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TRANSACTIONS (TM)

ELECTRONICALLY CONTROLLED INJECTION IN DIESEL ENGINES

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Electronically controlled injection in diesel engines

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SYNOPSIS

Only if the electronic system acts directly upon the injection valves and if each cylinder is separately activated can one speak of electronically controlled injection. This makes it possible to optimise the combustion process systematically for any operating conditions; minimise fuel consumption, for instance, by taking advantage of ambient temperatures while continuously optimising ignition pressure. But if the injection pressure is too high, piston ring wear and fuel consumption increase. Another limit is component temperature. In future, engine loads—both mechanical and thermal—may also be controlled by the system. Test trends are shown for injection point, mean injection pressure and the injection pressure curve. A two-stage servo-valve actuator system is described.

1. GENERAL PRINCIPLES

1.1 Remote control

Remote control systems of recent design feature electronically controlled, automatic, sequential control programmes for diesel engine start, run-up, manoeuvring, crash reversal or stopping. This is not surprising since the new microprocessor technology affords ideal conditions for storing functional inter-relationships and deriving control variables from these, whenever necessary.

After some initial difficulties, micro-processors and, in particular, the final servo system performed excellently in service.

1.2 Volume control

The main controlled engine variable is always injection volume. By altering the fuel volume injected into the cylinders, mean effective pressure and torque are changed and, consequently (assuming the same resistance to propulsion) the engine rev/min and ship's speed.

Microprocessor technology, as such, has introduced nothing new as regards the remote control elements of the engine proper. Only if the electronic system acts directly upon the actuators of injection, or if each cylinder is separately controlled, can one speak of electronically controlled injection in the proper sense.

2. CONTROL OF THE HEAT RELEASE RATE

2.1 The fuel situation

A great deal has lately been said and published about the present and the future fuel situation. M A N's diesel engine development is based on predictions by various mineral oil companies for the next few years.

Fig 1 shows important parameters, describing the impact of these changes on the fuels and the action taken to cope with them. I do not want to go into further details here as regards this table, since the following trends may suffice for a discussion of electronically controlled injection in diesel engines:

2.1.1 fuels are becoming more and more expensive;

2.1.2 the combustion qualities are deteriorating all the time and vary greatly between bunkers;

2.1.3 the percentage of abrasive and corrosive components in the fuel is on the increase.

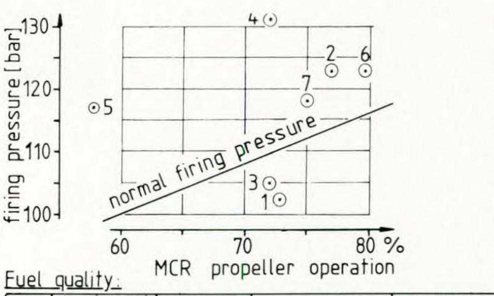
It is the first two points that are of most interest in the context of injection. The first implies that we must make optimal use of the fuel throughout the engine and under all operating conditions. The second point implies an injection system which is readily adaptable to the different fuel grades. This involves new requirements to be met by the injection system.

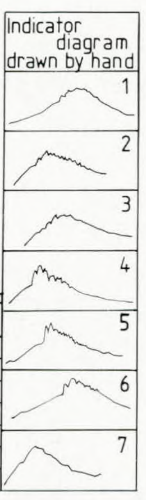
2.1.4 Preventing knock

Timing the beginning of injection pressure to serve only the needs of volume control will not meet future requirements completely.

	Unit	Valid until 1985		Valid as from 1985		
		ESSO	SHELL	ESSO	BP	SHELL
Density/15°C	g/ml	0,99	0,99	—	0,99	—
Viscosity at 50°C at 100°F	mm²/s(cSt) sec Redw.I	480–500 4800	460 4500	600 6000	600 6000	600 6000
Conradson Carbon Residue	Wght %	20	16,5	20	22	20
Asphalt	Wght %	10,5	—	14	—	—
Sulphur	Wght %	5,0	4,5	5,5	5	5
Ash	Wght %	0,1	0,1	0,15–0,2	0,2	0,15
Vanadium	mg/kg	500	—	500–600	—	—
Water	Vol %	1,0	1,0	1,0	1,0	1,0
Sediment	Wght %	0,25	0,25	0,25	0,25	0,25
Flash point, min.	°C	60	60	60	60	60
Pour point, max.	°C	30	24	30	30	30

FIG 1 Heavy fuel oil qualities forecast by various oil companies for the periods up to, and after, 1985





Fuel quality:

Nº	bunkered port	sp.gravity g/cm³, 15°C	viscosity Sec.RW 100°F	viscosity cSt 50°C	flash point °C
1	NAGASAKI	0,9418	AB 700	95,7	162
2	BENICIA 1/2 + LOSANG. 1/2	-	-	-	-
3	NAGOYA	0,9483	AB 750	101,7	104
4	BENICIA	0,9848	AB 730	101	93,3
5	BENICIA	-"-	-"-	-"-	-"-
6	R'DAM 3/4 + BENICIA 1/2	-	-	-	-
7	ROTTERDAM	0,9764	AB 670	93	89,2

FIG 2 Firing pressures and hand-drawn indicator diagrams when burning heavy fuel oils from various bunkering stations

In a number of ports fuel grades are offered today that are liable to interfere with a diesel engine's combustion process. Even the diagrams in Fig 2 with their arbitrary time scale give an impression of the knock rating of some of the fuels offered. On the strength of operating experience we found that some of these fuel grades were causing ignition pressures up to 20 bar higher than those from conventional fuels.

