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LPG: Pollutant emission and performance enhancement for spark-ignition four strokes outboard engines

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Abstract

Experimental research into the use of LPG in spark-ignition outboard engines is presented. Two different outboard engines were adapted for operation with bottled LPG dosed in gaseous form. The aim of the study was to determine the basic parameters and quantify the emission index for carbon monoxide, unburned hydrocarbons, and nitric oxides when LPG is used instead of gasoline.

The results obtained indicate that with the use of LPG, specific fuel consumption and CO emissions were much lower without noticeable power loss while HC emissions are shown to be little affected by fuel substitution. In contrast, NO_x emissions were higher, but could be kept below current and future emission limits.

Keywords: Outboard spark ignition engine; LPG; Exhaust emissions; Low power; Four strokes

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1. Introduction

Emissions from marine engines tend to be concentrated in specific areas (ports, coastal and recreational areas, lakes and rivers, etc), and, therefore, local levels of pollutants may be high. Consequently, an emission control program that addresses CO, HC, NO_x and PM emissions from marine engines may be an important tool in reaching the goal of reducing the health and environmental hazards associated with these pollutants [1–4].

The work of the European Commission on emission limits has been focused on on-road applications. Indeed, work on small craft exhaust gas requirements has not been declared high priority. However, some European countries developed such requirements years ago; in fact, in 1993, Austria, two German federal states and a Swiss Canton published jointly the regulation dispositions of Lake Constance (also known as Bodensee) [5]. These emission levels had to be determined using the BSO (Bodensee–Schiffahrts–Ordung) eight-mode steady-state test.

The International Council of Marine Industry Associations (ICOMIA) and the International Marine Engine Manufacturers' Committee (IMEC) proposed a regulation on exhaust gas emissions to be developed in two stages (IMEC 1 and IMEC 2). The marine industry also proposed those requirements to the European Commission and since 1998 all new engines sold in the member countries must fulfil these limits (Directive 94/25/EC) [6]; although, ICOMIA recognized at the time that most two- and four-stroke outboard engines would not fulfil these limits.

On the other hand, the United States, based on their NEVES study (Nonroad Engine and Vehicle Emission Study), published in 1996 a plan for increasing exhaust emission requirements between 1998 and 2006. The EC, in an attempt to harmonize its criteria with those established by the American Environmental Protection Agency (EPA), accepted those limits (Table 1). Both European and EPA's limits have incorporated the five mode duty cycle ISO E4 duty cycle in the test procedure for gasoline spark-ignition marine engines [7–11].

As a result of these increasing limits, the marine industry was forced to make a concerted effort in reducing emissions. Indeed, two-stroke outboard engines, so abundant in recent decades, have now been displaced by more ecological and efficient four-stroke engines. In spite of this, the technology needed for the fulfilment of current and future limits may not be affordable for some small power engines, and thus different solutions need to be found to deal with this numerous market segment. In fact, the greater control obtained by the use of electronic fuel injection systems is only available today in outboard engines of more than 73.5 kW. Two-stroke outboard engines are now including direct injection technology for the purpose of meeting their current and future

Table 1
Outboard emission limits (g/kW · h)

		NO_x	HC	CO
Bodensee	2-St Gasoline	10	$39 + \frac{100}{P^{0.75}}$	$150 + \frac{600}{P}$
	4-St Gasoline	15	$6 + \frac{50}{P^{0.75}}$	$150 + \frac{600}{P}$
	Diesel	10	$1.5 + \frac{2}{P^{0.5}}$	10
EPA	Gasoline	15	6.4	145
94/25/EC	Diesel	9.8	1.5	5

P stands for the rated power of the engine (kW).

requirements. The use of automotive-type catalizators and EGR valves in outboard engines raises various difficulties such as the lack of space under the outboard's hood, the risk of water reaching these components due to the use of exhaust and water mixing for body temperature control, etc. The solution proposed in this study is the use of bottled LPG as fuel, which is characterized by the following aspects:

- Automotive LPG composition and main characteristics are fully regulated since 1983 by the European Standard IN589.
- LPG is stored and transported in liquid phase at ambient temperature and at pressures ranging from 500 to 1000 kPa, enhancing its energetic density and therefore reducing the space required inside the vehicle.
- The market for automotive LPG bases its interest fundamentally on economic reasons, of energy and environmental diversification [12].
- Although the use of LPG as fuel for motoring is a recent phenomenon, there is generalized experience all over the world.

