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The multi-fuel diesel engine

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SYNOPSIS

It has become common practice in the marine industry to design and apply large diesel engines for heavy fuel operation.

This statement is valid for practically all engines classified by speed from around 1000 rev/min down to the largest of the low speed diesels running at around 60 rev/min. In terms of power per unit this means from about 500 kW to 50 000 kW.

Internationally valid specifications for marine fuel oil do exist. These specifications are usually very wise and can, in fact, be considered an umbrella for a multitude of fuel oils.

Apart from that, special applications, especially in the industrial section, quite often call for the use of fuels with data outside the range of normal marine fuels.

Such fuels comprise a wide spectrum of both gaseous and liquid hydrocarbons and, although admittedly very seldom commercially materialised, the basic research work has to be done for the preparation of quotations and for the accumulation of knowledge.

With a view to the current low speed diesel engine programme of MAN B&W, this paper discusses the following items: (1) current marine fuel specifications and deliveries; (2) off-spec hydrocarbon fuels; (3) gaseous fuels, such as natural gas and lean gases.

Correlated engine design features are outlined, and actual service and test results described.

LIQUID FUELS IN SERVICE

Fuel oil quality specifications

Most commercially available fuel oils can be used with MAN B&W two-stroke low speed diesel engines. For guidance on purchase, reference is made to ISO 8217, BS 6843 and to the CIMAC recommendations (second edition 1986), regarding requirements for heavy fuel for diesel engines, according to which the maximum accepted grades are RMH 55 and K55.

For reference purposes, an extract from relevant standards and specifications is shown in Table I.

Based on general service experience, and as a supplement to the above-mentioned standards, a guiding fuel oil specification has been prepared and is shown in Table II.

In both tables, the analysed data refer to fuel oil as delivered to the ship, ie before on board cleaning.

Fuel oils limited by this specification have, to the extent of their commercial availability, been used with satisfactory results.

It should be noted that current analysis results do not fully suffice for estimating the combustion properties of fuel oils. This means that service results may depend on oil properties which cannot be known beforehand. This applied especially to the tendency of the fuel oil to form deposits in combustion chambers, gas passages and turbines. Ongoing research work aims at clarifying these issues.

If fuel oils exceeding the data in Table II, especially with regard to viscosity and density, are to be used, the engine builder should be contacted for advice regarding possible modifications required to the fuel oil system.

Fuel oils delivered

Tables I and II show the purchase specifications to which the supplier of oil should deliver. Fuels actually delivered may differ widely, mostly by having better data but occasionally having data exceeding the limits. In order to obtain uniform and reliable information on fuels actually delivered, many owners today subscribe to a fuel quality testing/analysis service which is provided by, among others, Det Norske Veritas (DNV) and Lloyd's Register (LR). In order to get unbiased information on which fuels were actually bunkered by ships equipped with MAN B&W MC engines, DNV were asked to make a survey from their data bank, and below we quote extracts from the report and data received.

> 'Vessels with MAN B&W 'MC' type engines contracted to Veritas Petroleum Services for fuel analysis numbered 221 as at 24th April '88. In the period from January '87 to May '89, these vessels submitted 2691 samples representing quality as delivered.'
>
> The data has been used in two main ways – the overall pictures that come from the total population, and the trends from comparing samples for the first quarter of 1987 with those for the first quarter of 1989, numbering 176 and 314 respectively.

The Veritas Data Base contains information on the actual grade of fuel that the purchaser has ordered for most of the

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Table I: Residual marine fuel standards (extract)

CIMAC			A 10	B 10	C 10	D 15	E 25	F 25	G 35	H 35	K 35	H 45	K 45	H 55	K 55
ISO 8217 F-RM = BS 6843	1)		A 10	B 10	C 10	D 15	E 25	F 25	G 35	H 35	–	H 45	–	H 55	–
BS MA 100 (obsolete)			M 4		–	M 5	–	M 6	–	M 7	–	M 8	–	M 9	–
Characteristic	5)	Dim.													
Density at 15°C	2)	kg/m³	975	991		991	991		991		1010	991	1010	991	1010
Kin. Viscosity at 100°C		cSt	10			15	25		35			45		55	
Flash point		°C	60			60	60		60			60		60	
Pour point		°C	0/6 3)	24		30	30		30			30		30	
Carbon Residue		% W	10/12		14	14	15	20	18	22		22		22	
Ash		% W	0.10			0.10	0.10	0.15	0.15	0.20		0.20		0.20	
Water		% W	0.50			0.80	1.0		1.0			1.0		1.0	
Sulphur		% W	3.5			4.0	5.0		5.0			5.0		5.0	
Vanadium		mg/kg	150		300	350	200	500	300	600		600		600	
Aluminium	4)	mg/kg	30			30	30		30			30		30	

1) Apart from the grades shown here, ISO RMK 35 and 45 and RML 35, 45 and 55 grades have no limit to density and are therefore not suitable for diesel engines.

2) Approximate equivalent viscosities (for information only):

Kinematic viscosity (cSt) at 100°C	10	15	25	35	45	55
Kinematic viscosity (cSt) at 80°C	15	25	45	75	100	130
Kinematic viscosity (cSt) at 50°C	40	80	180	380	500	700
Sec. Redwood I at 100°F	300	600	1500	3500	5000	7000

3) 6°C winter, 0°C summer.

4) No limit to Aluminium is specified in ISO 8217

5) Except for Flash Point, all are max. values

Table II: Guiding fuel oil specification

Guiding fuel oil specification (max values)		
Viscosity	cSt/50°C	700.0
Density	kg/m3 at 15°C	991.0*
Flash point	°C	>60
Conradson carbon	% weight	22.0
Asphalt	% weight	14.0
Sulphur	% weight	5.0
Water	% weight	1.0
Ash	% weight	0.2
Aluminium	mg/kg	30.0
Vanadium (V)	mg/kg	600.0
Sodium	mg/kg	30% of V

* May be increased to 1010, provided adequate cleaning equipment is installed, ie new types of centrifuges.

Table III: Fuel grades ordered for MC engined vessels, % of samples

Grade, cSt at 50°C	*1st quarter 1987*	*1st quarter 1989*
Unknown	22.0	7.3
180	3.2	8.1
280–350	1.1	1.8
380	71.1	80.3
>380	2.6	2.4
	100.0	**100.0**

Table IV: Viscosities of fuel delivered to 'MC' vessels, % of samples

Viscosity cSt at 50°C	*1st quarter 1987*	*1st quarter 1989*
15.1–100	1.7	2.4
101–250	27.1	23.0
252–400	66.8	71.9
>400	4.4	2.7
	100.0	**100.0**

samples. While the number of unknown fuels makes it difficult to detect any trend from Table III, the delivered viscosity picture from Table IV points to an upward move towards 380 cSt.