What is a chief engineer to do with a normally equipped engine,

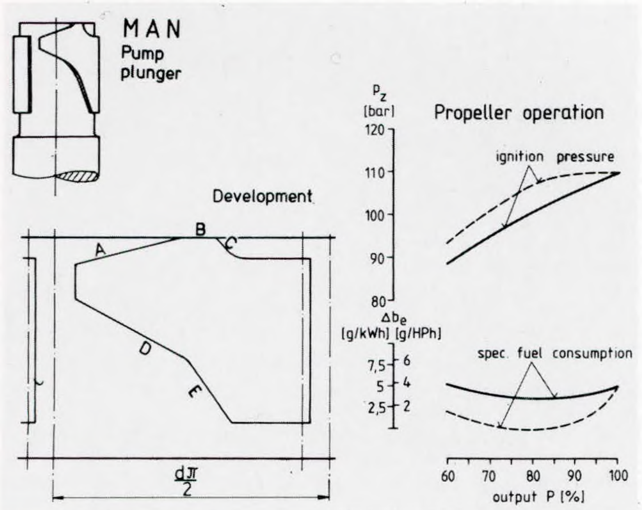


FIG 3 New development of control edge configuration of M A N injection with firing pressure (p_z) and specific fuel consumption (b_e) ———— with old control edge ------------ with new control edge

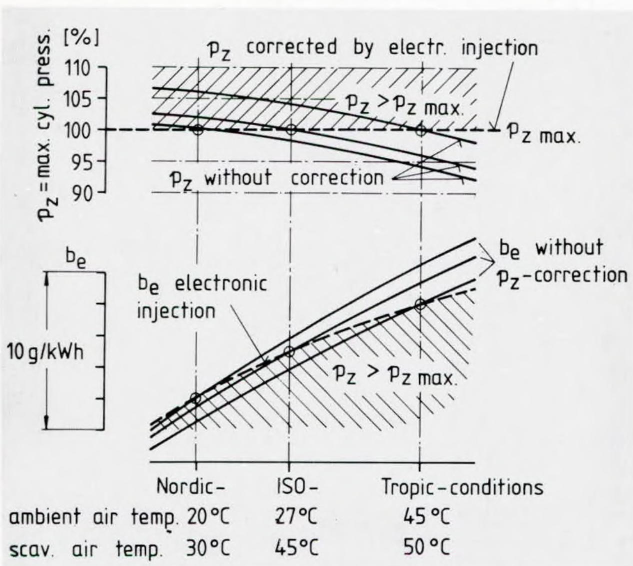


FIG 4 Influence of ambient conditions (intake air and scavenge air temperature) on firing pressure (p_z) and specific fuel consumption (b_e) of a two-stroke engine

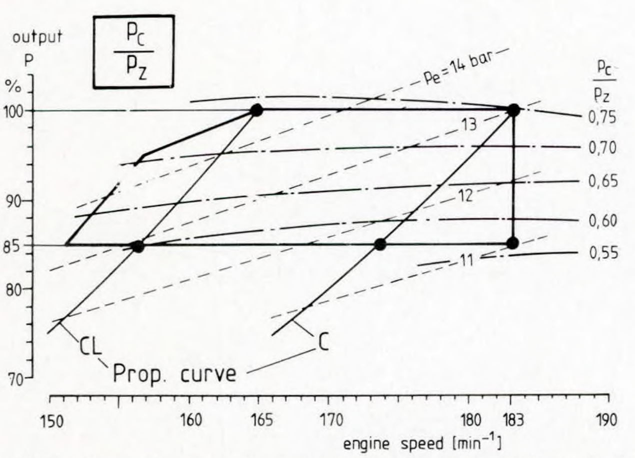


FIG 5 Lines of constant compression pressure (p_c) to firing pressure (p_z) ratios between 85% and 100% power at constant full-load pressure

once he has bunkered such fuel? Apart from other action to be taken, he would with much effort have to alter the point of injection, and thus the combustion process, since a reduction in rating alone does not always suffice. Even with a 50 per cent derating, diesel knock has been observed on medium speed engines.

2.1.5 Influencing the combustion process

Being able to alter the start of injection is desirable not only because of the varying heat release rates of different fuel grades. Even if a modern engine were adjusted for optimal fuel consumption rate, this condition could only be maintained if the service conditions remained the same. If, for instance, resistance of the vessel increases due to marine growth, or if the vessel operates under different climatic conditions, readjustment of timing becomes necessary.

Undoubtedly, even a mechanically controlled fuel injection system can, under constant conditions, be adapted to a single characteristic curve. This is demonstrated by new developments in injection pumps (Fig 3). Skilled configuration of the plunger control edges, for instance, enables ignition pressure to be maintained over a fairly wide load range, thus achieving a favourable fuel consumption, not only on full load but also in the range of maximum use, ie, at 85 per cent output.

Since, however, such a control edge implies a compromise between the needs of injection volume, mean effective pressure and control of fuel admission, adaptation to a different propeller curve or different climatic conditions must be imperfect in terms of optimal injection point; and, therefore, of optimal fuel consumption.

Let us suppose a two-stroke engine has been optimally matched to ISO conditions (Fig 4). If the vessel is trading in the tropics without change of the injection point, the ignition pressure will fall. Since air supply to the engine also deteriorates at higher temperatures, the fuel consumption rate increases markedly, by about 4.5 g/kWh. If, however, the ignition pressure is readjusted to a constant value, the increase in consumption can be reduced to about 3.0 g/kWh.