2. Experimental equipment

Two small outboard engines were prepared for operation with LPG and gasoline (see Table 2 for their main characteristics). It was necessary to design a system that allowed the use of commercial membrane dosimeters in the outboard engines without modification of any crucial part in order to maintain its original performance with gasoline.

Each engine output shaft was connected to a hydraulic dynamometer (Marine 2000) for torque measurement. Engine speed was measured by a spark detector installed on the engine. Fuel consumption was determined by a calibrated load-cell installed under the gasoline tank or the LPG bottle. Inlet air flow was determined through fuel consumption, fuel composition and exhaust gas composition, according to ISO 8178 [14]. Every test was performed according to ISO 3046 [15], and the maximum estimated uncertainties were below the limits imposed by that standard.

Exhaust gas composition was obtained by the extraction of a continuous sample of gas from the exhaust stream. Gas sample was passed through an unheated line, a water separator and a treatment line (see Fig. 1). The exhaust gas was then conducted to the gas analyzers. The sensors were

Table 2
Main characteristics of the tested engines [13]

	F15	F8
Engine type	4 stroke outboard	4 stroke outboard
Model	Yamaha F 15 AMHL	Yamaha F 8 BMHL
Rated power @ Speed	11 kW @ 5000 rpm	5.9 kW @ 5500 rpm
Diameter/stroke (mm)	59/59	59/42
No. cylinders	2	2
Compression ratio	9.19	9.30
Displacement (cm^3)	323	232

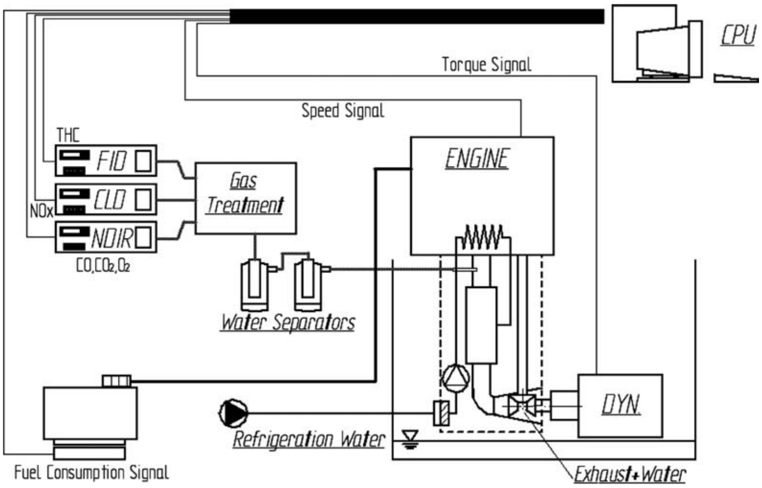

Fig. 1. Schematic of experimental installation.

calibrated using certified standard gases. Exhaust gas analysers used in this study were the following:

- Horiba Mexa 574GE NDIR (Non Disperse Infra-Red) for the determination of CO_2, CO, and O_2 concentration, as well as an estimation of air/fuel equivalence ratio (λ).
- Horiba FIA-510 FID (Flame Ionization) for the determination of THC.
- Horiba CLA-510SS CLD (Chemi-Luminescence) for the determination of NO and NO_2 (NO_x) emissions.

The output signal of every sensor was collected by a data acquisition board (National Instrument Model PCMCIA DAQ-700) and sent to a PC. Data was processed and displayed using a custom program developed with Lab-View software (National Instruments).

