Wolfgang Wegner, MAN, Nuernberg, Germany

BRODSKI DIZELSKI MOTORI S "COMMON RAIL" TEHNOLOGIJOM UBRIZGAVANJA GORIVA

Sažetak

Dizelski motori za pogon motornih jahti se razvijaju i poboljšavaju iz dana u dan. Glavne smjernice tog razvitka su: smanjenje potrošnje goriva, povećavanje pouzdanosti i smanjenje otrovnih sastojaka u ispušnim plinovima.

U radu je prezentirana nova generacija MAN-ovih dizelskih motora za pogon motornih jahti, s posebnim osvrtom na novu tehnologiju ubrizgavanja goriva, tzv. "common rai" tehnologiju. Objašnjeni su glavni dijelovi "common rail" sustava, a pokazano je i da "common rail" tehnologija uistinu omogućava bolju kontrolu potrošnje goriva i bolju kontrolu sastava ispušnih plinova. Ukratko su opisani motori nove generacije, uspoređeni su međusobno, a uspoređeni su i s motorima nekih konkurentnih proizvođača.

Ključne riječi: dizelski motori, motorne jahte, "common rail" tehnologija

COMMON RAIL DIESEL ENGINES IN MARINE APPLICATION

Summary

Yacht engines are getting improved every day. Most important developmental goals are low fuel consumption, high reliability and reduction of toxicant substances in exhaust gases.

In this work, a new MAN yacht diesel engines generation is presented in respect to the new fuel injection technology, called "common rail" technology. Common rail system and it's most important parts are shown. Also, it is shown that common rail technology allows better control of fuel consumption and structure of exhaust gases. In short are described different engines inside this new generation, engines are compared to each other and to engines of other competitive manufacturers.

Key words: diesel engines, yacht, common rail technology

1. Introduction

Two years ago, when 1500 hp V12 engine was presented, it was announced that it would be the last yacht engine with an in-line injection pump. So it was, and today we have the first of a new yacht engine generation; the D 2848 LE 423 with common rail injection technology. It truly is an engine generation since all engines have been converted, i.e. including the V10, the V12, the V12 two-stage and the R6 in-line engine to this injection technology. Reason why common rail technology was chosen can be explained by giving a comparison of the different injection systems, in respect to the tasks that should be fullfilled by the injection pump or injection systems, which are to transport:

- the necessary injection quantity to the combustion chamber,
- at the right time,
- for the desired period,
- at the right pressure,

and this at all times of operation; i.e. at any speed and load point.

Today's V engines all have an in-line pump and can therefore influence only the injection quantity depending on load and speed. For the 6-cylinder in-line engine we currently have a control slide pump with which the start of injection can also be individually adjusted. In both cases there are actually only very few ways of influencing combustion. If on the other hand you look at the CR system, MAN has not developed the pump-line system, you can see that there is a great deal more freedom here. It is only with the CR system that all four of the parameters can be influenced at the same time, independent of each other.

2. Common rail systems

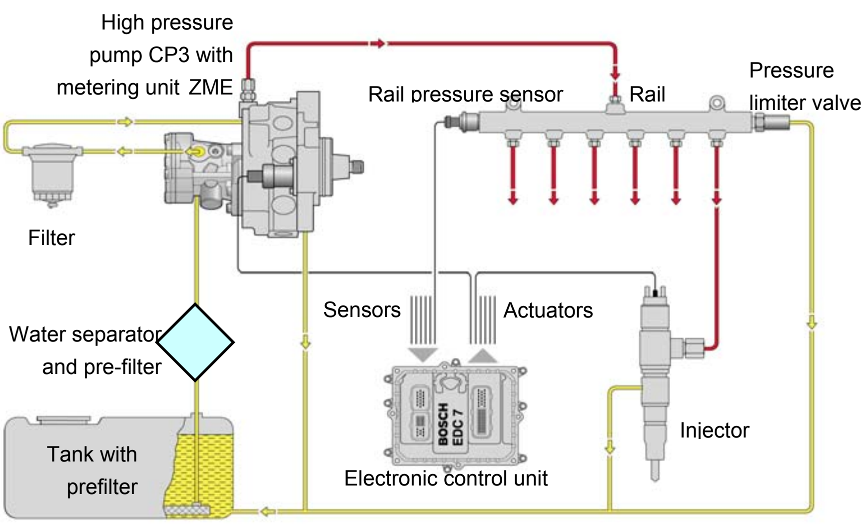


Fig. 1 Common rail system

Slika 1. "Common rail" sustav

As in the past we have a low and a high-pressure circuit. The fuel is supplied to the pre-delivery pump via a pre-filter with a water separator. The fuel reaches the high-pressure pump through the diesel filter. The filtering of the fuel is crucial to the functioning of the CR system. And for this reason too the mesh size of the filter paper is just 2 µm. This high degree of cleanliness is necessary so as not to put the injector at risk. A maximum pressure of 1400 bar can be built up in the high-pressure pump, and this can be achieved regardless of the engine speed. From the high-pressure pump the fuel necessary for the combustion now goes into the common rail and the fuel that is not required flows back into the tank. Here too the amount for rinsing serves to prevent any excessive overheating of the fuel. Pre-stressed fuel is now available in the common rail for injection into each cylinder. Not only that this is good for the combustion it also has the disadvantage that constantly pre-stressed fuel is only made possible at the expense of power consumption by consumption of the CR system. This constant provision of fuel at high pressure requires a higher power input than a conventional in-line injection pump. If compared; a V12 in-line pump needs about 15 kW and the CR pump 2/4V about 25 kW which amounts to an increase of 66 %. This is balanced up only by the better combustion of the CR system so that at the end of the day the specific fuel consumption is lower. From the rail the fuel flows to the individual injectors. And there is also a leak rate from the diesel injected through the nozzles into the combustion chamber which is returned to the tank.

The main components of the CR system are described in following text.

CP 2/4V high-pressure pump

The high-pressure pump is attached to the engine in the same position as the in-line injection pump – it is just smaller. The ratio no longer has to be 1:2 but can be freely selected. In our case it is still i = 1:2 . The fuel delivery pump is also integrated in the high-pressure pump. In addition the high-pressure pump has a second speed sensor which records the speed via a pulse wheel, which depends on the number of cylinders and compares it with the main speed sensor on the flywheel. If any deviation or implausibility is detected the engine changes over into an emergency driving program.