The diagram shown assumes that, to save fuel at full load, the change air is cooled down as much as the seawater temperature will permit. At part-loads this will not be done but, rather, the temperature downstream of the charge-air cooler will be kept high to improve combustion.

If a vessel whose engine has been optimally matched to ISO conditions trades in cold zones, utilisation of the low charge-air temperature would be economical. However, the corresponding output cannot always be developed since the permissible ignition pressure would be exceeded (cf upper half of the graph, Fig 4). If, however, the ignition pressure is re-matched, not only can the output be raised but, on changing from ISO to 'nordic' conditions, fuel consumption can also be reduced by about 3 g/kWh.

Ideal conditions for fuel consumption are achieved if the engine takes advantage of ambient temperature and seawater temperature while, at the same time, operating at a continuously and optimally matched ignition pressure. That is, over a wide service range, it can operate at its designed ignition pressure.

The future therefore demands that the injection system should be readily adaptable but, to achieve this, engine performance must be known precisely.

2.2 Engine performance

The electronic injection system here under discussion has been developed in co-operation with Bosch who have a wealth of experience in electronic control systems used in automotive engineering.

Since they have already been described in other parts, it is not the electronic controls that are to be highlighted here but rather the engine operational matters.

The fact is that even optimal control technology does not get us anywhere unless the mathematical functions by which control is to be effected are clearly defined. What is important is therefore the scanning of all operating parameters under test conditions with a view to:

2.2.1 optimal fuel consumption rate;
2.2.2 low thermal loading of the combustion chamber constituents;
2.2.3 keeping within the mechanical limits of the engine;
2.2.4 minimising the amount of fuel projected against the cylinder running face;
2.2.5 compliance with emission control legislature;
2.2.6 discovering limits of injection control.

Maximum designed ignition pressure must not be exceeded but, as explained, it is of advantage to operate at this pressure over a wide range of conditions. A decisive limitation is, however, the rate of ignition pressure rise.

This value is difficult to determine aboard the vessel. In a diesel engine with a normal combustion process, ignition pressure rise and the ratio of compression pressure to maximum combustion pressure are, however, closely linked. Unless this ratio is smaller than 0.55, the mechanical loading and the noise level of the engine can be coped with.

If, however, the engine is not running smoothly enough, damage to piston rings and bearings may result. Fig 5 shows the limits within which the M A N two-stroke engines operate on constant ignition pressure, ie, the lines of the constant compression/ignition pressure ratio.

On calculating fuel jet penetration, one comes up against another limit: if the injection pressure is too high, not only is the cylinder liner struck by oil but consumption increases. Tests on a large 10-cylinder crosshead engine (Fig 6) and on other engines with various nozzle types showed an optimal fuel consumption rate with a penetration of 0.65 to 0.70. (Penetration is defined as the ratio of the computed jet length to the maximum that is geometrically possible.) It is mainly determined by the pressure differential between nozzle blind hole and combustion chamber on the one hand and the size of the nozzle bore on the other.

Another limit is the component temperature, especially of the liner's running face. Any optimisation of the injection system therefore involves measurements of component temperatures. Fig 7 shows these as a function of penetration.

Desirable as it may be with centralised injection to distribute the fuel as efficiently as possible in the area of maximum air supply, ie, along the outer circumference of the combustion chamber, there are definite limits to the permissible injection pressure. If the cylinder liner at the reversal point of the piston rings becomes too hot, not only does the lubricating film on the cylinder liner burn off but a large amount of abrasives also accumulates in the running area.

This has been repeatedly confirmed by service experience. Combustion residues form annular marks on the piston crown at points where the fuel jets can be expected to strike. If the centres of these marks are close to the outer circumference of the piston crown, ie, if the fuel jet penetrates deeply into the space available, piston ring wear is bound to increase.

Admittedly the temperature curves on cylinder head and cylinder liner are fraught with some uncertainties and will be studied further. Nevertheless, it has become clear that the possibilities of heat release control are distinctly limited and that measurements of component temperatures provide a sensitive approach to the problem.

2.2.7 The importance of "software"

The descriptions that follow are the results of long hours of engine testing, aimed at optimising injection within the given limits over the entire range of conditions, with a view to minimising the fuel consumption rate. Therefore actual test figures are omitted. Once an electrically controllable injection system has been conceived and the manoeuvring logic formulated, the greater part of engine development work consists in creating the software and in optimising each individual operating variable.

In any injection system the point, mean pressure and pressure curve of injection can each be controlled. As may be seen from Fig 8, our present system uses an almost rectangular pressure curve in the blind bore before the nozzle bore. This maximises utilisation of the stored energy to inject a large amount of fuel within a short period. However, it is possible that an even more detailed knowledge of the relationship between injection curve and heat release rate would open up exploitation of further possibilities inherent in the electronic injection system, ie, optimal control of the injection pressure curve in itself.

Fig 9 compares the pressure in the blind bore before the nozzle bores when using a standard mechanical injection system with that of electronic control, optimised for consumption. In both instances, operation is along the propeller curve so that, in the second case, the pressure need not remain constant throughout the entire output range of the engine, nor need the pressure drop to a point which is inevitably reached with mechanical injection.