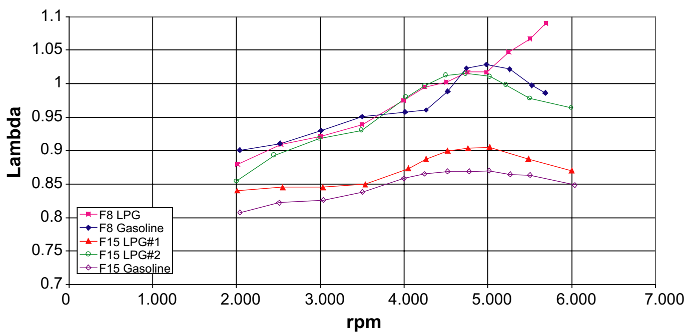

Fig. 2. Lambda variation with engine speed at WOT.

For this study, two commercial fuels were used. Unleaded gasoline (95 RON) meeting 98/70/CEE standard was used together with bottled LPG. The bottled LPG used in this study was a mixture of butane and propane in a mass proportion of 70/30.

3. Experimental results

Tests were conducted by varying engine speed at full throttle and measuring engine performance and emissions. The tests were repeated with different gas dosimeter settings to obtain different air/fuel equivalence ratios (λ). No modification on gasoline λ evolution with speed was

Table 3
Engine performance

	Unit	Unleaded 95	LPG	Variation (%)
		F 8 BMHL		
Max. power	6.02 @ 5487	6.06 @ 5473	0.6	
Consumption	g/kW · h	432	362	−16.3
Torque	N · m	10.49	10.58	0.86
		F 15 AMHL		
Max. power	kW @ rpm	11.15 @ 5510	10.55 @ 5267	−5.04
Consumption	g/kW · h	427	311	−27.2
Torque	N · m	19.31	19.11	−1.03

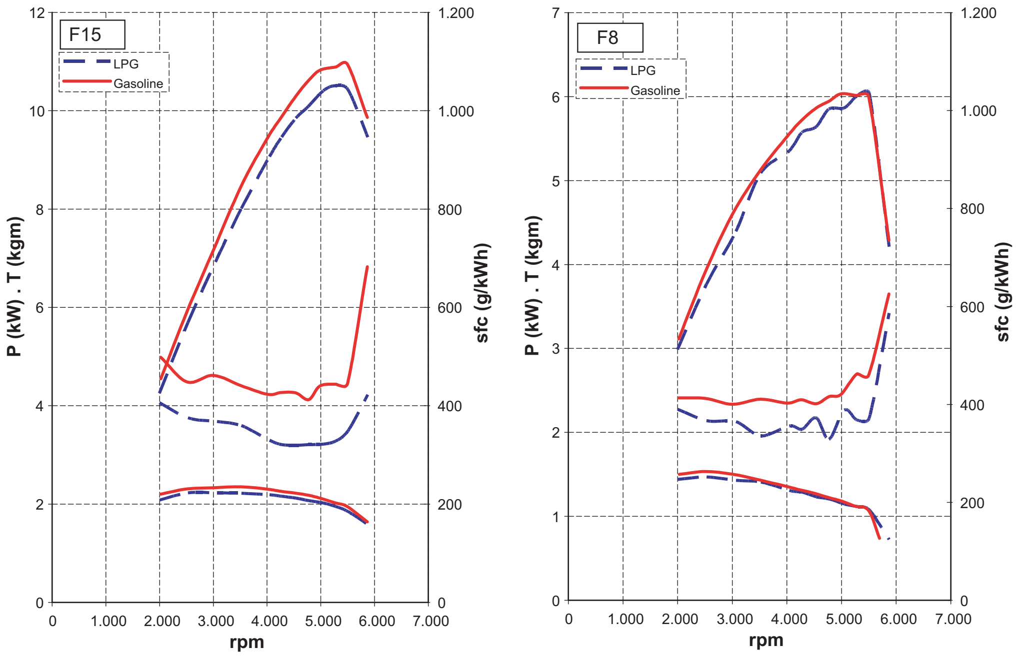

Fig. 3. Engine performance comparison.

made. In Fig. 2 we can observe the highly rich mixtures used by standard engines for specific power enhancement and for idling stability.