Rail

Depending on the number of cylinders to be supplied, the rail is fitted with connections for the injection lines, a rail pressure sensor and a pressure limiting valve on the front. It is the job of the pressure sensor to convey the current pressure to the control unit so that, in turn, the control unit can set the defined pressure in the high-pressure pump via the metering unit. The pressure limiting valve is an overflow valve which opens at a defined limit pressure, from 1650 bar to 1750 bar, to prevent the injection equipment from bursting. However, once the overflow valve is opened the output is reduced since a maximum pressure of just 600 bar can now be regulated.

Injector

Injector is the most complicated part of the CR injection system. The fuel comes through the inlet from the high-pressure pump via the rail to the injector. The injection quantity here is timed, that is for as long as the solenoid valve is lifted. As long as the solenoid valve is closed the high pressure applied is maintained in the “red" range. When the valve is lifted fuel can flow out of the drain valve and the pressure drops. This causes the force on the compression to be bigger than that acting on the valve timing piston and the nozzle opens.

Control unit

The control unit is still the main information centre. Not only is the beginning of the injection controlled here but the rail pressure is regulated too. In the V engines we needed two control units since one unit has only six output stages. Both of the control units are permanently fixed in the V of the engine.

Low-pressure circuit

The interfaces to the shipyard are the important factors here. The absolute fuel pressure at the delivery point to the system must be 0.5 bar to 1.0 bar. If this is not the case it can have an effect on the high-pressure side.

High-pressure pump CP 3.4

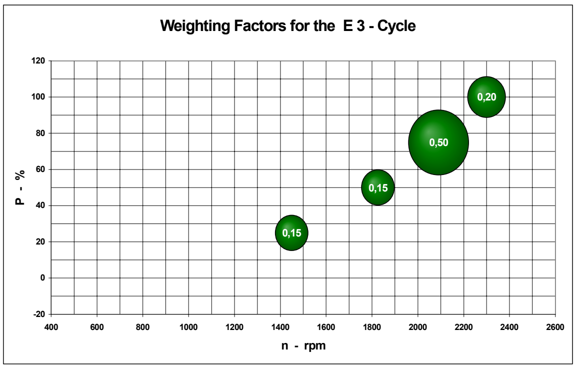
Unlike the V engines in the D 2876 LE 423 in-line engine we have the CP 3.4 high-pressure pump. We have taken over this pump from the vehicle engines since on the one hand they are adequate for our injection quantities and on the other hand they are more cost-effective as a result of the high sales numbers.

3. V engine D 2848 LE 423 with common rail system

What were the design criteria for V8 engine that led to development of common rail technology?

- high output; i.e. as high a mean pressure as possible with the given rated speed of 2300 rpm,
- low fuel consumption,
- low exhaust gas opacity in stationary operation and during acceleration,
- avoidance of white smoke in the idling position and under weak loads,
- compliance with the IMO emission limits,
- compliance with the EPA emission limits.

We have therefore examined the load points of the E3/E5 (Figure 10) cycles more closely. Both cycles are on a third degree propeller curve and the differences between them are the weighting factors and the additional idling point in the E5 cycle. In both cycles the exhaust gases are measured at outputs of 100 %, 75 %, 50 % and 25 %.



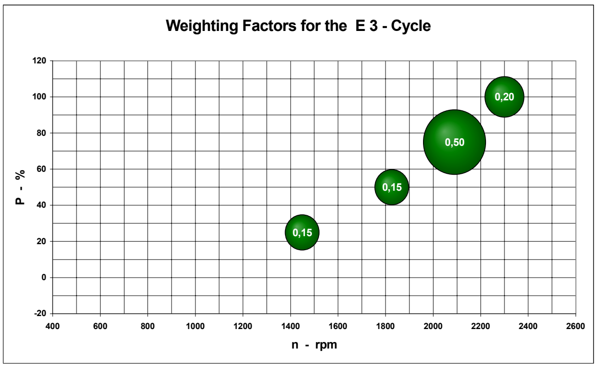


Fig. 2 ISO E3 cycle according the IMO, and ISO E5 cycle for recreational vessels

Slika 2. Ispušni plinovi prema IMO propisima (ISO E3), i ispušni plinovi prema propisima za rekreacijska plovila (ISO E5)

Trade off: fuel consumption against NO_x at 25% point (Figure 3)

We know that the reduction of the specific fuel consumption and the oxides of nitrogen at the same time is not possible. We have applied this here for the 25% point of the E cycle. With the CR system it is now possible to run this point with varying injection starts and rail pressures. And this is where you can see the big advantage of the CR system: with other systems you may be able to vary the start of injection but not the rail pressure. In other systems this depends on the speed. We have run with injections starting at 4° before top dead centre up to 20 ° before top dead centre, and here we have examined the rail pressure from 600 bar to 1400 bar. The striking fact here is that the curves with different injection starts join up. But this means that you can achieve a point on this curve with different injection starts and rail pressures.

Trade off: fuel consumption against NO_x (without injection start) (Figure 4)

In the figure, we have marked all the points identically here, you can see the connection between the specific consumption and NO_x emissions even more clearly: the same point was run 70 times with varying injection starts and rail pressures, you can't escape from the divergence between consumption and NO_x. It is also crucial that one doesn't fall short of a certain consumption minimum and fortunately this is a very large range

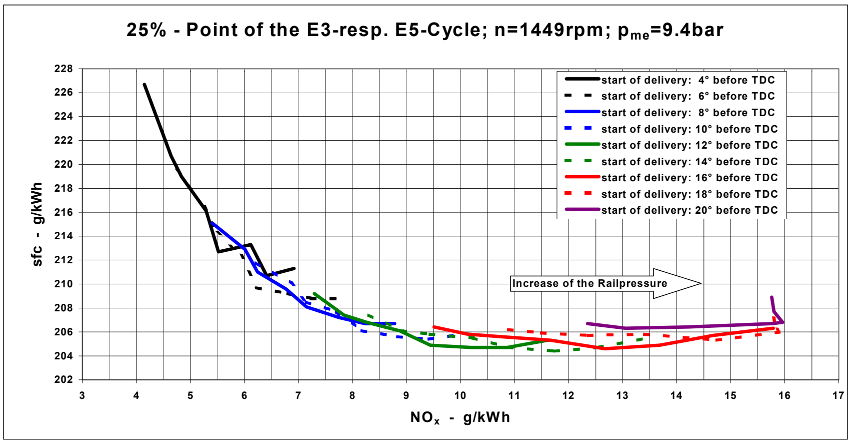


Fig. 3 Fuel consumption against NO_x at 25% point

Slika 3. Specifična potrošnja goriva u ovisnosti o koncentraciji dušikovih oksida NO_x, pri 25%-tnom opterećenju