The injection pressure has to be lowered to ensure an optimum fuel consumption rate and reduced thermal loads on the cylinder liner at small outputs. This may well be due to the fact that, at the low gas pressure which then obtains in the cylinder, penetration of

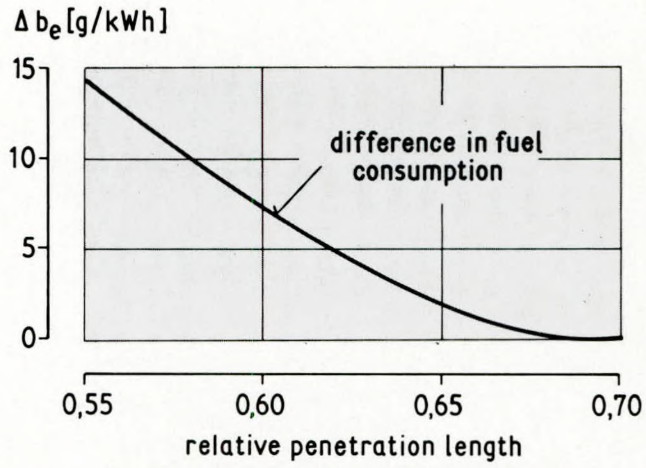


FIG 6 Influence of depth of fuel jet penetration on specific fuel consumption of a ten-cylinder two-stroke cross-head engine

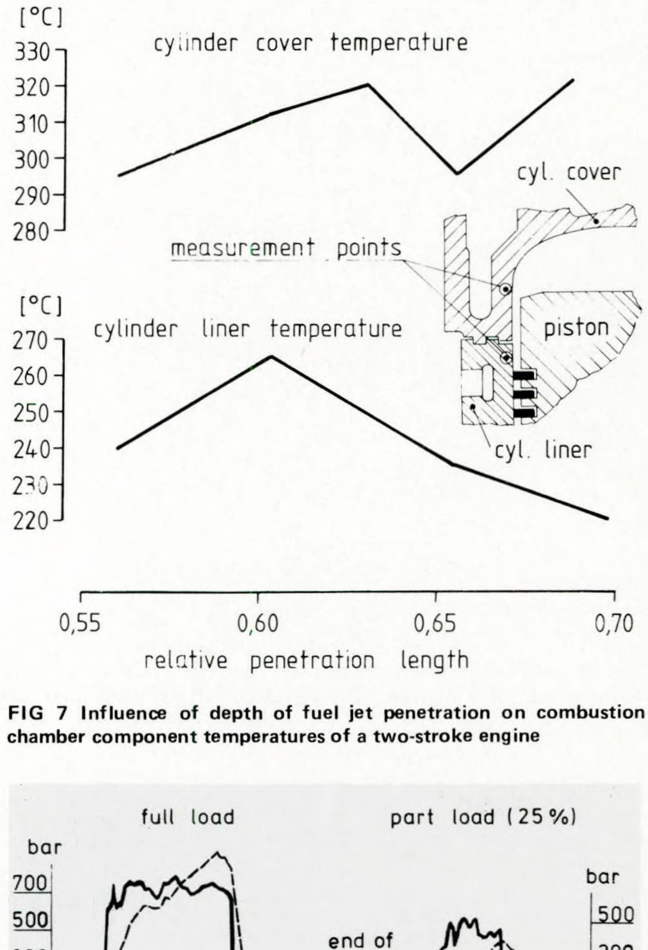


FIG 7 Influence of depth of fuel jet penetration on combustion chamber component temperatures of a two-stroke engine

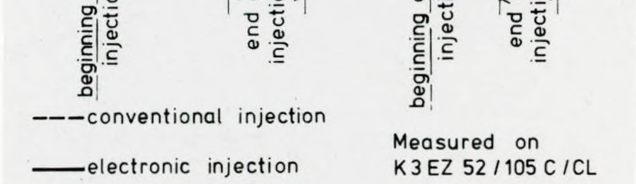


FIG 8 Comparison of pressure development in injection nozzle orifice, between conventional and electronic injection systems

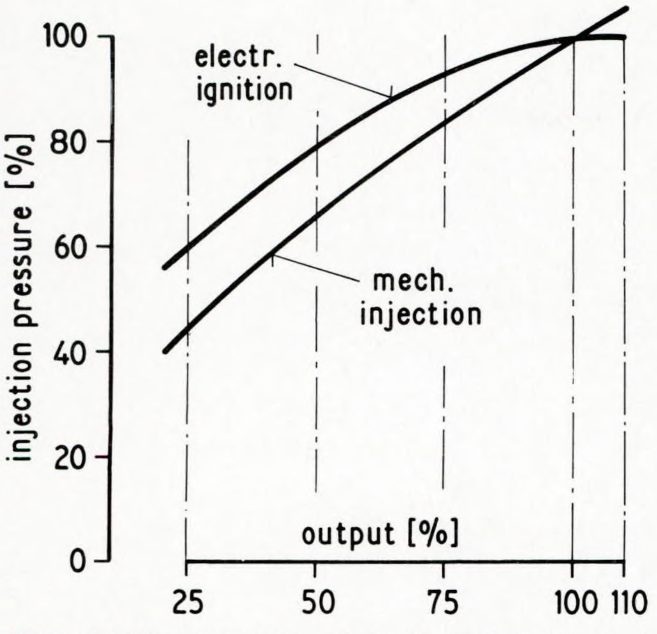


FIG 9 Injection pressure curve as a function of load with normal mechanical, and optimised control by electronic injection