Table V may seem to show little difference between 1987 and 1989. Sulphur and vanadium, being mainly crude oil dependent, do in fact vary more than the figure suggests due to changes in the patterns of crude oil usage – which is influenced by availability and pricing considerations. That carbon residue has not increased in the period is probably explained by the lack of incentive to crack more deeply while crude has been so cheap. This may well change if crude prices are again moving upwards. The aluminium situation is in line with the broader picture from the total Veritas data. It is believed that better housekeeping probably explains the apparent improvement, but again it remains to be seen if higher crude prices might also have an adverse influence. The apparently reasonable water situation should be viewed with caution. In particular, supplies at some Middle East ports quite regularly contain significant amounts of water, often exceeding 1.0% by volume.

Table VI shows that about half of the fuels are fairly close to or at the 991 kg/m³ at 15°C limit but that very few exceed it. The opportunities for higher density fuels, afforded by advanced centrifuge technology, do not seem to be significantly utilised so far. However, the incentive to promote such fuels will be stronger if the differential between heavy fuel and diesel oil prices widens as a consequence of higher crude costs.

It might be assumed from the foregoing that fuel quality has stabilised and that problems are perhaps no longer of significance. However, as any shipowner who has suffered well knows, one bad problem is one too many. Tables VII and VIII illustrate some of the degrees of quality exceptions that prevail, some of which could potentially be troublesome. The tables are based on the total sample population of 2691.

The ash thresholds of 0.07 and 0.12% are based on the assumption that, even with maximum refinery conversion, it is difficult to produce fuels that exceed 0.10% ash without

Table V: Historical fuel quality trends for MC engined vessels

		1st quarter 1987	*1st quarter 1989*
Sulphur % m/m	Mean	2.77	2.81
	Standard Deviation	0.79	0.80
	Maximum	4.31	4.52
	Minimum	0.56	0.16
Carbon residue % m/m	Mean	13.4	12.4
	Standard Deviation	3.05	2.85
	Maximum	20.7	19.4
	Minimum	6.5	3.3
Vanadium mg/kg	Mean	84.0	96.0
	Standard Deviation	50.0	76.0
	Maximum	339.0	430.0
Aluminium	Mean	7.0	5.0
	Standard Deviation	8.7	5.5
	Maximum	58.0	32.0
Water	Mean	0.3	0.2
	Standard Deviation	0.63	0.23
	Maximum	7.0	2.0

Table VI: Densities of fuels in 'MC' vessels, % of samples

Density, kg/m³ at 15°C	*1st quarter 1987*	*1st quarter 1989*
<952	6.3	2.4
952–961	10.7	8.1
962–971	10.7	15.5
972–981	20.3	18.6
982–991	46.7	51.8
992–1001	5.1	2.4
>1001	0.2	1.2
	100.0	**100.0**

Table VII: Ash exceptions; fuels in 'MC' vessels, number of samples

Port	*>0.07% m/m*	*>0.12% m/m*	*Max level*
Antwerp	14	3	0.23%
Fujairah	13	4	0.40%
Hamburg	22	2	0.62%
Houston	8	2	0.19%
Los Angeles	57	9	0.16%
New York	24		
Philadelphia	17		
Rotterdam	19	1	0.33%
San Francisco	13		
Seattle	10	3	0.16%
Other European (=14)	25	3	0.18%
Other US East and Gulf (=10)	26		
Remainder (=14)	31	5	0.29%

Table VIII: Carbon residue exceptions; 'MC' vessels, number of samples

Port	*>16.0% m/m*	*>18.0% m/m*	*Max level*
Amsterdam	10	2	20.5%
Antwerp	16		
Durban	15	12	20.1%
Fujairah	6	1	19.9%
Hamburg	13	1	18.2%
Houston	21	2	18.2%
New York	11	2	18.8%
Rotterdam	68	20	22.8%
Singapore	67	14	18.9%
Taranto	6	2	20.2%
Uddevalla	12	4	18.9%
Others (=25)	58	6	19.6%

Table IX: High sulphur exceptions; 'MC' vessels, number of samples

Port	*>3.5% m/m*	*>4.0% m/m*	*Max level*
Antwerp	7	1	4.08%
Copenhagen	11	9	4.57%
Fujairah	31	7	4.34%
Houston	10	1	4.01%
Kuwait	12	7	4.07%
Mena Saud	12	4	4.13%
Rotterdam	69	7	4.21%
Singapore	125	17	4.31%
Other Far East (=13)	33	1	4.02%
Other Mid East (=4)	4		
Other N Europe (=7)	16	2	4.17%
Other Mediterranean (=13)	25	2	4.15%
Other US (=10)	27	1	4.33%
Rio Grande	2		

Table X. Lower sulphur exceptions; 'MC' vessels, number of samples

Port	*<1.0% m/m*	*Max level*
Abidjan	1	0.96%
Bergen	1	0.93%
Buenos Aires	3	0.42%
Copenhagen	2	0.95%
Jacksonville	1	0.99%
Los Angeles	2	0.89%
Oslo	2	0.77%
Port Harcourt	1	0.41%
San Francisco	4	0.92%
Santos	2	0.67%
Shanghai	1	0.14%
Xingang	1	0.16%

someone adding some wastes or other materials. The Fujairah situation is largely accounted for by the sodium from excessive sea water. At Los Angeles, however, other metals than the usual four, ie vanadium, sodium, aluminium and silicon, are commonly found, particularly calcium and others that may be associated with spent lube oils.

High carbon residue levels are, of course, largely accounted for by thermal cracking, and the particularly bad areas are clear from Table VIII. Although not necessarily related just to carbon residue *per se*, Durban fuels do seem to cause a fair amount of problems for some shipowners, particularly sludges that may not be accounted for by tests such as hot filtration.

Finally, Tables IX and X give a picture of where both the higher and lower sulphur levels have been encountered. Despite all that has been said by the oil industry in the past, there are few fuels exceeding 4.0% and only one marginally above 4.5%. As Table X shows, very low sulphurs are negligible and even those below 1.0% are relatively few.

Summary – fuel deliveries

Because 'lower' quality fuels tend to be more prevalent at certain major ports, and because vessels with MC engines lift a larger proportion of their supplies at these ports than the average vessel, MC engines may encounter such fuels more regularly than other engines.'

It is thus clear that for low speed engines like the MC, heavy fuels are not only specified, they are also used, and a very wide range is in fact covered. Therefore, service experience, which has generally been good, should be seen and evaluated in the light of this.

