dependant on the fuel effect while the third one (limited volumetric efficiency) could sometimes (with fuels adapted for high load CAI) limit the level of maximum load in CAI independently of the fuel effect.

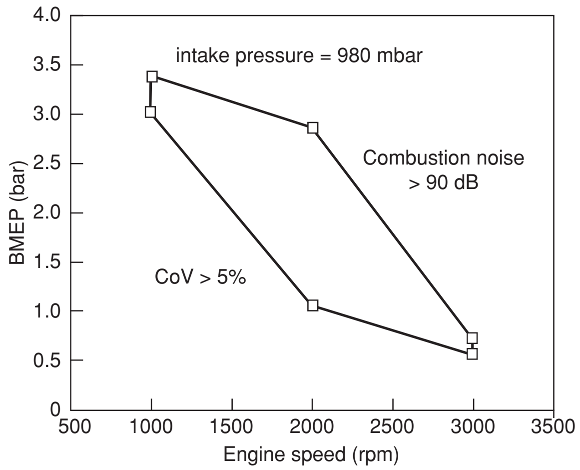


Figure 1

CAI running zone definition.

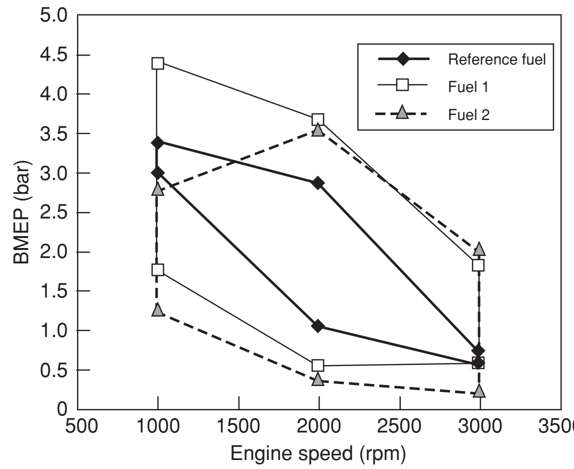


Figure 2

Comparison of fuel effect on CAI running zone.

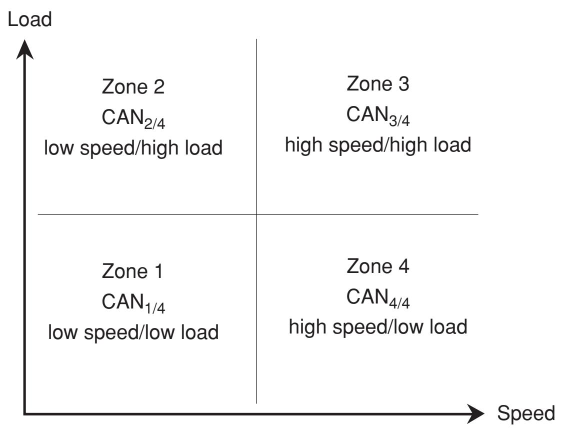


Figure 3

Speed/load field division in 4 zones.

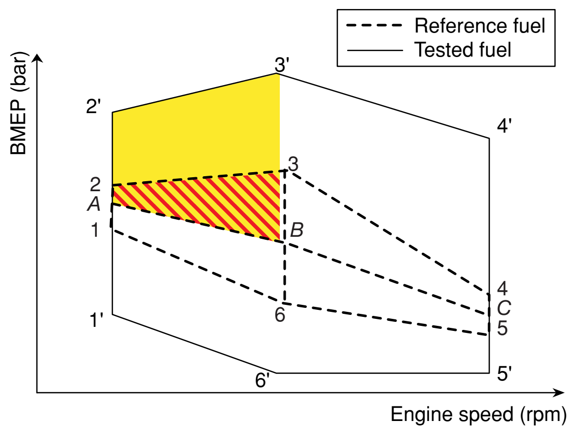


Figure 4

Principle of CANs calculation.

This method has been tested on various fuel types and it has been shown that:

– it allows one to discriminate fuels according to their impact on CAI running zone;
– nevertheless, this method was too simple to obtain a correct interpretation of combustion phenomena. Indeed, 2 fuels can have a similar index and have a radically different behavior, as shown in Figure 2. These Figures show that the 2 best fuels have a radically different behavior, despite their similar CAN indices: the fuel 1 tends to enhance CAI combustion for low speed/low load running points, while the fuel 2 tends to increase the CAI combustion in both low load and high load zones, especially at low engine speed. Consequently, the calculation of one value seems not to be sufficient to completely describe all the fuels behavior in 4-stroke CAI running conditions and has to be completed.