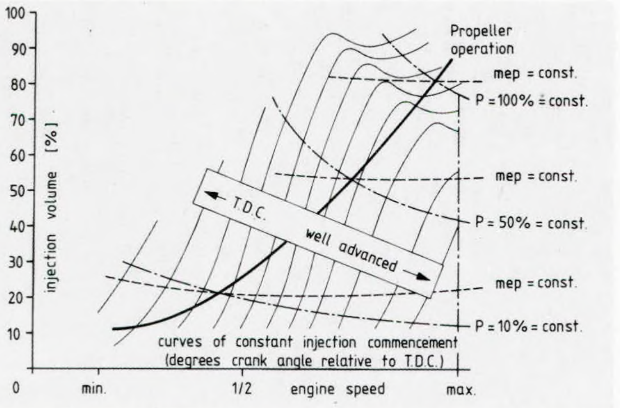


FIG 10 Lines of constant injection commencement pitted against engine speed and injection volume for optimal fuel consumption

p — power output mep — mean effective pressure

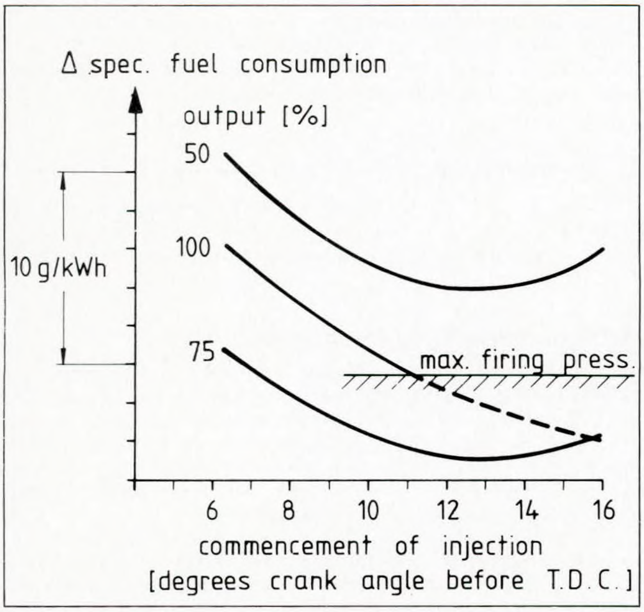


FIG 11 Curves showing the optimization of the commencement of injection

the fuel jets into the combustion chamber would otherwise be too deep, so that fuel-air mixing is correspondingly poor.

In the operating characteristics (Fig 10) of a slow-speed diesel engine, the advance of injection point before TDC for low fuel consumption at given limits is plotted against engine speed and injection volume. The downward slope of the lines of constant injection point in the upper range of the graph clearly demonstrates the constraints resulting from the demand for a constant ignition pressure between 85 and 100 per cent output.

The distance between the lines of constant injection commencement in Fig 10 is, with the exception of the distance farthest to the right, 2 degrees crank angle, relative to TDC.

Fig 11 shows the dependence of the fuel consumption on the commencement of injection at three load points of our K3EZ 52/105 CH/CLH test engine with smaller bore. At the time of the test run (March 1980), the fuel consumption warranted with 3 per cent tolerance for the KEZ 52/105 CH at 85 per cent load under ISO conditions and with LCV = 42 707 kJ/kg, was 187 g/kWh. Tests have been in progress since then with the aim of improving consumption.

It seems obvious that no variation of injection point with speed can be achieved in a mechanical injection system because, with the usual method of control by the plunger edges, the lines of constant injection could be achieved for only one operating curve, eg, the ideal propeller curve, by a suitable configuration of the plunger control.

Approximately the same injection points as with electronic injection could be achieved for one operating curve, eg, the ideal propeller curve, by a suitable configuration of the plunger control edges. But this is not possible for the complete power range.

Let me reiterate that a sophisticated mechanical injection system can undoubtedly meet future demands. What I have in mind here is, for instance variation of injection timing, as is already standard on some diesel-engined trucks. But the one and only thing that would bring about real progress with respect to heat release control, would be direct interaction between the extremely adaptable electronics and the mechanics of the injection system.

I should like briefly to anticipate one particular possibility: the direct activation of the various cylinders. With electronic injection, even a three-cylinder engine will run smoothly at a speed as low as 1/6th of rated speed.

2.3 Indirect interaction between the electronics and injection

A new injection system must meet two important requirements:

2.3.1 to enhance adaptability, pressure generation must be separate from time and volume control;

2.3.2 time and volume control must be directly variable.

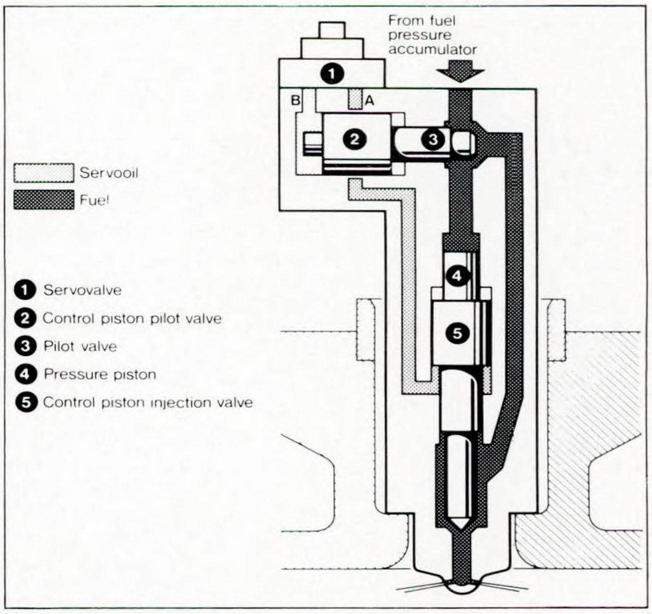


FIG 12 Schematic drawing of an electronically controlled injection valve with a pilot valve.