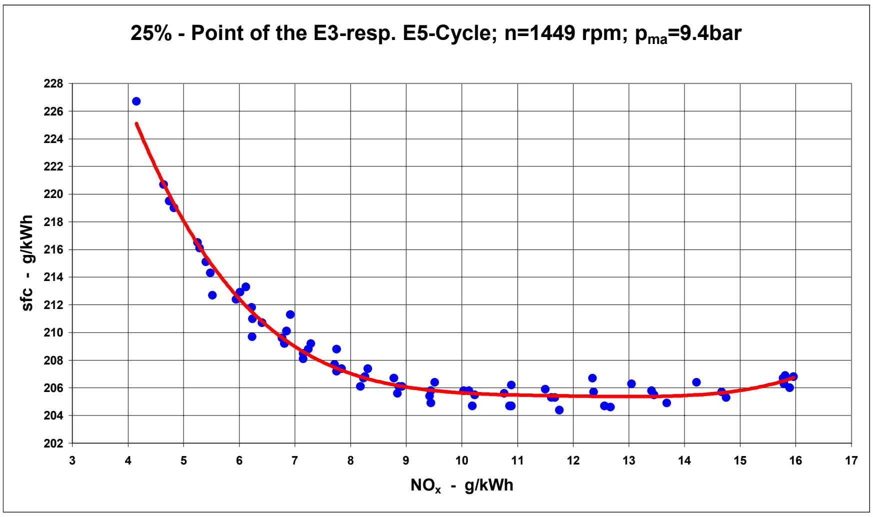


Fig. 4 Fuel consumption against NO_x (without injection start)

Slika 4. Specifična potrošnja goriva u ovisnosti o koncentraciji dušikovih oksida NO_x (bez upravljanja početkom ubrizgavanja goriva)

Trade off: fuel consumption against NO_x for all load points (Figure 5)

With the other cycle points it's the same: a wide area with constant consumption and a consumption increase at very low NO_x values. Whatever you try the trend is always the same.

Trade off: exhaust-gas opacity against NO_x (Figure 6)

It is known that not just the specific consumption but also the exhaust-gas opacity and hence emission of particulates run counter to the emission of oxides of nitrogen. However the curves here don't join up, but the start of injection is dominant for the NO_x emissions. It is also just as obvious that a high rail pressure reduces the exhaust-gas opacity and the particulate matters considerably.

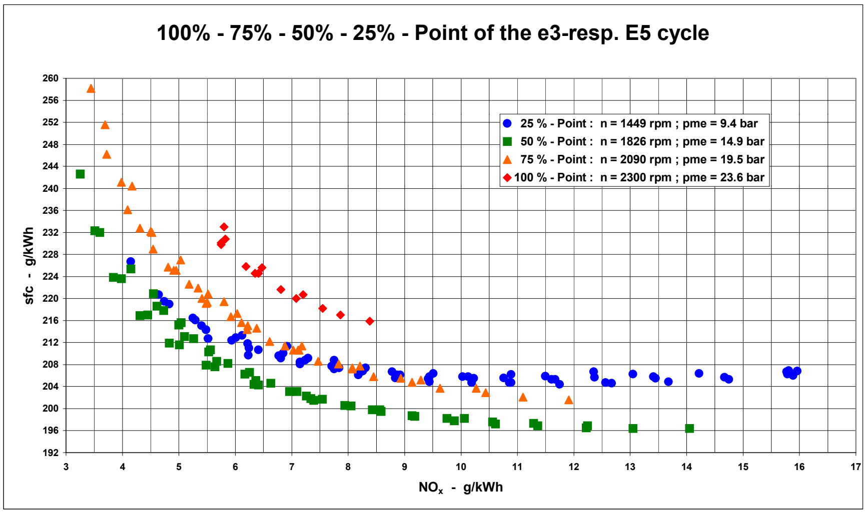


Fig. 5 Fuel consumption against NO_x for all load points

Slika 5. Specifična potrošnja goriva u ovisnosti o koncentraciji dušikovih oksida NO_x, za sva opterećenja

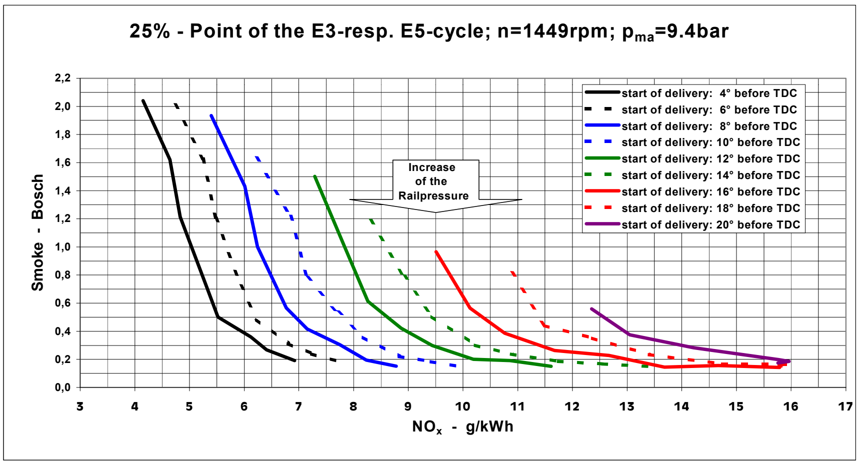


Fig. 6 Exhaust-gas opacity against NO_x

Slika 6. Zacrnjenje ispušnih plinova u ovisnosti o koncentraciji dušikovih oksida NO_x

Compromise between b_e, smoke number and NOx (Figure 7)

We have applied both the specific fuel consumption and the exhaust gas opacity via the NO_x emissions. In order to be able to keep to the EPA limits we have set ourselves a limit of NO_x=7 g/kWh. We can achieve this 7 g/kWh with a specific consumption of b_e = 209 g/kWh; and as we have seen this is possible with varying injection starts. In this case at 6...10° before top dead centre. If we now also take into account the exhaust-gas opacity at these injection starts we achieve:

0.9 Bosch at 10° before top dead centre,

0.5 Bosch at 8° before top dead centre,

0.3 Bosch at 6° before top dead centre.

It is obvious that we will opt for the 6° before top dead centre since here a minimum consumption and also exhaust gas opacity is achieved at a defined NO_x limit. The rail pressure here is 1200 bar. Thus, we have "constructed" the injection starts and rail pressures for the entire operational range.