1.2 Modification of the Characterization Procedure

As shown above, a comprehensive index indicating the fuel effect on CAI range has to describe all the speed and load running conditions. The CAN index for CAI 4-stroke engines has consequently been divided into 4 parts in order to describe the effect of fuel on the 4 types of running conditions (see *Fig. 3*):

In order to calculate these 4 indicators, the CAI range obtained with reference fuel (area 1-2-3-4-5-6 in Figure 4) has been divided into 4 zones, defined according to the mean value of minimum and maximum BMEP obtained for each engine speed:

– low speed / low load (zone 1);
– low speed / high load (zone 2);
– high speed / high load (Zone 3);
– high speed / low load (Zone 4).

– 1000 rpm $\left(\text{point A} = \frac{(1)+(2)}{2}\right)$

– 2000 rpm $\left(\text{point B} = \frac{(3)+(6)}{2}\right)$

– 3000 rpm $\left(\text{point C} = \frac{(4)+(5)}{2}\right)$

The 4 CANs are then calculated according to the formulas:

$$CAN_{2/4} = \frac{\text{area } (A - 2' - 3' - B)}{\text{area } (A - 2 - 3 - B)}$$

$$CAN_{1/4} = \frac{\text{area } (A - 1' - 6' - B)}{\text{area } (A - 1 - 6 - B)}$$

$$CAN_{3/4} = \frac{\text{area } (B - 3' - 4' - C)}{\text{area } (B - 3 - 4 - C)}$$

$$CAN_{4/4} = \frac{\text{area } (B - 6' - 5' - C)}{\text{area } (B - 6 - 5 - C)}$$

This method is more complicated than the first characterization method. Nevertheless, its main advantage is to allow more accurate analysis of the phenomenon linked to CAI combustion.

This method has been built in order to compare the effect of fuel on the CAI combustion and to explain these effects. The goal of this study was not to define an absolute scale (as for instance for autoignition properties with the octane and cetane numbers). The CAN value is consequently strongly dependant of the engine properties and may not be transposable to another engine. Nevertheless, it can be used as a comprehension tool in order to better understand fuel impact.

2 IDENTIFICATION OF RELEVANT FUEL PARAMETERS FOR CAI RUNNING

The method described above has been applied on a set of fuels in order to obtain information on the most influent fuel parameters.

2.1 Description of the Fuel Matrix

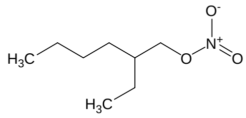
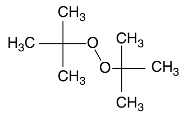
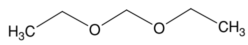
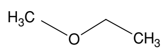
The tested fuels were divided in categories, according to their main characteristics:

– Reference fuel («REF»)
– Reference Fuel + additives («REF+»)
– Oxygenated compounds («O»), pure or in blends («BO»)
– Gasoline-like fuels («GLF»)
– Diesel-like fuels («DLF»)

The tested fuels are shown in table 1.

TABLE 1

Tested fuels composition

"REF"	Reference EN228 gasoline fuel (RON 97; MON 86)
"REF+$_1$"	Blend of reference fuel with 0.2% NEH (nitrate ethyl hexyl, a commonly used procetane additive)  **NEH**
"REF+$_2$"	Blend of reference fuel with 0.2% of ditertiobutyl peroxide (DTPe), another commercial procetane additive  **DTPe**
"DLF1"	Low sulfur Diesel fuel (50 ppm)
"DLF2"	Euro III Diesel fuel (350 ppm sulfur)
"DLF3"	*n*-heptane
"DLF4"	Wide cut kerosene, called Jet B or NATO F45, characterized by its high volatility (initial boiling point around 80°C) and an intermediate cetane index (35)
"DLF5"	Fischer-Tropsch fuel, characterized by a very high cetane number
"GLF"	Blend of fuels DLF4 (Jet B) and REF (gasoline fuel), 50% each
"GLF2"	Blend of fuels REF (EN 228 gasoline) and DLF2 (EN590 Diesel fuel)
"O1"	Ethanol
"O2"	Blend of ethanol and ethylal (50%vol each)  **Ethylal**
"O3"	Blend of methanol and methylal (50% each). This fuel was included in the fuel matrix but could not be tested, due to an engine failure  **Methylal**
"BO"	Blend of fuels DLF4 (Jet B) and O3 (methanol/methylal)