If the generation of pressure is to be separated from volume and timing control, a pressure accumulator becomes indispensable. Injection systems that incorporate such pressure accumulators have been known for a long time; they control the injection volume by means of the integral of valve opening with time, ie, the area under the pressure curve.

An electronic system on the other hand has to convert the minute control outputs in the milliwatt range to effect exact time and volume control of the injection valve under high pressures.

The forces involved in the injection valve of a K3EZ 52/105 C/CL engine (Fig 12) are as follows. An injection pressure of some 700 bar and a nozzle needle diameter of 10 mm result in a force of approximately 6000 N when the needle closes. With a closing time of 0.5 ms and a closing distance of 1 mm we arrive at a closing energy of approx. 12 000 Nm/s, or about 12 kW. Fig 13 shows the design of this valve.

The idea of having the nozzle needle actuated directly by the electronics must therefore be dropped. To attain the necessary needle velocity and lift for all nozzles, a total transient output of 450 kW would be required.

2.3.3 Two direct-response servo-stages

The two-stage servo-valve (Fig 14) constitutes the link between the electronic controller and the hydraulically controlled injection valve. It fulfils the difficult function of rapidly converting the mA signals into hydraulic forces of several thousand newton.

The development of this valve was one of the important milestones on the way to electronic injection in large-bore engines. In the first amplifier stage a baffle plate is acted upon from either side by oil jets issuing from control nozzles. The back pressure built up at these nozzles controls the action of oil upon the two faces of the valve spool.

The baffle plate is directly connected to the movable armature of the pilot solenoid. If the baffle plate is displaced by an electric signal from the electronic controller, the flow resistance at the nozzles changes proportionally. At the one end of the spool the oil pressure therefore drops, whereas at the other it rises. The spool instantly responds to the force resulting from the pressure differential and starts moving, thus uncovering the control ports of the second stage.

Its range of motion is, however, limited. After a certain distance a spring, secured to armature and baffle plate, imparts a force to the baffle plate which exceeds the force of the solenoid. The baffle plate then moves back slightly, the differential pressure drops slightly and a steady-state equilibrium is established until the force of the solenoid is altered: in which case the spool responds instantly until equality of forces is re-established.

In terms of magnitude and direction, spool movements therefore respond directly to the input signal at the solenoid. At present, only quasi-square wave activation of the solenoid and, consequently, an almost identically square pressure curve of the fuel in the nozzle blind hole, are used. Other control actions are equally possible, however.

The control piston acts as a four-way valve. In each operation two ways are uncovered and two closed at zero input. Control of the injection proper is through port A. When this is uncovered, a force is imparted to the control piston of the needle valve. The time elapsed between opening and closing of port A determines the duration and, consequently, the volume, of injection at the needle valve.

The pilot valve is operated through port B. To be on the safe side, it opens before, and closes after, the needle valve.

The 200 bar servo oil pressure required is generated by two pumping sets, one of which is on standby. During the switchover phase or in a black-out a gas pressure accumulator ensures pressurised oil supply for at least three minutes.

2.3.4 Two independent valves

Injection and pilot valve form a single component. Fig 12 shows the operating principle schematically with the needle valve open. The spool of the needle valve is opened by the servo oil pressure from the accumulator. Simultaneously, after a short lead time, the servo-pressure downstream of the pilot valve is relieved through port B of the servo-valve and the pilot valve is opened by the fuel pressure available from the pressure accumulator.

During closure of the needle valve, these functions are performed in reverse order, ie, the nozzle needle is closed by the fuel pressure operating upon the top face of the spool.

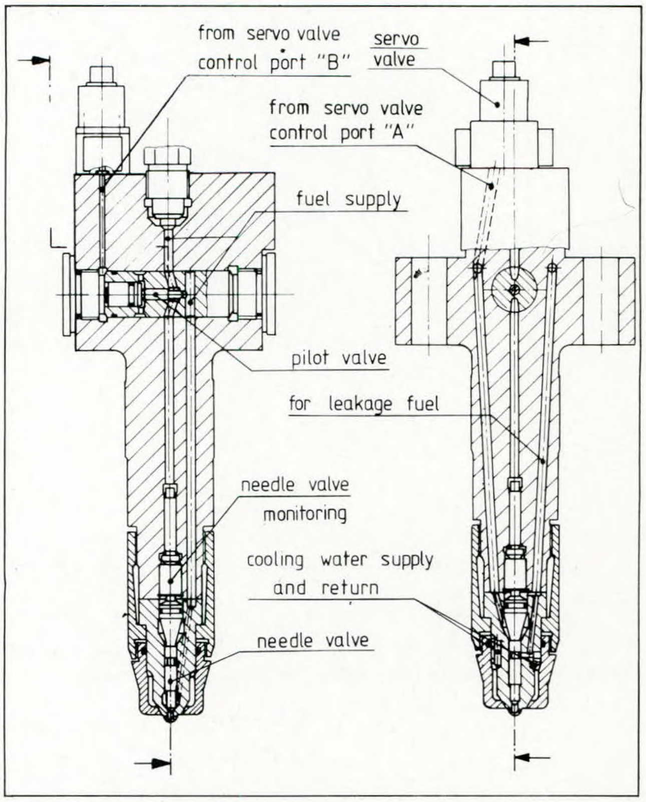


FIG 13 Electronically controlled injection valve for M A N two-stroke engines

Consequently, in the event of any malfunction of the nozzle needle, the pilot valve comes into action and delivers slightly more fuel.