The gaseous form of the dosed LPG allowed the reduction of the enrichment needed for idling stability and therefore reducing idling fuel consumption and operating costs [16].

3.1. Engine performance

Both engines showed full capacity of operation with LPG and gasoline with a small decrease of power with LPG, probably due to the loss of volumetric efficiency when using a gaseous fuel due to the intake air displacement. Table 3 shows the main differences in performance obtained for the different engines and the different fuels used in this study. Although the maximum power developed by the F8 engine was almost the same in LPG as in gasoline, its performance over the whole speed range was about 5% lower. On the other hand, specific fuel consumption in LPG is, at every speed between 15% and 25% lower (see Fig. 5). Power loss and specific fuel consumption enhancement fit perfectly with the references consulted (Fig. 3) [17,18].

Engine noise was measured from different positions at a distance of 1.5 m. The average noise at wide open throttle (WOT) showed that, at low speed, noise emission coming from the LPG engine was much lower, reaching the same level at high speeds. Table 4 shows the data obtained for the F15 engine.

Table 4
Noise emissions (dB) vs speed at WOT

	Speed (rpm)				
	1000	2000	3000	4000	5000
Gasoline	72	86	90	92	96
LPG	64	82	88	91	96

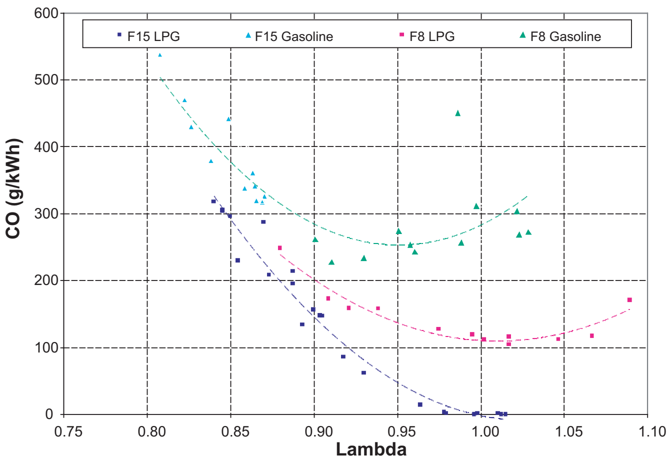

Fig. 4. CO specific emissions.

3.2. CO emissions

It is known that carbon monoxide emissions from internal combustion engines are controlled primarily by the air/fuel equivalence ratio. Fig. 4 shows that this conclusion perfectly fits with the data obtained in this work. In Fig. 4, CO specific emissions are plotted against the relative air/fuel ratio (λ).

Though CO emissions are controlled by the air/fuel equivalence ratio, they seem to be also influenced by the kind of fuel. As shown in Fig. 4, LPG emissions at the same air/fuel equivalence ratio were lower. This may be due to the better mixing obtained by gaseous fuel dosification and due to the higher cylinder-to-cylinder uniformity achieved. Also, the fact of the F8 LPG having a slightly greater tendency to produce CO may be due to its higher combustion chamber surface to volume ratio and thus a proportionally higher charge cooling and flame quenching effect.

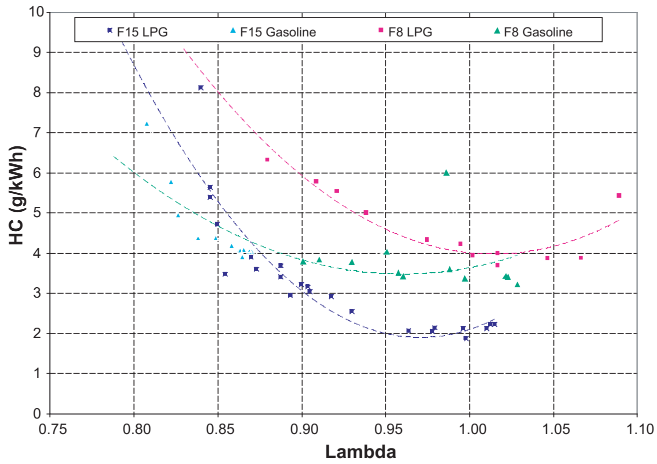

Fig. 5. HC specific emissions.