COMBUSTION QUALITY OF HEAVY FUEL OIL

In order to prepare for future qualities of heavy fuel oil, and to widen knowledge of those employed today, a series of fuel oils have been tested in a one-cylinder L42MC research engine.

A major oil company was asked to supply the author's company with some fuels which were entirely out of specification.

Many different test fuels were received, including the following intermediate refinery products:

1. lslr: low sulphur long residue;
2. lssr: low sulphur short residue;
3. lscsr: low sulphur cracked short residue;
4. lsfcr: low sulphur cracked short residue, flashed;
5. lccco: light cat cracked cycle oil.

Analytical data appear in Table XI.

Table XI: Test fuel raw materials

	lslr	*lssr*	*lscsr*	*lsfcr*
Density at 15°C, kg/m^3	925.5	972.0	1009.1	1028.7
Viscosity at 100°C, cSt	15.7	159	121	332
Viscosity at 50°C, cSt app	100	4000	3000	10–15 000
Viscosity at 150°C, cSt	5.25	26.5	19.5	35.9
Ramsbottom cr, o/o (m/m)	4.4	10.0	15.7	18.0
Micro carbon, o/o (m/m)	5.1	11.7	17.7	– –
Ash 550°C, o/o (m/m)	0.006	0.014	0.027	0.026
Sulphur, o/o (m/m)	0.83	1.19	1.06	1.28
Asphaltenes, o/o (m/m)	0.30	2.0	8.5	8.8
	lccco			
Density at 15°C kg/m^3	907			
Viscosity at 50° mm^2/s	2.78			
Ramsbottom cr o/o (m/m)	0.25			
Sulphur content, % m/m	0.92			
ibp, °C	137			
25%, °C	230			
50%, °C	292			
75%, °C	355			
fbp, °C	522			
(ibp: initial boiling point) (fbp: final boiling point)				

From these 'raw materials' test fuels were blended using the lccco as diluent. A low viscosity synthetic fuel, high in density and low in viscosity, was also used as a diluent. These were used in order to avoid improving the ignition quality by the light fraction. Test fuel data appear in Table XII.

As can be seen the test fuels have, to some extent, specifications which exceed the guiding fuel specifications in Table II. It is also worth noting that the fuels cover a wide range of CCAI values, and include fuels which might be troublesome.

The test schedule comprised a total of 11 tests on about half of the fuels, covering low load to full load along the propeller curve, as well as at constant engine speed and two different scavenge air temperatures. On the other fuels, a smaller number of tests were carried out, mainly aimed at searching out problems. Altogether, 75 tests were performed. During each test, all normal engine observations were recorded together with complete component temperature measurements, as well as particulate and gaseous emissions.

Furthermore, the cylinder pressure was recorded as the average of 150 cycles, and this data was subsequently analysed. By means of the company proprietary cycle analysis calculation program the rate of heat release curve, the indicated mean pressure, the maximum rate of pressure rise, and the ignition delay were determined.

The results in general were considered slightly disappointing. It had been expected that among the fuels tested there would have been fuels with inferior combustion or ignition behaviour, at least in part load, but no such fuel characteristics were found. Actually, the most pronounced problem-indication was a significant increase in particle emissions (soot) found during the low load tests of fuel No 10, which has a high Conradson carbon value. This increased soot emission will hardly influence the engine itself, provided that more frequent cleaning of the turbocharger's turbine side is carried out. However, it may very well lead to severe problems with the exhaust gas boiler, unless suitable cleaning equipment is installed and frequent soot blowing of the boiler carried out. Although not a direct-engine related problem, a soot fire in the boiler, with the associated risk of a complete melting down of the boiler is a serious event from an economical as well as a total machinery reliability point of view.

Although slightly disappointing against the background of the expected problem level, the test results certainly deserve more attention than space allows in the present paper. As an example of the results, Table XIII gives a summary of the ignition and combustion quality relevant data for some of the more interesting fuels. As can be seen the ignition delay is, in any case, very short and without any negative influence on the combustion, which is very smooth in all cases. The rate of pressure rise, an important parameter for piston ring running conditions, is extremely modest and hardly exceeds the maximum value during compression. Figure 1 shows, as an example, the rate of heat release curve at full load and at 25% load

Table XII: Specification of fuels tested on the L42MC test engine, compared with MAN B&W Diesel's guiding fuel oil specification (max values)

Fuel No	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*Guiding fuel specification*	*Units*
Viscosity	2.27	3.8	84	85	141	198	255	470	520	560	690	710	700	cSt/50°C
Density	843	968	995	970	993	938	977	985	983	1010	1008	1030	991*	kg/m³ at 15°C
Flash point	65	98	84	80	103	100	106	90	95	90	79	84	60	°C
Conradson carbon	0.01	0.3	17.2	12.1	13.3	9.4	14.5	16.8	14.8	17.3	22.1	24.7	22	% weight
Asphalt	0.00	0.78	15.1	8.9	9.2	3.7	10.0	11.3	12.8	14.6	19.3	29.0	14	% weight
Sulphur	0.22	0.10	2.72	1.16	0.91	0.83	0.87	0.90	1.18	2.22	3.52	3.30	5	% weight
Water	0.00	0.01	0.01	0.01	0.00	0.01	0.02	0.02	0.01	0.00	0.00	0.00	1.0	% weight
Ash	0.00	0.00	0.065	0.025	0.03	0.03	0.025	0.03	0.035	0.04	0.07	0.09	0.2	% weight
Aluminium	–	–	–	–	–	–	–	–	–	–	–	–	30	mg/kg
Vanadium (V)	0	0	220	20	23	12	17	24	45	122	300	370	600	mg/kg
Sodium	0	0	27	23	24	25	40	35	22	22	24	50	30% of V	mg/kg
CCAI	805	912	874	849	866	807	843	844	841	868	864	885	No specification	

* May be exceeded provided adequate cleaning equipment is installed, ie new types of centrifuges.
Fuel No 1 is Danish gas oil, used for reference. Fuel No 6 is Lloyd's reference fuel (paraffinic).