2.3.5 Not cheaper but better

One is inclined to think that an engine with an electronic injection system should be particularly economical in terms of material and costs. This, however, applies only up to a certain point since the same, or even a somewhat higher, energy is pumped into the high-pressure accumulator by the fuel pumps, as is injected directly into the cylinder by mechanical injection pumps. A servo-system has to provide additional control energy and requires pumps and tubing. The system as a whole comprises high-performance multiple electronic controllers and monitoring modules which ensure and maintain overall system reliability.

3. ELECTRONIC INJECTION FOR THE FUTURE

It can be said that electronic injection is particularly indicated whenever its performance exceeds that of the corresponding mechanical system. This will happen to an increasing extent in the future.

3.1 Injection independent of wear

The injection nozzle, however controlled, incorporates parts subject to wear. However, where each cylinder has its own electronic control system, it will be possible to circumvent the wear problem within certain limits. What is important is the development of a system which feeds information on the combustion process in the various cylinders into the electronic controller which is ideally suited to initiate sophisticated control action.

The cylinder pressure is at present measured by indicators, and exhaust gas temperature by thermometers. It will not be long before sensors in the combustion spaces of each cylinder signal temperatures and pressures directly, feeding them into the electronic controller as computational variables. Injection will then be perfect despite wear on the nozzles.

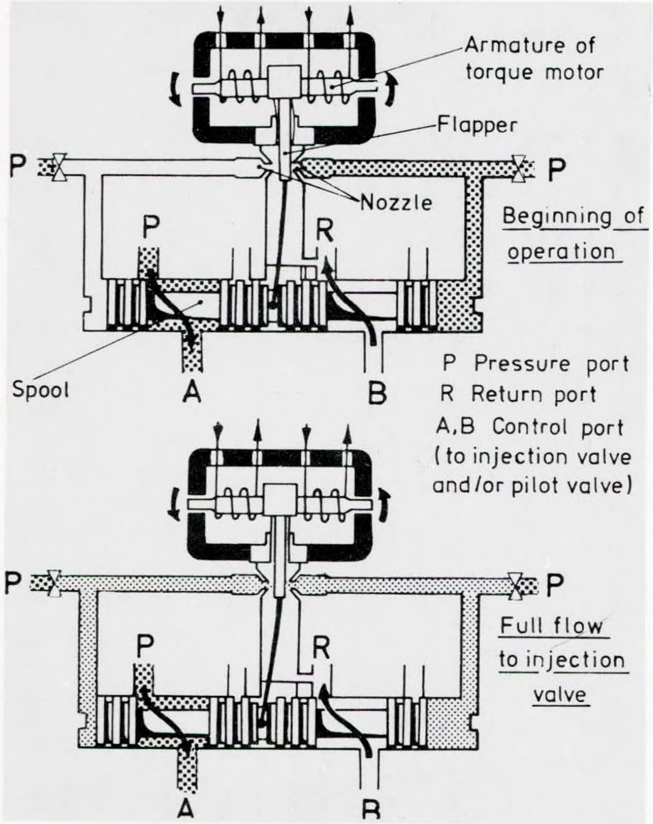


FIG 14 Schematic drawing depicting the operating method of the two-stage servo-valve

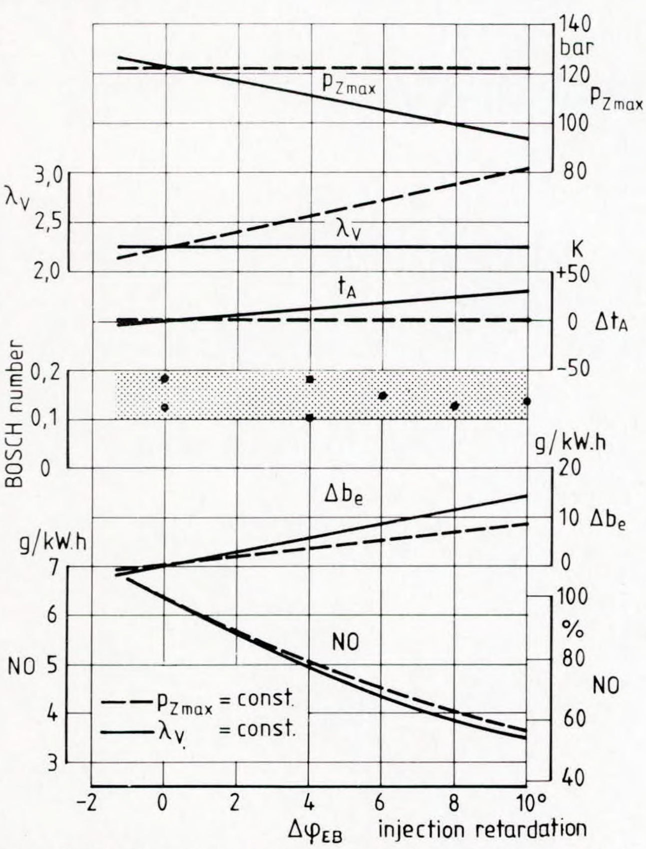


FIG 15 Operating values as a function of injection commencement

P_z max	=	firing pressure
λ_v	=	air/fuel ratio
t_A	=	exhaust gas temperature
b_e	=	specific fuel consumption
NO	=	nitric oxide
EB	=	injection angle in degrees of crank angle

3.2 Thermal and mechanical loads can be controlled

Thus the effect of wear can be corrected by an electronic system but there are other parameters that undergo changes. Misgivings about the heat release rates of different fuel grades and how the engine can be matched to different service conditions will be dispelled when each engine cylinder is capable of signalling how, and with what effect, its combustion process is proceeding; and when its injection is controlled accordingly.