HC emission in the idling position (Figure 8)

Here it is particularly important to avoid white smoke, i.e. unburnt hydrocarbons. On the one hand we achieve this by increasing the compression from ε = 13.5:1 to ε = 15.5:1 which leads to a far higher final compression temperature. This means that we can leave the cylinder cutoff which in some ships caused problems in the propeller set-up. On the other hand we have again varied the injection start and rail pressure. This time we aimed at a compromise between low HC and low exhaust gas opacity. With the HC a minimum is achieved in the range from 6° before upper top centre to 10° before top dead centre. Irrespective of the rail pressure the values here are under 100 ppm.

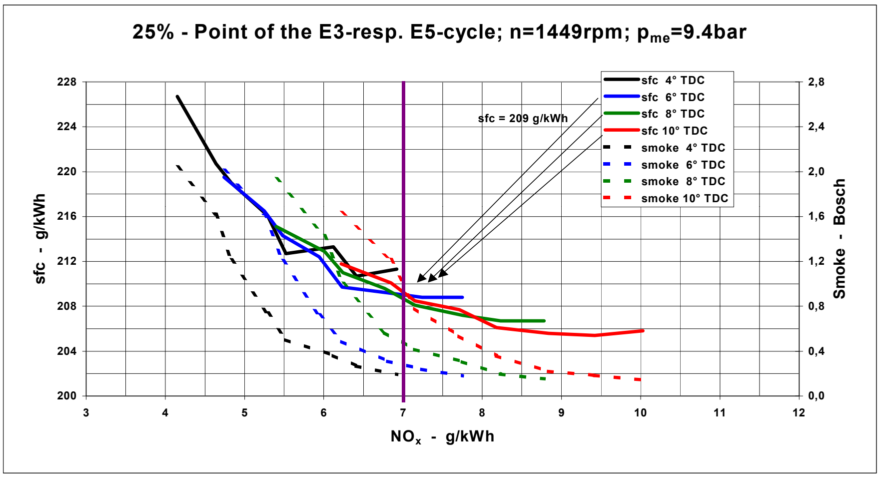


Fig. 7 Compromise between b_e, smoke number and Nox

Slika 7. Kompromis između dimnog broja i koncentracije dušikovih oksida NO_x

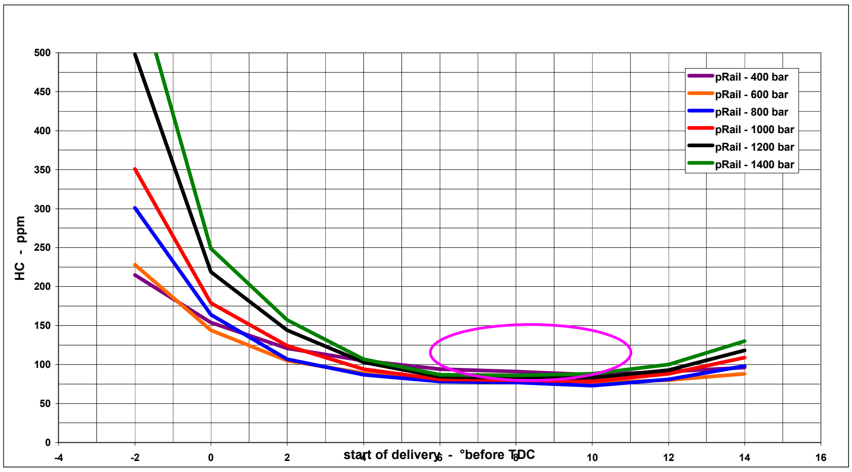


Fig. 8 HC emission in the idling position **Slika 8.** Ugljikovodici u ispušnim plinovima u praznom hodu

Compromise between HC and smoke number (Figure 9)

You have to use a larger scale to recognise any differences at all. It's just the same with the exhaust gas opacity. We achieve a good compromise under the following conditions:

Injection start : 10° before top dead centre, Rail pressure : 1000 bar,

which means that the exhaust gas opacity remains at 0.01 Bosch and the HC emission amounts to only 78 ppm.

Now what are the engine values to which all these considerations and general conditions have led? In Figure 10 the torque curve in comparison with our previous V8 is shown. The following are the differences in detail:

- power increase from 800 hp to 900 hp (amounts to +12.5 %),

- increase of the maximum torque from 2550 Nm to 2900 Nm (amounts to +13.7 %),

- increase of the torque in the lower speed range.

And this was achieved together with the simultaneous reduction of the exhaust gas opacity:

- reduction of the exhaust gas opacity,

- reduction of the oxides of nitrogen from IMO limit 9.2 g/kWh to EPA limit of 7.2 g/kWh (amounts to – 21.7 %).

The combustion would also permit an even higher torque in the lower range; however the available charging assemblies could no longer cope there, as you can see in the next figure.