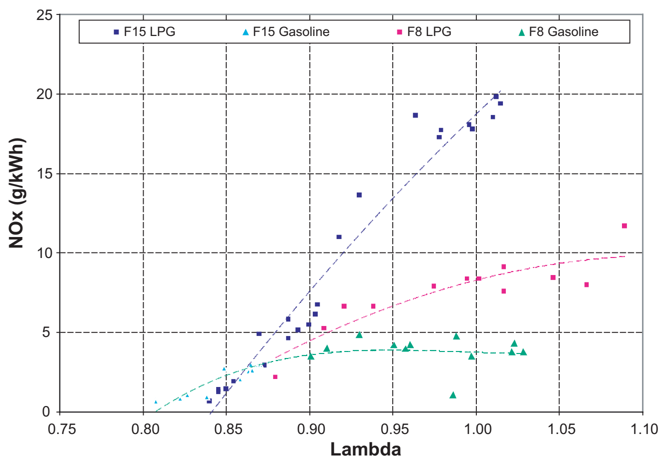

Fig. 6. NO_x specific emissions.

3.3. HC emissions

Hydrocarbons (organic emissions) are the consequence of incomplete combustion of the fuel, due to fuel access to the exhaust stream, during overlap period, without being retained in the combustion chamber or due to the fuel absorption–desorption mechanism in the oil layer. In Fig. 5 the HC emissions measured in each engine and each fuel are plotted against λ.

In Fig. 5 we can see that there exists some kind of parallelism between LPG HC emissions in both engines. The difference between LPG and gasoline emissions is quite low, maybe due to the fact that the controlling characteristic is engine design, with the distribution arrangement and combustion chamber design being of crucial importance. In fact, the longer valve overlap period at low speed may explain the higher HC emissions obtained and may also explain the fact that LPG emissions at low speed are higher than gasoline emissions. The reason could be the higher inertia of gasoline liquid droplets and thus their lower tendency to follow intake air in its bypass

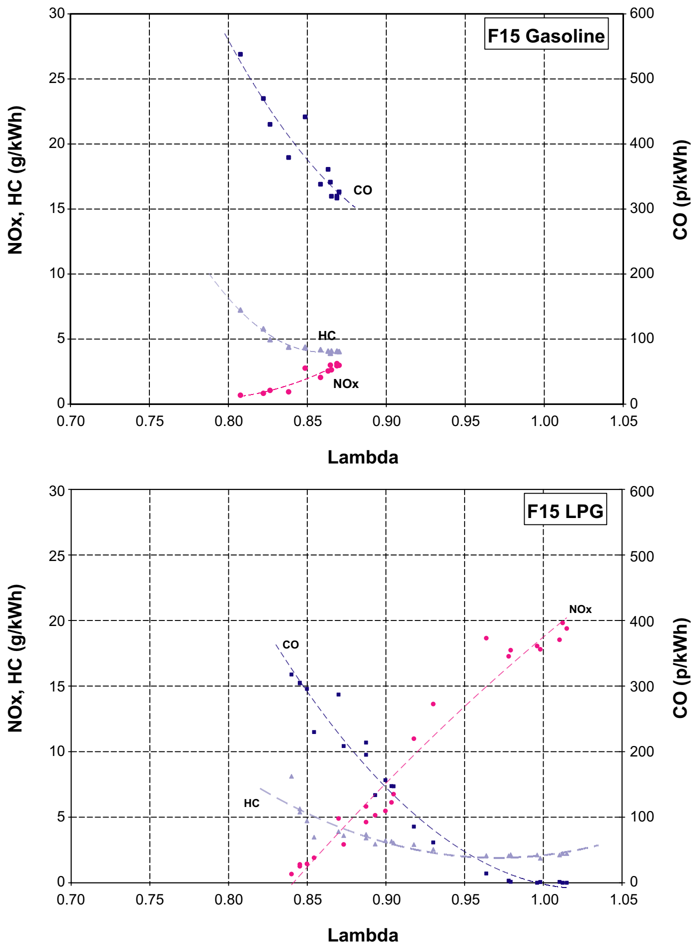

Fig. 7. F15 engine emissions evolution with lambda.