Table XIII: Summary of the most interesting ignition and combustion related test results for some of the test fuels; '–' indicates not tested

Fuel No	*1*	*2*	*10*	*11*	*12*	*Units*
CCAI	805.0	912.0	868.0	864.0	885.0	–
Ignition delay at MCR	1.7	1.3	1.8	1.4	1.5	deg CA
Ignition delay at 25%	0.0	–	0.7	–	0.9	deg CA
Rate of pressure rise at MCR	3.3	3.7	2.6	3.0	2.5	bar/deg CA
Rate of pressure rise at 25%	3.4	–	1.8	–	3.3	bar/deg CA
Emission corrosion to 15% O_2:						
NOx at MCR	1660.0	1690.0	1590.0	1710.0	1490.0	PPM dry
CO at MCR	16.0	18.0	40.0	26.0	27.0	PPM dry
HC at MCR	94.0	98.0	52.0	52.0	47.0	PPM wet
Soot at MCR	7.0	10.0	46.0	67.0	72.0	mg/Nm³
Soot at 25%	7.0	–	85.0	–	64.0	mg/Nm³

(propeller curve) for the reference fuel (gas oil) and for two fuels with high CCAI values. As can be seen there are no ignition spikes, and the rate of pressure rise is correspondingly, as previously mentioned, extremely modest. Consequently, from a combustion point of view, no problems would be expected from the fuels tested. It must be concluded that, within the range tested, the CCAI value cannot be considered an applicable tool for predetermining the combustion and ignition quality on MC low speed engines.

Although the tests seem to indicate that the MC engine still has a wide margin to cope with deterioration of the fuel oil quality, it should be mentioned that the absence of engine combustion problems, during the test program of course, does not prove that such problems cannot result from the use of other commercial fuels in service.

Summary – fuel testing

The fuel test can be summarised as follows:

1. the oil quality influences SFOC by a maximum of ±1%, when corrected for a lower calorific value;
2. the ignition delay on the research engine is insignificant;
3. the ignition delay seems unaffected by scavenge air temperature;
4. CCAI cannot be used as a criterion for ignition quality on the company's low speed engines.

The above proves that the low speed diesel has a large potential in the field of further degraded liquid fuel quality. It will be in handling systems which will be quite unconventional that modifications and adaptations are made (for more details see Ref 4).

GASEOUS FUELS

Design of the MC-GI engine

Gas burning diesel engines have been available for years, however, with the drawback that the specific power output and thermal efficiency have been low due to the technique applied.

During the last few years, research and test work in the gas engine field has accelerated using the high pressure gas injection system. The significant advantage is that the gas does not take part in the compression stroke of the engine, which completely eliminates any risk of knocking, and which is the limiting factor for mean effective pressure and hence the power output of engines using a traditional low pressure gas injection system. Furthermore, the high pressure gas injection system has the advantage of being insensitive to the gas composition. This also means that lean gases with a relatively low calorific value can be used.

Based on fundamental research work carried out by our

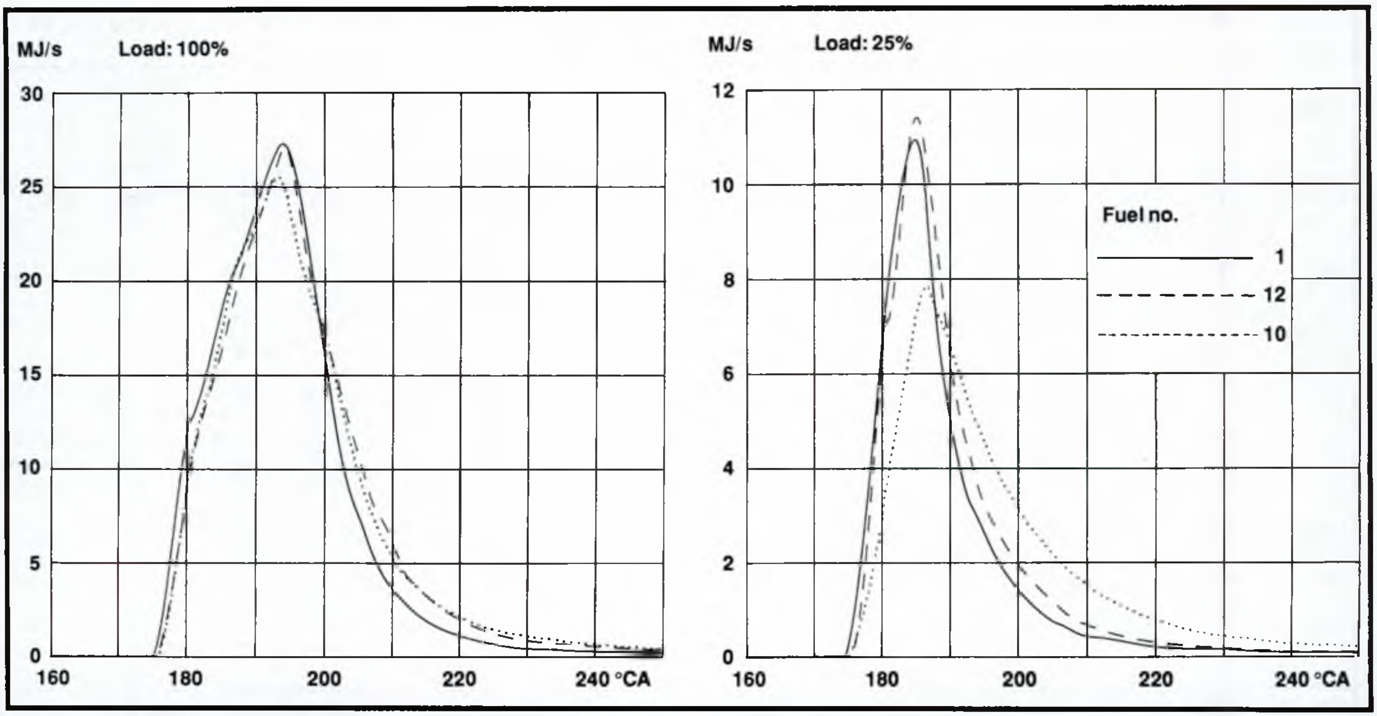


Fig 1: Comparison of rate of heat release at MCR (left side) and 25% load on the propeller curve (right side) for the two 'high CCAI' fuels Nos 10 and 12, with that of gas oil (No 1)

licensee Mitsui,[1] the standard high pressure gas injection system has been developed and designed jointly by Mitsui and MAN B&W Diesel, leading to the dual fuel version of the two-stroke, crosshead MC engine, designated MC-GI.

The targeted market sectors are LNG carriers and industrial application.

The MC-GI engine series is, in terms of engine performance (output, speed, thermal efficiency, exhaust gas amount and temperatures, etc), identical to the well-established heavy-fuel burning MC engine series.

As regards the design and application potential of the MC engines, Refs 1, 2 and 3 will provide adequate background, for which reason the following description will only deal with issues of particular relevance to the MC-GI engine.