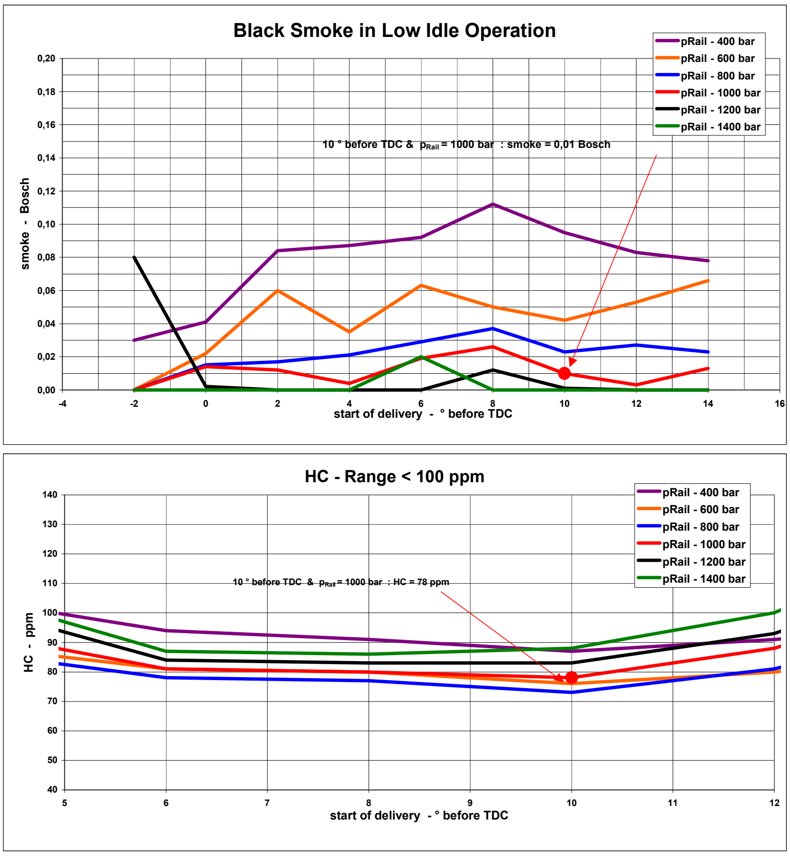
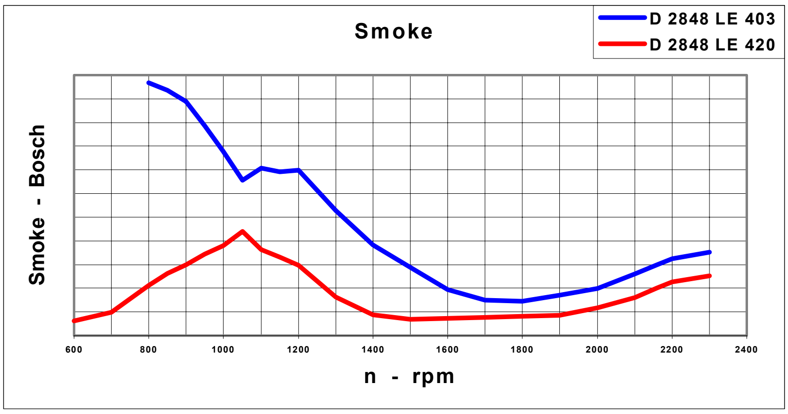
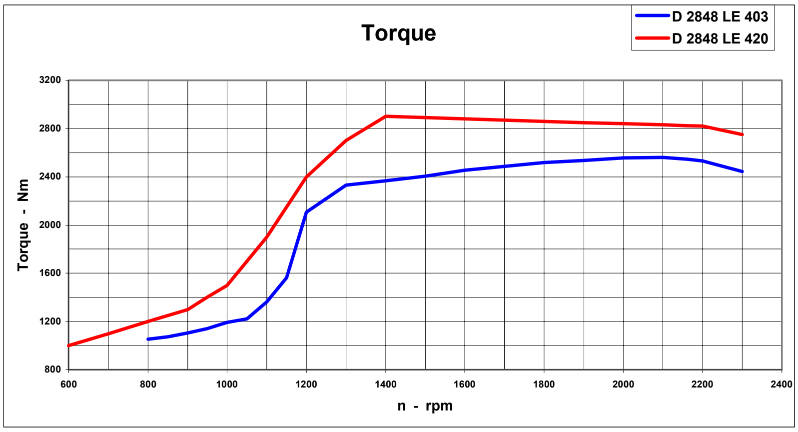


Fig. 9 Compromise between HC and smoke number

Slika 9. Kompromis između emisij ugljikovodika u ispušnim plinovima i dimnog broja





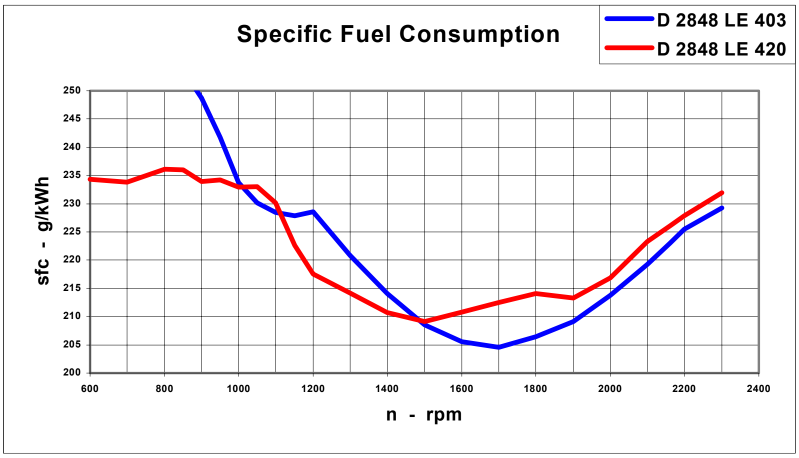


Fig. 10 Engines comparison **Slika 10.** Usporedba nekih MAN-ovih motora stare i nove generacije

4. Other benefits using common rail systems

Rail pressure at rated output (Figure 11)

One point has so far not been mentioned, i.e. that we even reach absolute higher pressures with the CR system. Unlike the RP 21 with which Bosch permits ~1100 bar, with the CR system we can achieve1400 bar with the V engine and 1600 bar with the in-line engine. This may not be a fundamental difference because one can also conceive an injection pump with higher pressures, but this pump does not happen to be available. Depending on the system in the rated output point the pressures 1100 and 1400 bar are available. In both cases, with the D 2842 LE 409 and also with the D 2842 LE 433 the duration of the injection is ~ 30° crankshaft or 2ms.In the case of the CR engine we achieve the injection duration with far smaller nozzles. The hydraulic flow here amounts to just 1200 $cm^3/30s$ instead of 1650 $cm^3/30s$ with the in-line pump. The higher injection pressure considerably improves the mixture preparation, which accordingly leads to lower fuel consumption and lower exhaust gas opacity values. Later we will again see the distinct difference when we compare the two full-load curves.

Rail pressure over the full and half load (Figure 12)

Let's look at the pressure curves under full and half load in the two-stage V 12.

As already mentioned, with the in-line injection pumps, and the other cam-controlled systems, we have a drop in the fuel pressure towards lower speeds. At n = 1200 rpm it is only half as large; or vice versa in the CR system twice as high, which leads to a considerable reduction in exhaust gas opacity.