The main characteristics of these fuels are summarized in Table 2

TABLE 2

Main test fuels characteristics

	RON*	Cetane number*	Density (g/l)	IBP (°C)	FBP (°C)
REF_{+1}	70-80	< 0	740	< 50	150-200
REF_{+2}	70-80	< 0	740	< 50	150-200
DLF1	< 0	50	840	> 200	> 300
DLF2	< 0	50	830	> 200	> 300
DLF3	0	56	680	50-100	100-150
DLF4	< 0	35	810	< 50	200-250
DLF5	< 0	93	760	150-200	> 300
GLF	< 50	10	770	< 50	200-250
GLF2	30-40	40	780	< 50	> 300
O1	50-60	-	820	50-100	50-100
O2	> 100	-	790	50-100	50-100

2.2 Impact of Fuel Parameters on CAI Running

2.2.1 Cetane Index

Figure 5 shows the impact of cetane number on CAI range for low speed running points:

This Figure shows that the impact of cetane index is strongly different at low load (zone 1: increase of CAI range when the cetane index is increased) and at high load (zone 1: decrease of CAI range when the cetane index is increased). Indeed, at low load the engine temperature is low, and the main issue for CAI combustion is the start of the combustion. If the cetane index is high, the auto-ignition of the fuel will be easier, even at low temperature. The engine stability is consequently enhanced, inducing a more important CAI combustion zone.

On the contrary, at high load the CAI zone is limited by the noise level, which is linked to the start of combustion. If the cetane index of the fuel is high, the combustion will begin earlier in the cycle, the heat release rate will be higher and the noise will be increased.

Figure 5 also shows that other physical parameters have to be taken into account. For instant, the fuel «DLF5» (Fischer-Tropsch), with a very high cetane index, should be the most efficient in enlarging the zone 1 (low load, low load). This Figure shows that, on the contrary, this fuel gives one of the smallest $CAN_{1/4}$. This effect may be explained by the low density of this fuel (impact on volatilization) or by its chemical composition (paraffinic basestock).

The particular behavior of this high cetane diesel fuel shows that the best fuel for CAI running has to be chosen according to a compromise between fuel properties. It has indeed been said that a high cetane diesel fuel, due to its short ignition delay, can help the combustion ignition, and consequently increase the CAI zone at low load. Nevertheless, the low $CAN_{1/4}$ of DLF5 shows that the combustion initiation is not the only fuel parameter that has to be taken into account. All the fuel physical properties have consequently to be studied in association with combustion properties such as combustion initiation, but also overall combustion speed (heat release rate), end of combustion, etc.

2.2.2 Density

The engine used for this study was a direct injection gasoline engine. The density of the fuel may consequently have an influence on the combustion, via processes such as air/fuel mixture quality.

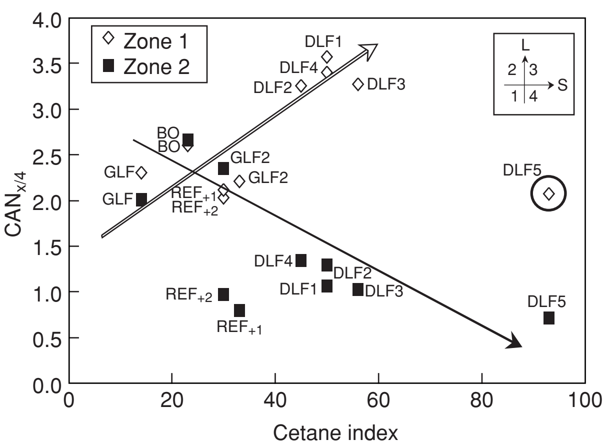
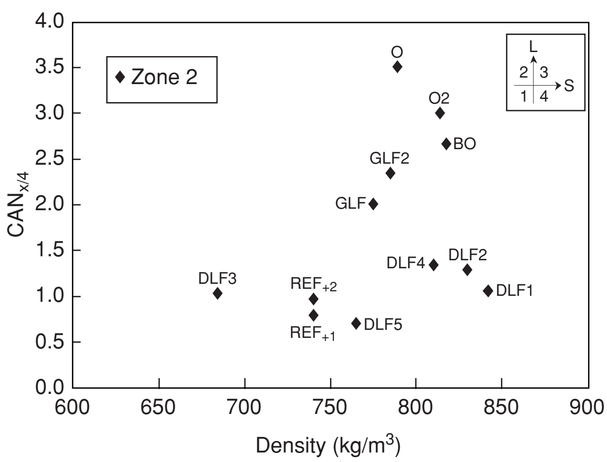


Figure 5

Impact of fuel cetane index on CAI running zone.