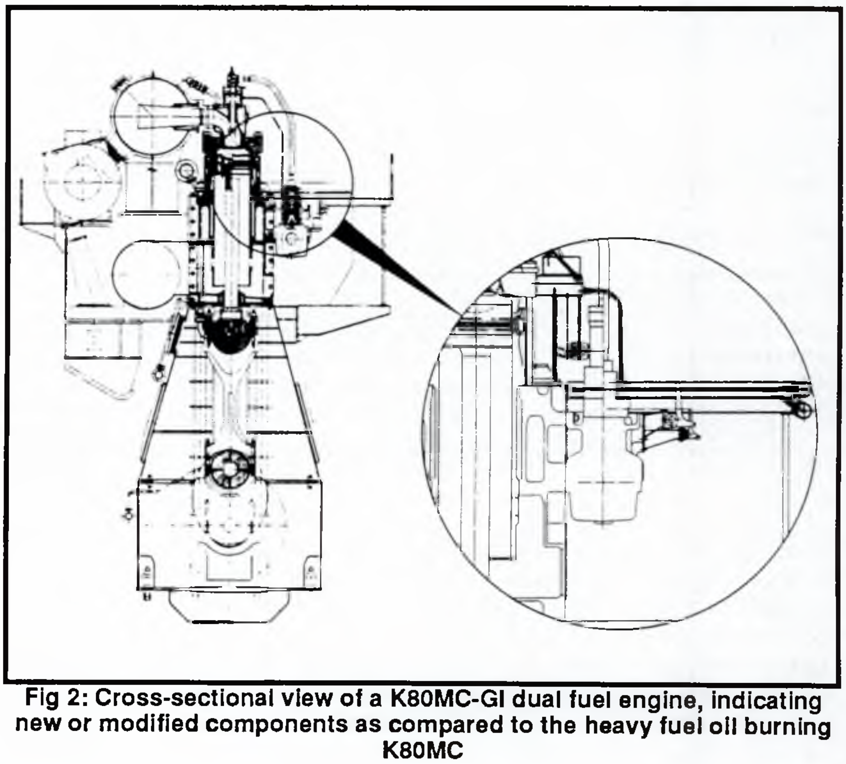


Fig 2: Cross-sectional view of a K80MC-GI dual fuel engine, indicating new or modified components as compared to the heavy fuel oil burning K80MC

General description

Figure 2 shows a cross section of a K80MC and, in the circle, the new/modified parts of its K80MC-GI counterpart, comprising gas supply piping, gas distributor block with accumulator on the (slightly modified) cylinder cover, combined fuel oil/gas injection valves and a slightly modified camshaft system incorporating an extra, small, fuel oil pump for controlling the amount of injected gas. Further to this, minor modifications have been made to the exhaust gas receiver, the exhaust valve and the control and manoeuvring system.

Apart from these systems on the engine, the engine auxiliaries will comprise some additional units, the most important being:

1. a high pressure gas compressor, inclusive of cooler, to raise the pressure to approximately 250 bar, which is the pressure required at the engine inlet;
2. a buffer tank inclusive of condensate separator;
3. a compressor control system;
4. safety systems, which should include a hydrocarbon analyser for checking the hydrocarbon content of the air in the compressor room and the engine room.

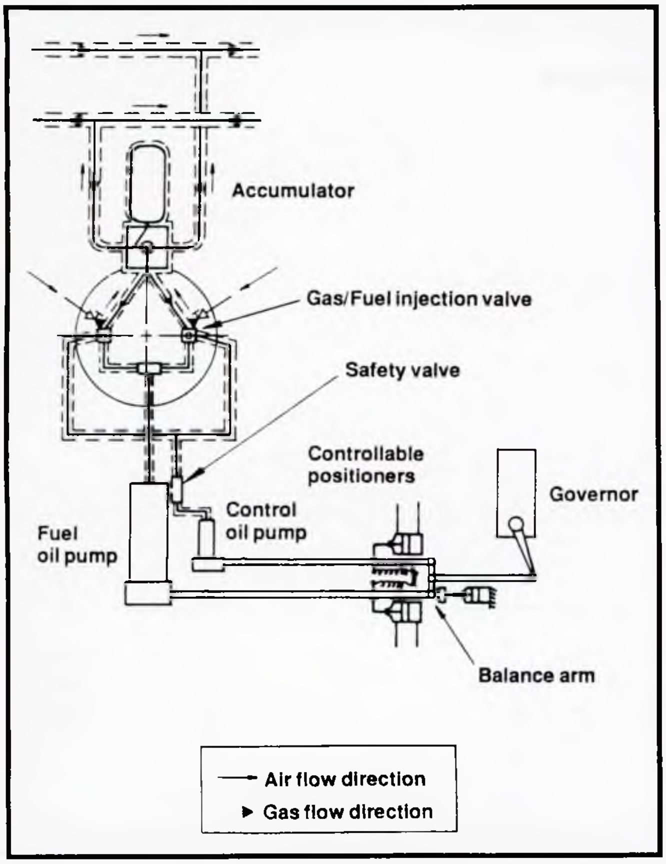


Fig 3: Fuel and control system for MC-GI engine (schematic)

Concerning the safety system for such units, the regulations to be complied with have to be investigated case by case. Figure 3 shows the system layout for the engine in schematic form. The high pressure gas from the compressor unit flows through the main pipe (positioned alongside the engine's upper gallery), *via* narrow and flexible branch pipes to each cylinder's gas distributor block and its associated buffer volume. The narrow and flexible branch pipes perform two important tasks:

1. they separate each cylinder unit from the rest in terms of gas dynamics, utilising the well-proven design philosophy of the MC engine's fuel oil system;
2. they act as flexible members between the stiff main pipe system and the engine structure, thus safeguarding against extra stresses in the main and branch pipes caused by the inevitable differences in thermal expansion of the gas pipe system and the engine structure.

Also the buffer volume, containing about 20 times the injection amount per stroke at MCR, performs two important tasks:

3. it supplies the amount of gas injected with only a slight but predetermined pressure drop;
4. it forms an important part of the safety system.

Since the gas supply system is a common rail system, the gas injection valve must be controlled by another system, the control oil system. In principle, this is the fuel oil system of an L35MC engine, consisting of its standard fuel injection pump, supplying high pressure control oil to the gas valve, and thereby opening the gas valve and keeping it open during the period necessary for injecting the required amount of gas.

The normal fuel injection pump, which supplies pilot oil in dual fuel operation mode, is connected to the high pressure pipe of the control oil pump by a combined timing and safety valve.