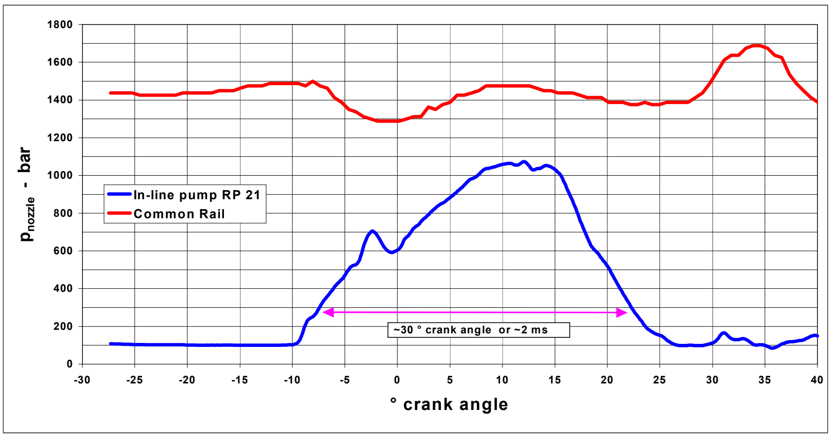


Fig. 11 Pressure in the nozzle: In-line pump vs Common Rail

Slika 11. Tlak u mlaznici: usporedba "in-line" pumpe s "common rail" tehnologijom

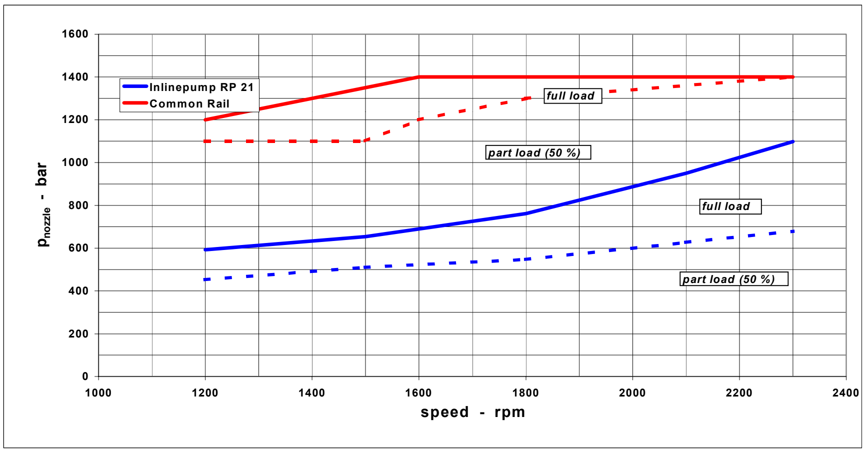


Fig 12 Pressure in the nozzle **Slika 12.** Tlak u mlaznici

Multiple injection

One advantage, which we haven't looked at so far, is the multiple injection.

A distinction is made between: - pre-injection, - main injection, - postinjection.

In our yacht engines we have used the pre-injection and main injection, the reason being that the pre-injection has a major influence on the noise development, in particular in the idling position and the partial load range. The pre-injection is achieved by a brief opening of the nozzle; the injection quantity is about 1.0 % to 1.5 % of the injected fuel quantity at the rated output. Here the pressure increases after the main injection is crucial for the development of noise. In conventional injection the needle is opened once and the entire quantity is injected. Depending on the combustion process there is a longer or shorter delay in ignition which always entails a large increase in pressure. The delay in the ignition is reduced considerably by the pre-injection and the connected advance reaction. This causes a considerable reduction in the increase in pressure. The reduction in the pressure increase is the reason why the engine runs quietly.

5. Engine values of some idividual models

D 2876 LE 423

In our 6-cylinder in-line engine we have increased the rating from 700 hp (or 730 hp) to 800 hp. At the request of our sales people we have fixed the rated speed at n = 2300 rpm so that all the engines in the D 28 range have this rated speed. We have not only increased the speed but also the torque and this has been done practically over the entire full load. Since to date there have been no problems with the acceleration of our 6-cylinder engine this should also be the case here with the higher rating. The consumption curve does not look too good in the lower speed range. This is mainly due to higher power consumption of the CR system and a larger charging assembly (compressor and turbine housing) which was necessary to cope with the 800 hp. But since this area is only passed through during acceleration this will certainly not have any effect on the average consumption. However in the main cruising area, from 1200 rpm to 2000 rpm, we have consumption advantages on the full load curve, while on the propeller curve it is vice versa. Since yachts are run in the region between the two curves one can assume the fuel consumption will react more or less neutrally. And this is in compliance with the new EPA limits which will apply from 2006. As we know from the development of our truck engines, with reduced NO_x limits you must normally expect higher fuel consumptions. Since there will be no change here we are sure to remain competitive. The emission of black smoke which was already low has been considerably reduced again.

D 2848 LE 423

If you continue in accordance with the outputs we come to the V8 which now has 900 hp with CR. You already know the engine values from previous text.

D 2840 LE 423

This engine is the V10, now with 1100 hp. With our current V 10 with 1050 hp in some yachts there was a conflict of interests between acceleration behaviour on the one hand and exhaust gas opacity on the other. This problem should be solved with the new CR engine which has a 700 Nm to 1000 Nm higher torque in the range from 1200 rpm - 1300 rpm. This comes with a reduction of black smoke by over 50 %. The exhaust gas opacity values on the propeller curve are, of course, correspondingly low. The design takes the EPA limits into account in this case as well.

D 2842 LE 423

According to our information the V12 with 1300 hp runs without any problems. This will certainly be the case with the CR engine with 1360 hp and this – if one considers the exhaust gas opacity values under full load and the propeller curve, with considerably lower opacity values.

D 2842 LE 433

This is two-stage V12 engine. In this engine, in view of the load on the components, we have raised the rating to only 1550 hp. Our main goal here was to reduce the specific fuel consumption and the exhaust gas opacity. We have been successful with the aid of the CR system. In all operational areas both on the full load and the propeller curve we managed to achieve values that are below the values of the predecessor model with the in-line pump. Once again, the EPA limits are, of course, complied with.