Fgure 6

Correlation $CAN_{2/4}$ - density of the fuel.

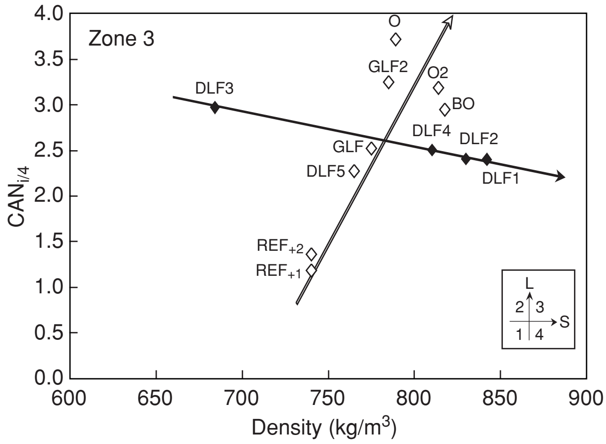


Figure 7

Correlation $CAN_{3/4}$ - density of the fuel.

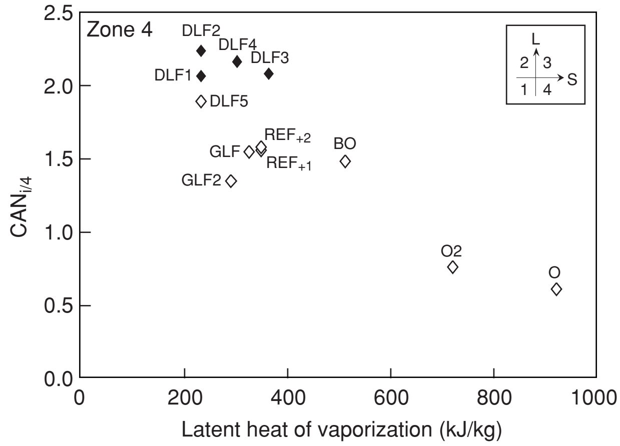


Figure 8

Correlation between LHV and $CAN_{4/4}$.

On a first approach, it seems that no clear link can be found between fuel density and $CAN_{2/4}$ (see *Fig. 6*). Nevertheless, it can be observed that the Diesel-like fuels have a different behavior. For the other fuels, the CAI zone is linked to the density (higher density means wider CAI combustion zone), while for diesel-like fuels, no clear link can be found.

In the zone 3 (high speed, high load), this behavior remains the same, as shown in Figure 7.

These Figures show that:

– for low cetane fuels, a higher density tends to increase the CAI combustion zone;
– for high cetane fuels, the density is a parameter of secondary importance.

This observation can be linked to:

2.2.3 Latent Heat of Vaporization

The latent heat of vaporization corresponds to the energy which is necessary to vaporize 1 kg of the product. A molecule with a high LHV will take away an important quantity of energy when it is vaporized, and consequently will decrease the temperature of the air/fuel mixture.

This parameter is strongly linked to the oxygen content of the molecule. Indeed, the presence of oxygen in the fuel induces the formation of intermolecular H-bonds (Van der Waals bonds), and consequently an important increase of the LHV.

The impact of this parameter on CAI running is linked to the running point (low load/high load), as shown in Figures 8 and 9.

As underlined above, all the fuels have close heating values, except oxygenated fuels.

The impact of this parameter on CAI zone is different according to the running point:

– for low load running points (zone 4), an increase of the LHV induces a decrease of the CAI zone. Indeed, the cooling effect induces a decrease of the cylinder temperature and consequently ignition difficulties at low load;
– for high load running points, on the contrary, the cooling effect tends to calm down the combustion and consequently to enhance the CAI zone.