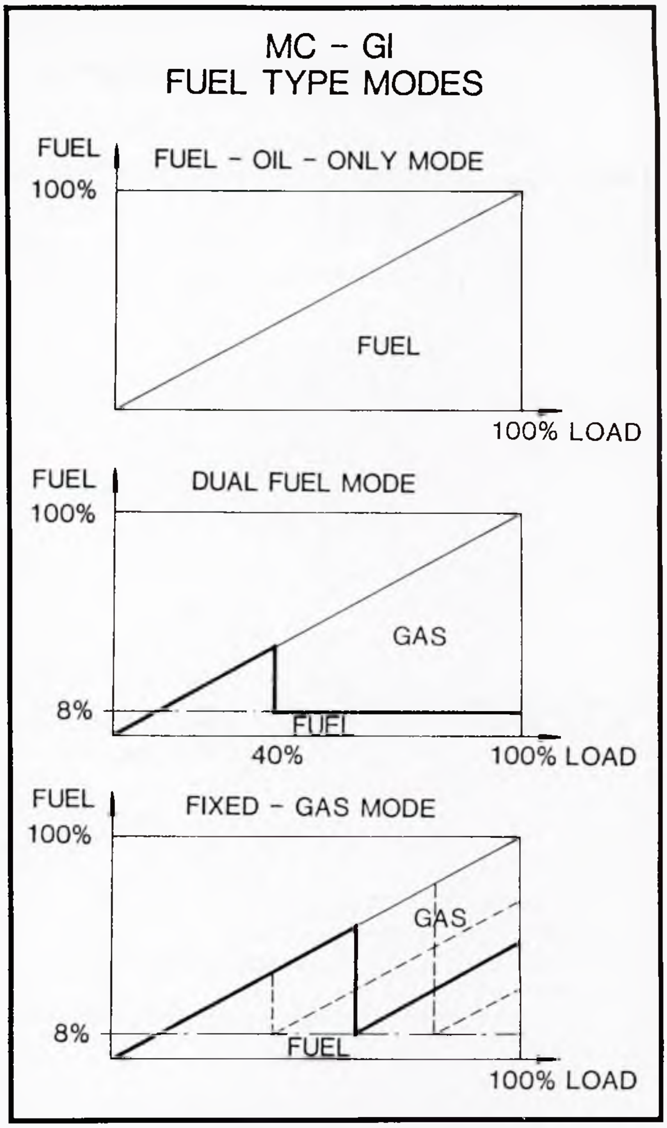


Fig 4: Operating modes of MC-GI engine

The control and manoeuvring system incorporates a balancing arm as well as controllable positioners in the two regulating shaft systems. By means of these positioners, the engine can be operated in the various relevant modes: normal dual fuel mode with minimum pilot oil amount, fuel-oil-only mode and fixed-gas mode. The latter is only relevant where a limited gas supply is obtained from the external source, the amount being less than the engine needs to develop the required output.

The operating modes are shown in Fig 4.

Gas injection system

The injector for liquid and gaseous fuel constitutes a key component.

The media to control, and to be controlled by, the injectors are gaseous fuel, liquid fuel, control oil and sealing oil.

Basically, liquid fuel is injected first and allowed to ignite as in a normal diesel engine after which the gaseous fuel is injected alongside the burning fuel, which acts as pilot fuel for the gas. The gas injection is controlled by the control oil and the sealing oil keeps the media apart in the injectors.

Based on comprehensive tests and modelling, it was decided to design the injectors as two separately identifiable valves, one for liquid fuel and one for gaseous fuel, but integrated into the

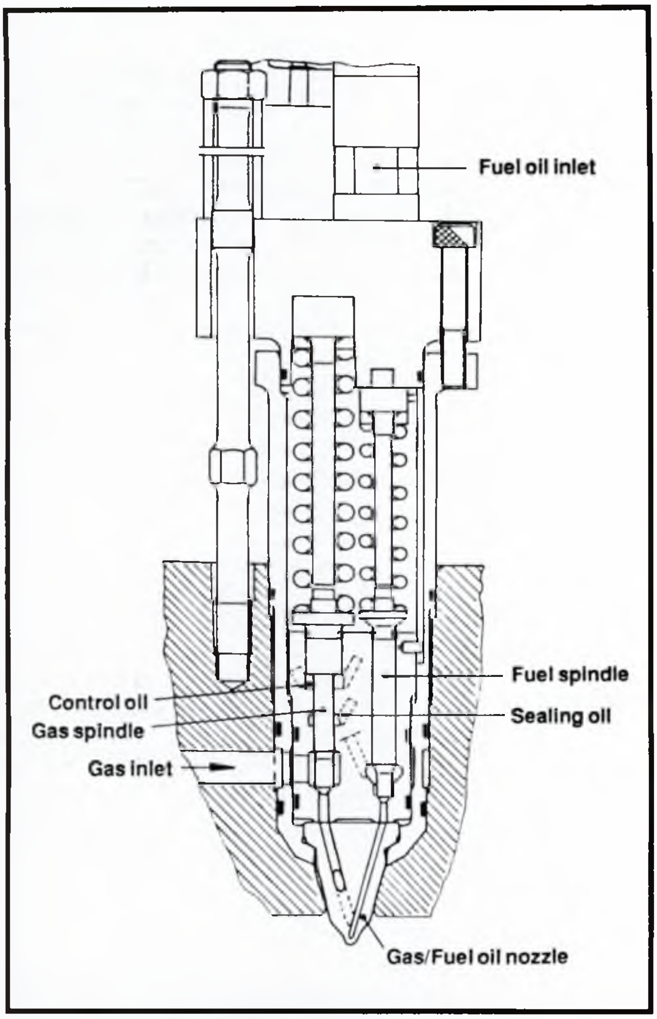


Fig 5: Actual design of a combined fuel oil/gas injection valve for an L35MC engine