In Figure 13. emission comparison in respect to NO_x is shown. Here we have an overview of the NO_x (or NO_x+HC) values. As you can see, during the development of the CR engines it was necessary to halve some of the total NO_x+HC values. If you consider that not just cycle points but the entire NTE zone (not-to-exceed zone) had to be trimmed to the low NO_x values the consumption and opacity values I have just shown are good and competitive. To sum up we can say that as far as exhaust gas is concerned the yacht engines have caught up with the vehicle engines since they are at the Euro 2 level, and this is despite considerably higher specific utilisation.

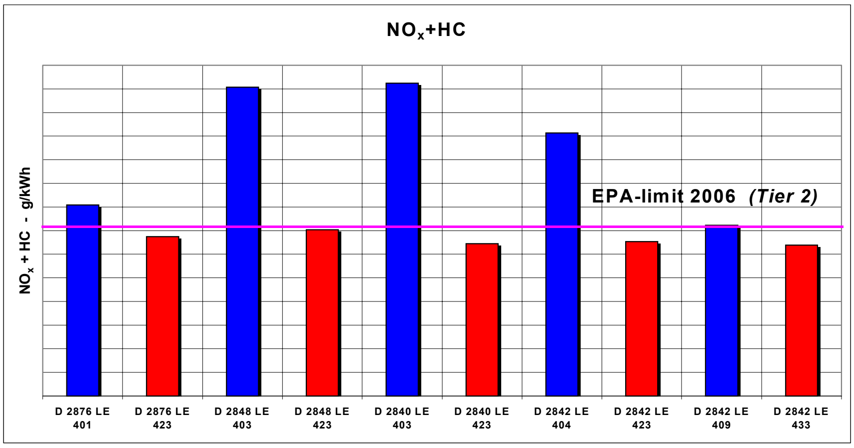


Fig. 13 Emission comparison in respect to No_x and HC

Slika 13. Usporedba motora nove i stare generacije s obzirom na koncentraciju dušikovih oksida i ugljikovodika u ispušnim plinovima

In Figure 14 emission comparison in respect to PM is shown. With the particulate matter values we are considerably below the limits defined by the EPA. In some cases at less than half, which is the equivalent of the currently valid Euro3 values. This does not result from the particularly comfortable limits but from the fact that we at MAN played the right cards and opted for a common rail injection system!

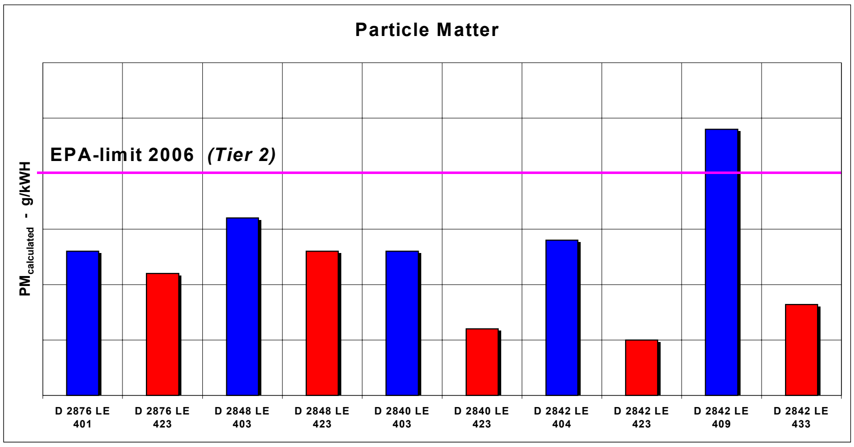


Fig. 14 Emission comparison in respect to PM

Slika 14. Usporedba motora nove i stare generacije s obzirom na koncentraciju čestica u ispušnim plinovima

6. Comparison of competition

Comparison of competition - dimensions

The 1500 hp class is best for this. Two of the main competitors are CAT and MTU.

We have compared: MTU : 10 V 2000M 93, CAT : C 30, MAN : D 2842 LE 433.

In the dimensions – length, width and height – our design is considerably smaller than the C 30 and also shorter than the new V10 from MTU. Only the width of the V10 is a bit smaller; this is due to the fact that the charging assembly was moved to the interior. But with two of the important parameters we're way ahead, these are the weight and the piston speed. Since we have the lowest weight we have advantages in the acceleration and since we have the lowest piston speed we have lower wear and tear on the piston rings and on the cylinder liners.

Comparison of competition – engine values

The values of our competitors which we have compared come from their own sales documents. Compare the full-load curves: although the CAT does have constant power characteristics in the upper speed range, in the lower speed range it has a lower torque than our two-stage V12.And as we know the acceleration in this range in which the yachts still run with positive displacement is important. What is lost at the beginning of the acceleration stage cannot be later recovered; keep in mind that the CAT engine is also considerably heavier than ours. The new V10 from MTU has a lower torque over the entire speed range. It is clear that this engine cannot achieve anything like our driving performance. The very high rated speed of 2450 rpm is a very striking feature. They obviously want to persuade the shipyards to use the smallest possible propellers since there is not an awful lot of torque available in the lower speed ranges. Even if you compare the specific fuel consumption we come off a lot better than the CAT. We do considerably better over the entire speed range. On average we need ~10 % less fuel. From MTU I was able to find only one value – the one at rated speed. There the specific fuel consumption is 218 g/kWh. In view of the high rated speed this value is very optimistic.