2.2.4 Oxygen Content

In the fuel matrix, 3 fuels contain oxygenated compound: “O” (pure ethanol), “O2” (blend ethanol/ethylal) and “BO” (blend JetB/Methanol/Methylal)

Figure 10 presents the results obtained for these fuels.

This Figure shows that the impact of fuel oxygen content is dependant from the engine load. For low load (zones 1 and 4), an increase of the oxygen content leads to a decrease of the CAI running zone. On the contrary, for high load running points, an increase of the fuel oxygen content leads to an increase of the CAI running zone.

The study of the zone 1 show a specific behavior: ethanol (“O”) induces a negative CAN. The blend with ethylal (fuel “O2”) induces a strong increase of the CAN. This evolution is not due to LHV, but more to cetane number increase with ethylal.

2.2.5 Engine/Fuel Adequation

Each of the fuel properties that have been listed above have an impact on CAI combustion, and it has been outlined that it remains difficult to obtain a clear view of the global impact of the fuel.

In order to assess this impact, it is compulsory to evaluate the impact of fuel on combustion, and not only on engine behavior.

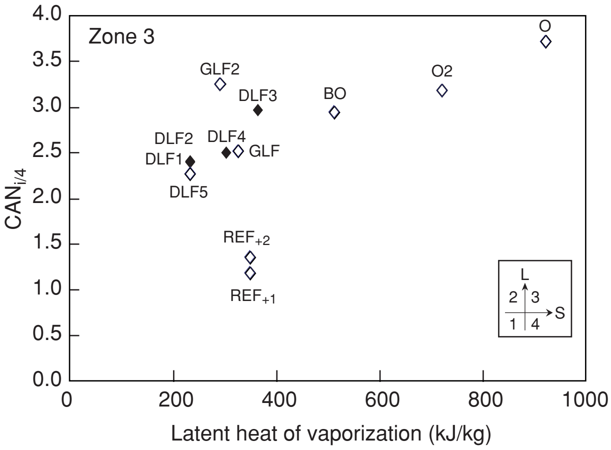


Figure 9

Correlation between LHV and $CAN_{3/4}$.

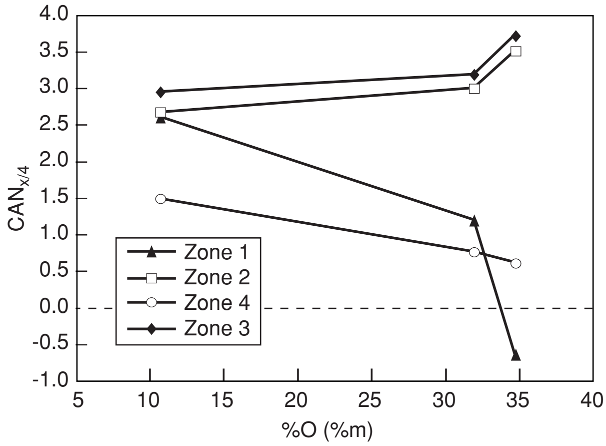


Figure 10

Correlation between fuel oxygen content and $CAN_{x/4}$.

It has been outlined above that 3 main parameters have a fundamental impact on CAI combustion:
- the start of combustion (represented by CA10, 10% burnt fraction);
- the combustion speed (represented by MHR, the maximum heat release rate);
- the end of combustion (represented by CA90, 90% burnt fraction).

If we consider all the tested fuels together, it can be outlined that the CAI limits are linked to combustion properties, as shown in Figure 11.

This Figure allows one to see the fuel impact from another point of view: it can be seen that with all the fuels, the CAI limit in terms of combustion are the same, linked to engine tuning. Indeed, the main limitations (noise, stability, NOx emissions, etc.) can be linked to combustion parameters. By presenting the running point on this type of Figure, it can be seen that the goal of the CAI development (engine geometry, engine tuning, fuel formulation) will be to extend the CA10/MHR limits or to modify the running points in order to be inside this zone.

The fuel can consequently be considered as a way to tune the combustion in order to reach the CA10/MHR limits. If we consider that the CAI combustion can occur only when the CA10 and the MHR are inside the limit defined in red in the Figure 11, the fuel can then be seen as a means of modifying these combustion parameters and consequently to obtain CAI by tuning the combustion parameters. This vision allows us to extrapolate the conclusions to all types of engines: as the fuel impact is described as a way to tune the combustion, it will remain the same for all the engines. After having characterised the engine behaviour in terms of combustion process, the fuel can be chosen in order to tune the main combustion parameters.