path. At higher engine speed, when ram and tuning effects control gas motion during the overlap period, LPG HC emissions are comparable or even lower than gasoline emissions for the same engine. The fact of LPG CO emissions being much lower on the overall speed range may support this idea because not much HC may thus be expected to come from an incomplete combustion.

3.4. NO_x emissions

The mechanism of NO_x formation from atmospheric nitrogen has been studied extensively and it is accepted that it is greatly dependent upon temperature due to the high activation energy needed for the reactions involved. For the formation of NO_x compounds, the presence of oxygen is also needed. As a result, high temperatures and high oxygen concentrations will lead to high NO_x formation rates.

As the temperature and oxygen concentration in the cylinder normally increase with air/fuel equivalence ratio in the range $0.90 < \lambda < 1.05$, lambda will have a strong effect on NO_x formation.

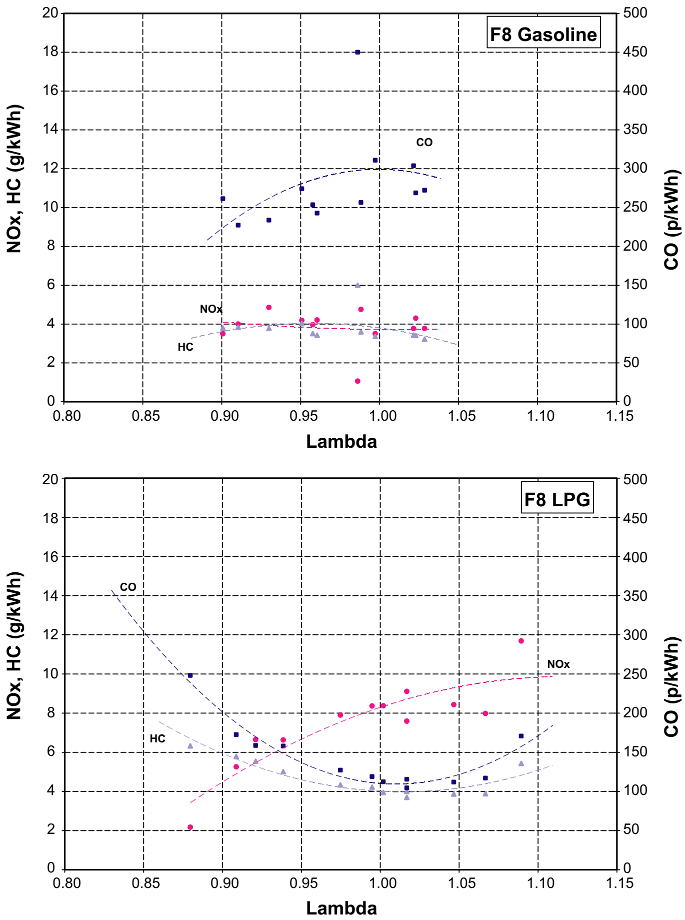

Fig. 8. F8 engine emissions evolution with lambda.

LPG combustion normally produces higher temperatures due its slightly superior heating value, its higher burning speed and its lack of charge cooling effect (obtained with gasoline by its evaporation). The effect of fuel substitution and the effect of air/fuel equivalence ratio are shown in Fig. 6 where NO_x specific emissions are plotted against lambda.

Despite of the great dependence between lambda and fuel characteristics, NO_x emissions seemed to be also related to engine construction (probably to combustion chamber surface to volume ratio). The more adiabatic combustion chamber of the F15 engine leads to higher temperatures supporting NO_x formation.