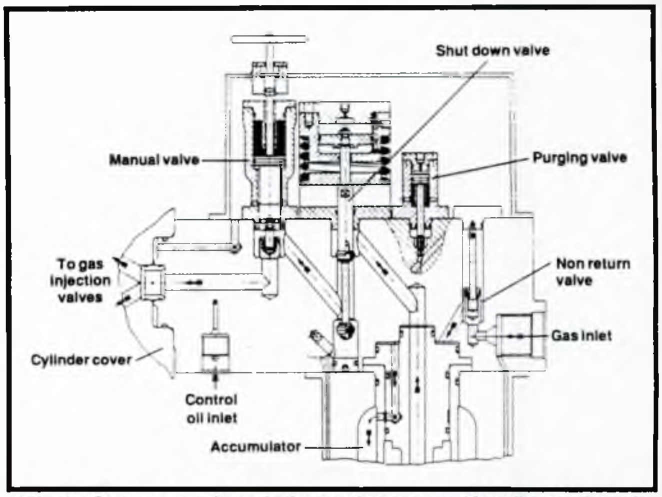


Fig 6: Cross-sectional view of the gas distributor block

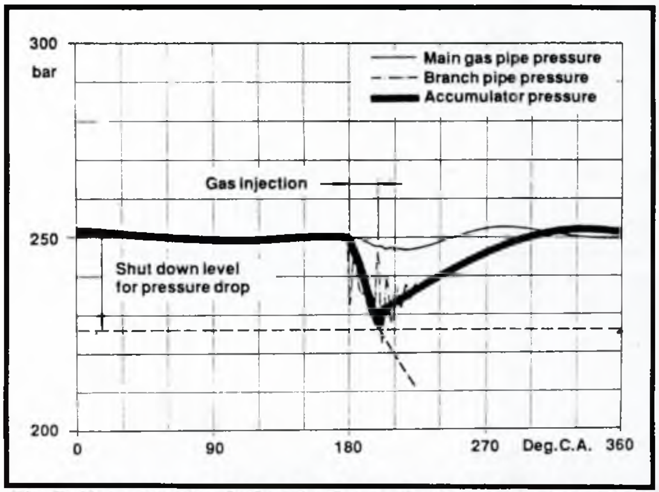


Fig 7: Pressure variation in the main gas pipe at the fuel valve and in the accumulator during gas injection

same combined valve housing so as to ensure an almost parallel injection of liquid fuel and gas.

The actual design of the combined valve is shown in Fig 5.

The position and direction of the fuel oil sprays and the gas jets are almost the same, leading to the same thermal load pattern on the combustion chamber walls, and ensuring stable ignition of the gas in dual fuel operation with a minimum supply of pilot oil.

The pilot oil can be heavy fuel and/or diesel oil, as preferred in each individual case.

Whereas the cylinder cover and the regular fuel pump are nearly unchanged, the control oil systems comprise an additional fuel pump fitted on the camshaft housing. An L35MC pump is used and the control oil operating medium is the same as for pilot oil and, in the standard operation, forms an integral part of the fuel oil circulating system.

For the sealing oil system, which is a separate system, a small high pressure pump, with a supply pressure higher than that of the high pressure gas system, is required. Heavy fuel or lubricating oil can be used.

Gas pipes

The gas pipes are double-walled, with the outer shielding designed to prevent gas outflow to the machinery spaces in the event of rupture of the gas pipe. The intervening space, including the space around valves, flanges, etc, is equipped with separate mechanical ventilation with a capacity of at least 10 air or inert gas changes per hour.

The gas pipes are connected to a nitrogen purging system, which is activated when the engine changes over to the fuel-oil-only mode.

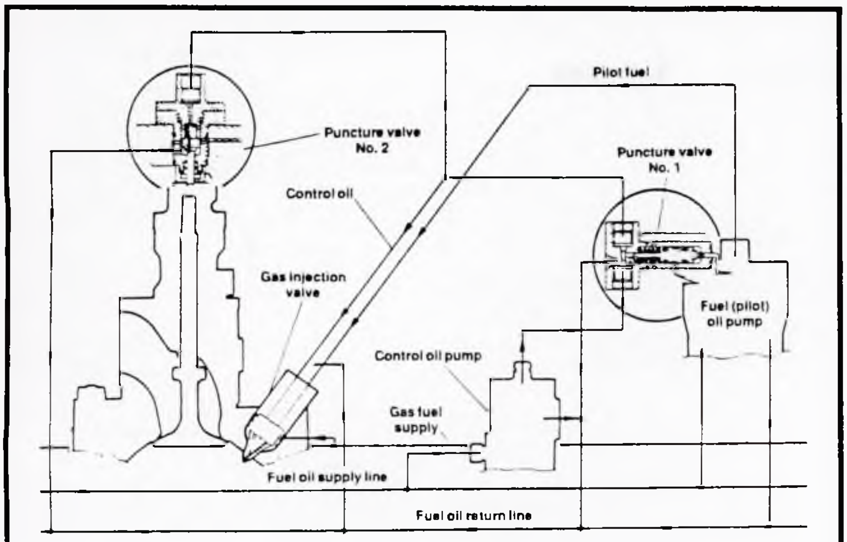
Gas distributor block

An important new engine component is the gas distributor block, shown in Fig 6. Since a number of valves are class requirements, and these have to be made in 'double wall' execution, we have found it practical to incorporate all valves in a separate block per cylinder, bolted to the side of the cylinder cover and carrying the accumulator as well. This provides a compact design and facilitates overhauling work on the engine.

MC-GI safety systems

The key target of the safety system has been to design for preventing faults rather than to detect faults when and if they occur.

In the engine room of a ship or the engine hall of a power station, the presence of leaking gas will be detected by a hydrocarbon analyser (HC). The same applies for the ventila-



Event	Action
Small leak from gas valve:	T_{exh} + C_{HC} Alarm + shutdown
Large leak from gas valve:	Δp accu. Alarm + shutdown
No pilot oil injection:	No gas injection due to puncture Valve 1
Sticking exhaust valve: (no compression – no ignition)	No gas injection due to puncture Valve 2

Fig 8: Summary of MC-GI engine safety system

Fig 9: Gas supply unit, dominated by the large LNG tank

tion of the intervening space of the double wall piping, where alarm is given at a gas concentration of 30% of the lower explosion limit and shut-down occurs at 60%.

All starts and stops must be carried out on fuel oil only, and the safety devices on the engine will continuously monitor the functioning of the components involved in gas operation during service.

When changing over from gas operation to fuel oil operation at a predetermined load, the entire gas pipe system will be purged with inert gas, eg nitrogen. When the load of the engine is decreased, the changing back to diesel oil will only take place automatically at the same predetermined load, and the gas pipes are again purged automatically by inert gas eg nitrogen.

The main sources of faults during operation of the engine are:

1. defective gas injection valves;
2. failing ignition of injected gas.

In order to prevent large amounts of gas from entering the engine following a possible defective gas injection valve (seizure and/or sluggishness), the gas flow to each cylinder is monitored, as illustrated in Fig 7.

If the gas flow considerably exceeds the value corresponding to the actual load, the pressure in the accumulator will drop below the corresponding shut-down level and activate the shut-down valve in the gas distributor block.

Very small gas leakages are detected by exhaust gas temperature monitoring, while large gas leakages are detected by a pressure drop in the accumulator.