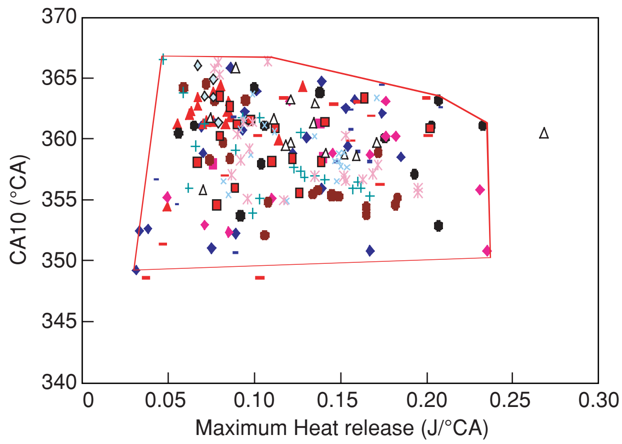


Figure 11

CA10/MHR correlation - all fuels.

The main fuel parameters that have been considered are:
- auto-ignition properties (RON/MON/cetane index);
- density;
- heating value;
- distillation properties;
- latent heat of vaporization.

Each property can then be studied according to its impact on combustion:
- a decrease of the auto-ignition delay induces an earlier combustion, and consequently a decrease of CA10;
- an increase of the density can induce volatilization difficulties, and consequently a later combustion begin;
- a higher latent heat of vaporization induces a decrease of the air/fuel blend temperature and consequently a later combustion start.

All these fuel properties can have conflicting effects, which can explain the behavior described above.

For instance, it has been outlined that, for the zone 3, the effect of density is linked to autoignition properties. For low cetane fuels, a higher density tends to increase the CAI combustion zone, while the effect is negligible for high cetane fuels. This behavior can be explained with this CA10/MHR theory: in the zone 3 (high speed/high load), the main limitation is the noise level, due to a high MHR and an early combustion (low CA10). For low cetane diesel fuels, an increase of the density can induce volatilization difficulties that can influence the CA10 and the MHR.

Moreover, this CA10/MHR vision implies the introduction of a more chemical view of the fuels, with for instance a strong influence of combustion kinetic, that is directly linked to the maximum heat release. As far as DLF5 is concerned for instance (synthetic fuel), it has been shown that its $CAN_{1/4}$ is low, despite it very high cetane. In the zone 1 (low speed/low load), the main limitation is the combustion stability: at these low temperatures, the CA10 is often too high, inducing misfiring. An increase of the cetane number can induce a shift of this CA10 towards low crank angles, and consequently a better quality of combustion start. In the case of DLF5, its particular chemical composition (linear paraffins) induce a very quick combustion and consequently a high MHR, despite the low temperature. This phenomenon is described in Figure 12.

On low speed/low load running points, the combustion is characterised by a high CA10 (late combustion) and a low maximum heat release, which quickly leads to non acceptable running points, out of the CA10/MHR limit. An optimized fuel will consequently be a fuel that is able to tune the combustion in order to move it inside the acceptable CA10/MHR zone. In this case, it is compulsory to decrease the CA10 and to increase the MHR. Nevertheless, Figure 12 shows that a simultaneous increase of MHR and decrease of CA10 can induce a decrease of the CAI zone, while a simple decrease of CA10 induces an increase of this zone. The case of DLF5 can be explained by such a phenomenon: even if the high cetane number of this fuel can induce a shift of the CA10 towards low values, the high combustion kinetic of this type of molecule also induces an important shift in the MHR towards high values (low heat losses). The combination between these effects imply that most of the running points are still out of the CA10/MHR zone and consequently the CAI zone is still limited.

2.3 SUMMARY

All the correlations that have been calculated can be put on a table in order to get a more global view of the most influencing fuel parameter. In table 3, a positive correlation is noted "+" and a negative correlation "–".