3.5. Overall emissions

Figs. 7 and 8 show the differences observed in specific emissions against air/fuel equivalence ratio (λ) over the whole operating range.

Emission standards for outboard engines are expressed in (g/kW h), according to ISO 8178 or BSO (for Bodensee limits). Depending on the regulation there is a set of points and weighting

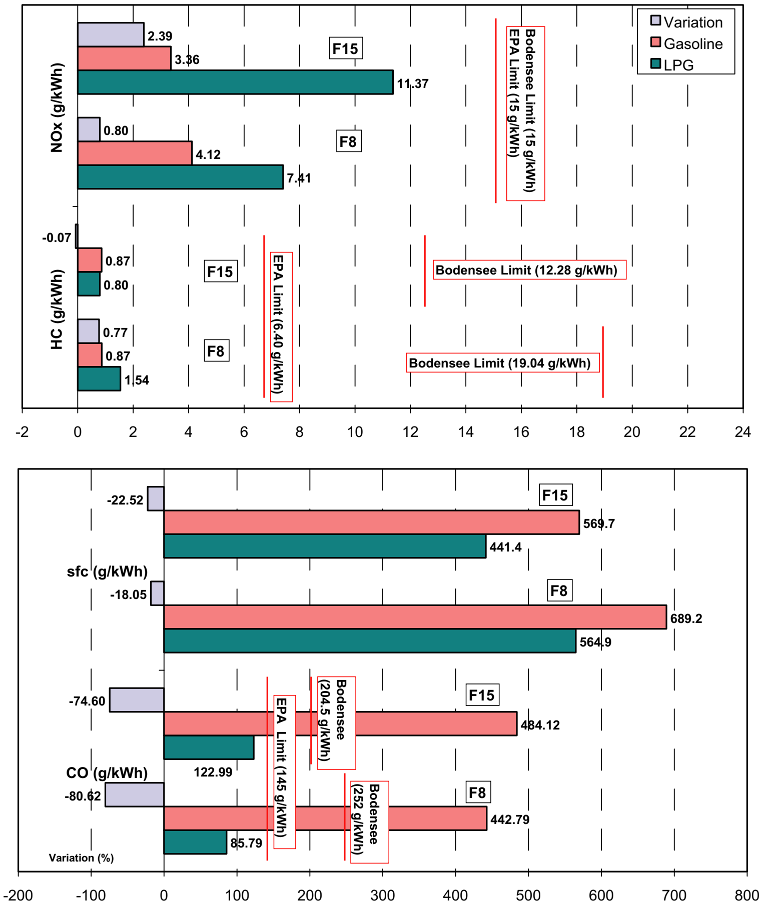

Fig. 9. ISO 8178 emissions and specific fuel consumption.

values that are supposed to represent an engine's normal operation cycle. The test cycle used in this study was ISO Cycle E4 which describes a five-mode test cycle based on a propeller law that relates engine speed with its load.

Following ISO 8178, overall engine specific emissions for gasoline and LPG engines were compared and plotted in a chart together with the limits mentioned in the introduction (Table 1). Fig. 9 shows that the use of LPG may solve the problem of those engines with technical difficulties for meeting actual or future limits.

4. Conclusions

We can conclude that the use of LPG instead of conventional gasoline will mean a great reduction in low power outboard engine fuel consumption and pollutant emission, with an imperceivable loss of power (5% at worst). Also, a reduction in fuel consumption of about 20% was found, moreover no highly rich mixtures were needed for stable idling operation, together with noise reduction.

The usual problem in gasoline carburetted engines is non-fulfilment of the CO specific emission limits, which could be solved by the use of LPG. It should be taken into account that the CO reduction is normally coupled with an increase in NO_x production, which requires careful configuration of the gaseous dosing device.

Furthermore, the disappearance of spills in bunker operations as a consequence of the use of a bottled fuel may be also taken into account. This would reduce pollutant flow into marine areas used for coastal operations.

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