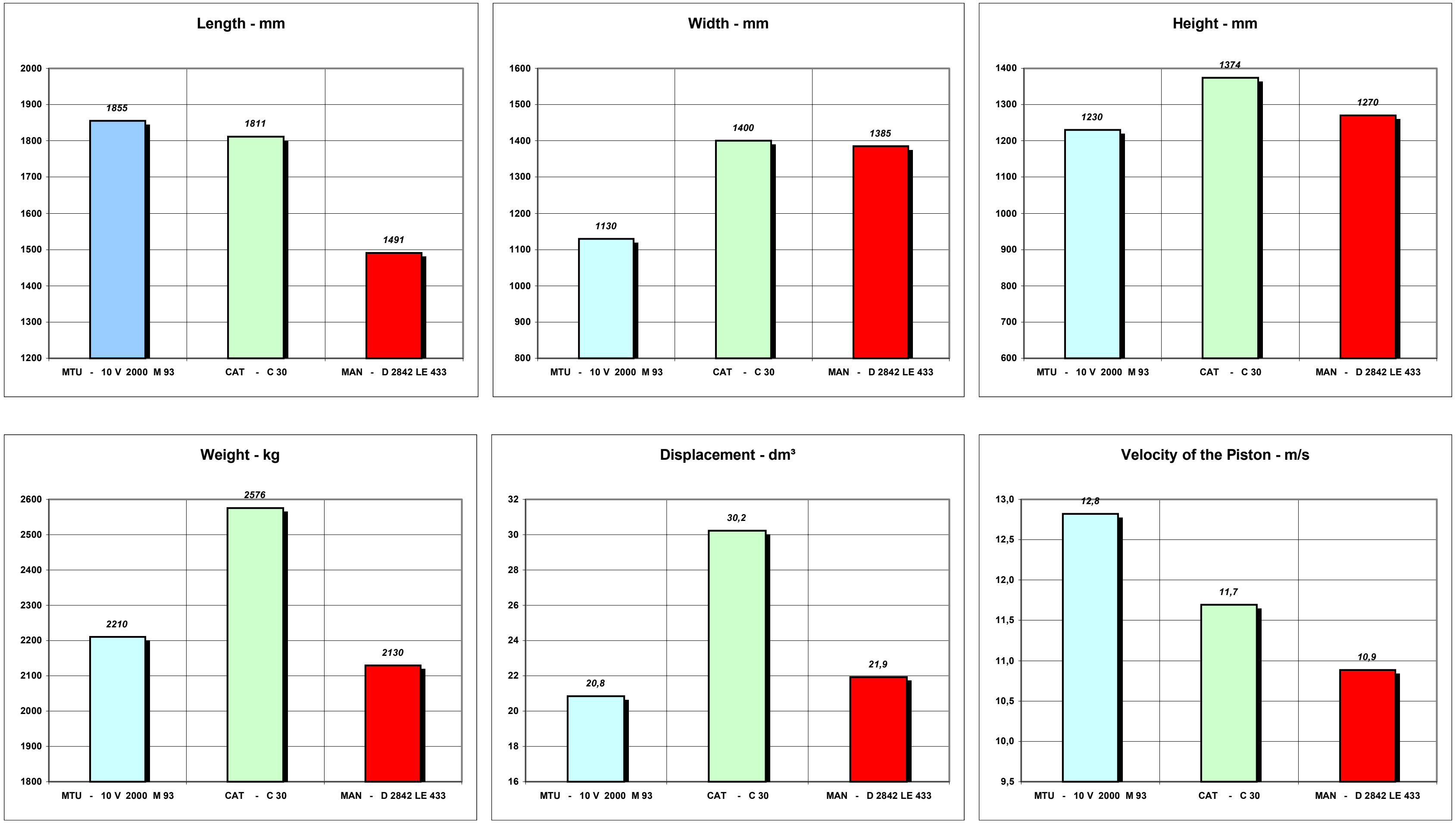


Fig. 15 Comparison of competition – dimensions

Slika 15. Usporedba MAN-ovih motora nove generacije s motorima nekih konkurentnih proizvođača s obzirom na dimenzije

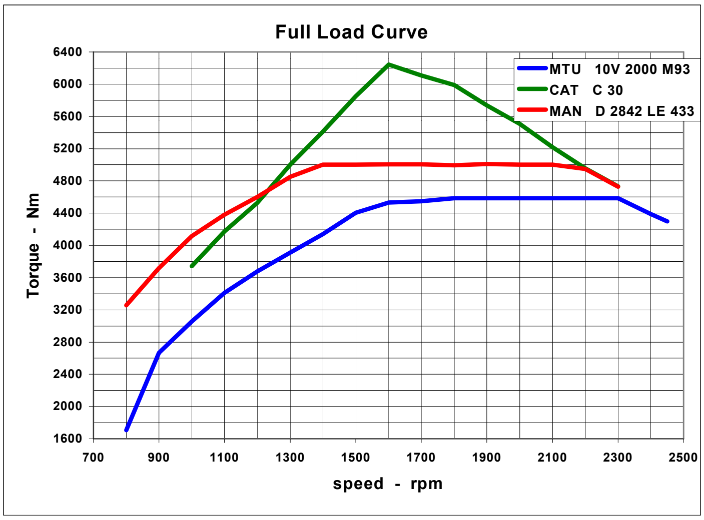


Fig. 16 Comparison of competition – full load

Slika 16. Usporedba s konkurencijom – moment pri punom opterećenju

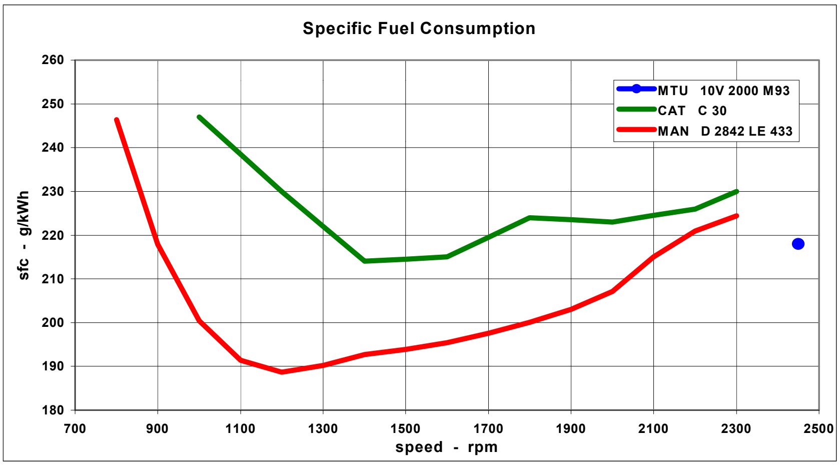


Fig. 17 Comparison of competition – specific fuel consumption

Slika 17. Usporedba s konkurencijom – specifična potrošnja goriva

7. Conclusion

From previously told, it is clear that new MAN generation of yacht diesel engines is improved if compared with older MAN yacht diesel engines, and also, this new generation is better than engines of competitive manufacturers in respect to egine dimensions and engine values.

Common rail technology is what allows such improvement, because only with common rail technology it is possible to influence the necessary injection quantity to the combustion chamber, at the right time, for the desired period and at the right pressure, and all four of the parameters can be influenced at the same time, independent of each other.

Common rail technology allows low fuel consumption, reduction of toxicant substances in exhaust gases and better engine values.