To ensure that no gas is injected in cases where no pilot oil is injected, the control oil pressure for opening the gas valve is only allowed to reach the gas valve if pilot oil pressure has built up. This is achieved by the pilot oil pressure activating a valve that otherwise will puncture the control oil circuit. One such valve is fitted in each cylinder's fuel injection system.

A second puncture valve for the control oil circuit is located on top of each exhaust valve so as to ensure that no gas injection takes place if there is no compression, and hence no ignition, due to a sticking exhaust valve.

As can be seen from the above, it is possible to safeguard both the engine installation and the personnel and, when taking the proper countermeasures, a most satisfactory service reliability and safety margin is obtained. The safety system is summarised in Fig 8.

The GI principle has also been introduced, in a slightly modified version, on our four-stroke 28/32-type engine, which will be the first to be delivered as a GI engine. An order has been secured to deliver a 16V28/32 GI, which is a 3.5 MW engine, to a combined heat and power plant in Denmark. Delivery will be in the summer of 1991.

Lean gas applications

If the gas employed contained large amounts of inert or low calorific-value gases, a large amount of gas will have to be injected per stroke. This will require a large flow area in the gas injection valve and its nozzle, and also a larger accumulator volume in order to avoid too large a pressure drop during the injection.

Furthermore, it is necessary to inject the gas at a low pressure in order to avoid creating too much swirl in the combustion chamber, and thereby increasing the heat load on the combustion chamber components. As a consequence, the combined gas injection/pilot oil valve shown in Fig 5 may not be large enough to accommodate the increased gas flow, and the alternative solution with separate gas injection valves and pilot oil injection valves may become necessary.

Recently a design concept has been developed which can utilise a special lean gas, containing approximately 65% carbon dioxide (CO_2), 7% nitrogen (N_2) and 28% methane together with other hydrocarbons. The gas in question is extracted from underground sources in Yugoslavia, owned by Naftagaz. Since the supply pressure is around 60 bar, a simple single-stage compressor is sufficient to deliver the gas to the engine (at around 190 bar pressure), and the compressor work is, consequently, less than 2% of the engine output.

In order to test the total design concept before finalising the design of an actual plant it was decided, in co-operation with the potential engine builder Uljanik and the potential customer Naftagaz, to carry out the design modifications and to test an artificial gas of a similar composition on an experimental 6L35MC engine set up at the company's Holeby works. For this purpose, one cylinder was converted to dual fuel operation in accordance with the MC-GI standard system, but in such a way that the engine could also operate on the lean gas.

Due to the large gas volume to be injected, a special cylinder cover was designed to accommodate separate gas injection valves and pilot oil valves.

The design of the gas injection valve is based on the principle used for the combined fuel oil/gas injection valve as well as experience gained with normal fuel valves.

To protect the gas injection nozzle against tip burning, the cylinder cover has been made with a protective guard in front of the gas injection nozzle.

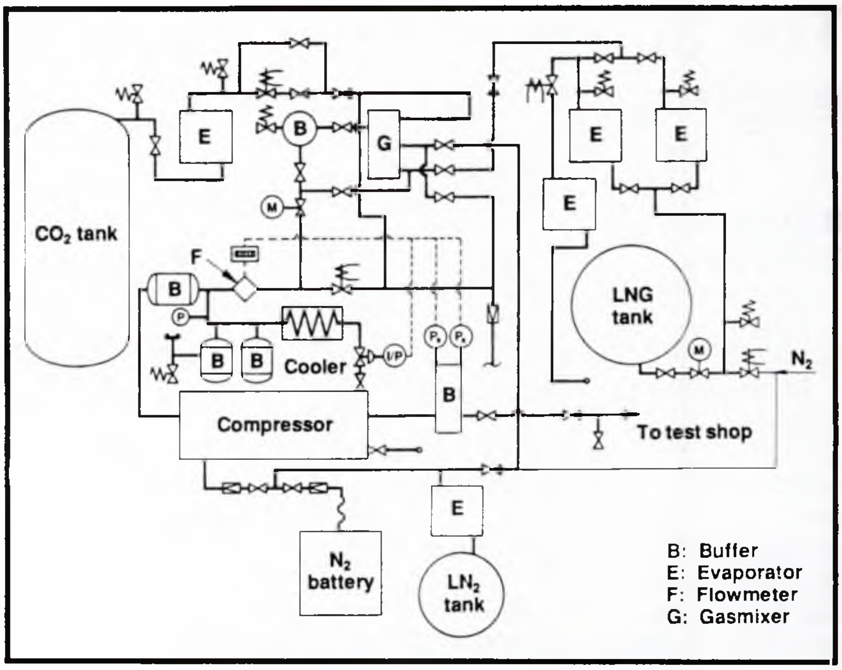


Fig 10: Gas supply system in schematic form

Also a number of other components were tailor-made for the test.

As no direct natural gas supply network exists close to the location of the test engine, a gas supply system has been installed which is capable of storing, mixing and compressing the various gas types to be tested.

The gas supply system, Fig 9, shown schematically in Fig 10, consists of tanks for liquid natural gas (27 m^3) and CO_2 (18t) and pressure bottles for nitrogen (2 x 200 Nm^3) as well as a tank with liquid nitrogen. From these, the gases are led (after vaporisation in the units shown) to a unit which mixes the gases in the desired ratio. From the mixer, the gas flows to a 1000 litre buffer tank, in which the pressure is kept at 10–12 bar, on through a quick closing valve to a reciprocating compressor with bypass pressure control. After the compressor, two 50 litre buffer tanks, a shut-off valve and a non-return valve are provided. The compressor is capable of supplying 300 Nm^3/h of gas to the test engine at up to 250 bar.

The tests with lean gases were completed in the summer of 1989 and the feasibility for their use was confirmed.

The gas supply system is presently being used to supply natural gas for testing of the 5L28/32 GI test engine, which forms the basis for the optimisation of the 16V28/32 GI engine on order.

Summary – gaseous fuel

The high pressure gas injection principle can be considered fully developed and commercially available for both marine and power plant application.

In a wider sense of application, the principle allows the combustion of any compressible gas with an LCV above 10 000 kJ/kg, which is only 25% of that of regular LNG or fuel oil.

ENVIRONMENTAL ASPECTS

It would be unrealistic in a forum like this not to mention environmental aspects. There is a rapidly increasing correlation between the feasible technical possibilities and their environmental impact. Technology is, however, available to meet any environmental legislation (see Ref 5).

CONCLUSION

Diesel engines are accepted as very efficient heat engines. This paper has illustrated that the merits of these engines can be obtained even with fuels far from those originally intended. Hence the application possibilities, including unconventional propulsion plants, are abundant.

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