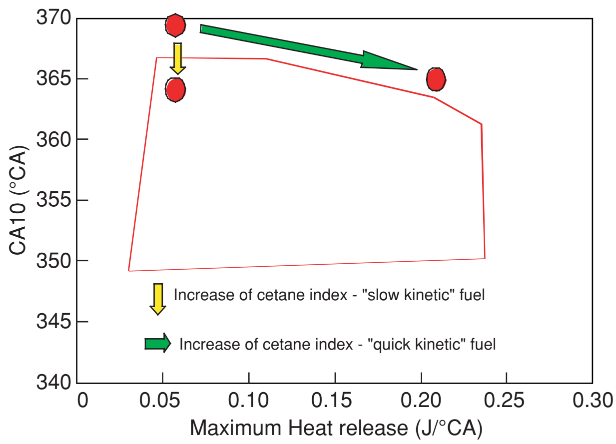


Figure 12

Impact of cetane and kinetic on fuel behaviour.

TABLE 3

Correlations between $CAN_{x/4}$ and fuel parameters

	RON	MON	IC	Density kg/m^3	Heating value kJ/kg	IBP (°C)	FBP (°C)
Zone 1	–		+		+	+	
Zone 2			–	*	–	–	
Zone 3				*			
Zone 4	–		+		+	+	

*: dependant on fuel cetane number

	%C	%H	%O	LHV	FBP-IBP	E 50	E 100
	%m	%m	%m	kJ/kg	°C	%vol.	%vol.
Zone 1	+	+	–	–			
Zone 2	–	–	+	+			
Zone 3	–		+			–	
Zone 4	+	+	–	–			–

According to this calculation, it can be seen that the increase of the CAI zone at low speed/low load (zone 1) can be obtained by:

- an increase of fuel cetane;
- a low oxygen content;
- a low latent heat of vaporization.

On the contrary, in the zone 2, the most efficient fuel should have:

- a high oxygen content;
- a high latent heat of vaporization;
- a low cetane index.

The optimal fuel consequently has to be a compromise between all these parameters.

Moreover, it has to be pointed out that the results obtained here are only preliminary results and deserve to be studied more precisely. Here, a set of fuels has been tested and some correlations have been calculated, without seeking to optimise the formulation or to decorrelate the fuel properties. It consequently remains very difficult to see which fuel parameter is the truly important one. For instance, the study of fuel distillation shows a positive correlation between initial boiling point and the CAI range for zones 1 and 4, which means that the optimal fuel for low load running points should be a heavy fuel. This observation is quite surprising, as the main difficulty on these running points is to obtain a good auto-ignition. It seems consequently more logical that a heavy fuel, with high initial boiling point and low volatility is not optimal. In fact, this correlation is due to the cetane number of the fuel: most of the fuels with high initial boiling points correspond to “diesel-like” fuels (diesel fuel, Fischer-Tropsch, etc.), with a high cetane number. On the contrary, most of the fuels with low initial boiling points correspond to “gasoline like” fuels (ethanol, gasoline, etc.) with low cetane number.

A new presentation, according to combustion parameters (CA10, MHR) and not engine parameters (engine speed and load), allow us to better understand fuel impact on the CAI combustion. Moreover, this vision allows one to be independent of engine technology and tuning (valve lift laws, etc.). Indeed, when the impact of fuel on the combustion has been characterized, it can be applied to all types of technologies, provided that the CAI combustion has been characterized in terms of CA10/MHR.

CONCLUSION

The IFP-developed CAI™ (Controlled Auto-Ignition) combustion system has been applied to a conventional gasoline automotive 4-stroke engine. This engine has been used to undertake a detailed study of the influence of the fuel formulation on the engine operating range that can be covered in CAI combustion mode. From the information and results generated by this study and presented in this paper, it is possible to draw the following main conclusions:

– it has been possible to develop a repeatable and discriminant testing procedure showing the fuel effect on the range of possible engine operation in CAI combustion mode;
– the development of this method has led to the definition of four indices according to the engine speed and load. The fuel impact has to be studied on each zone separately;
– the study of several fuel formulations has shown that some of them allow one to multiply by up to three times the CAI range in some of the four areas previously defined;
– correlation have been calculated in order to link the fuels’ physical properties and the CAI running area. It has been shown that the engine load is one of the main parameters influencing the fuel impact. For low load running points, the optimal fuel seems to be a high cetane, low LHV fuel, while at high load this fuel must have a low cetane number and a high latent heat of vaporization. A compromise is consequently necessary in order to get the optimal fuel;
– it has been shown that the CAI zone can be characterized by its combustion limits (CA10, maximum heat release rate), which allows one to better understand the fuel effects. Moreover, this view allows one to be independent from engine tuning parameters such as valve lift laws.

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