One possibility would be to have a meter determining the work done by each cylinder. On the strength of these data, the controller then equalises the output of the various cylinders by setting the programmed maximum pressure in each.

Again, temperature sensors in the combustion chamber and exhaust-gas manifold might monitor functions that could become dangerous for the engine.

The order of control priority is a sufficiently low component temperature and a not too high ignition pressure; then a correctly indicated output and a not too low ignition pressure. Tolerance bands are acceptable; if a cylinder can no longer be operated within the preset limits, an alarm is sounded and output reduced.

For such an engine, no cetane numbers (whose usefulness is limited anyway) would have to be ascertained to match the engine to the fuel grade. It would be able to cope with low-sulphur fuels since control would be according to the temperature at the combustion space surface.

3.3 Pollution

Ordinarily, human intervention in such a system would only be necessary if, for instance, environmental pollution were at issue. The impact of injection variation on environmental pollution is shown in Fig 15. In each case the turbocharging system was optimally matched to the operating points. These values were obtained on a medium-speed one-cylinder engine equipped with an electronic injection system.

With the exhaust discolouration remaining unchanged, NO can be substantially reduced by varying the injection point. The higher fuel consumption remains acceptable since it rises only while the ship is not at sea.

In conclusion it may be said that electronic injection is not only another decisive step towards a diesel engine with optimum injection and combustion efficiency but also maximises economy by automatically matching the engine to environmental conditions. With such a system the foreseeable future may be viewed optimistically.

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MR E. BRIGHT CEng, FIMarE (Gulf Chartering and Marine Services Ltd):
Everyone here is fully aware of the deteriorating quality of fuel supplied today as marine bunkers, and any organisation devoting research and effort to improve equipment and ensure a more efficient means of burning this fuel is to be complimented.

I have personal association with this project and know of the huge amount of work done and some of the disappointments encountered; including my own at not being able to have this equipment fitted to my Company's latest contract with the engine builders. However, I can assure you that at all times during out discussions on this contract, MAN have been completely honest and eventually convinced me that electronic injection would have to wait until the next contract, (if there is one), to enjoy the advantages of this sophisticated equipment.

The fact that fuels are becoming more expensive must now be accepted by all, and the problems of continually deteriorating combustion qualities must also be accepted. It has been seriously suggested to the Industry that in future it may be necessary to segregate different deliveries of fuel on board, but it will not be as easy as it sounds. Therefore, we will be forced to burn mixed grades of bunker deliveries.

With existing mechanical equipment, even by modifying propeller design around anticipated operating conditions and using the newer design injection pumps, we still have an imperfect condition in many ranges of operation and if this electronic equipment will help attain a higher degree of perfection in combustion, it must be seriously considered.

It would be impossible for me at this time to question the mathematical conclusions in this paper, knowing the amount of research carried out. To be able to run the test engine successfully at loads down to one sixth of the rated speed is a tremendous advantage, especially on a slow-steaming charter.

I have only two questions:

(1) Is the two-stage servo-valve the final accepted design?

(2) When is the equipment anticipated to be ready for a production engine? I would suggest that serious consideration should be given by the manufacturers to the retrofit of this equipment (when it comes into production) based on the probable cost against the actual savings.

Finally, without wishing to prejudice the paper, a colleague of mine owns a very expensive German-manufactured motor car fitted with electronic injection (I might add he is in the financial department and not the technical department!). He recently had combustion problems, the cause of which took the manufacturers two weeks to locate, and the repair cost three per cent of the value of the car.

I trust our friends in Augsburg will give this serious thought before going into production.

MR R.P. HOLBROOK, CEng, FIMarE (Lloyd's Register of Shipping):
I found the paper especially interesting, particularly in the context of poor quality fuels and the problems they are increasingly likely to pose in the future.

One aspect which must concern marine engineers is the enhanced corrosion and combustion residue build-up in gas passages, or spurious operation during manoeuvring when the engine fails to start. It may be accepted that the slow speed marine diesels operating on steady load at about the designed MCR will not be troubled too much with these future fuels. The main difficulties appear to occur during periods of part load operation on heavy residual fuels. In the past, this could be avoided by switching to distillate fuels during manoeuvring or part load operation. However, to burn these heavy residual fuels successfully demands a high fuel supply temperature. The fine engineering tolerances in the fuel pumps and injectors have to be maintained at the normal operating temperature. Switching to distillate fuels causes either severe gassing in the fuel system, if the temperature is not reduced quickly enough, or possible sticking of fuel pump plungers and injector needles, if the temperatures are lowered.

Would the author care to comment on whether the principle of electronically-controlled injection will be effective in influencing the efficiency of combustion over the whole range on heavy residual fuels, thereby avoiding some of the effects experienced during part load operation; or, whether the principle could be extended to a dual fuel arrangement when, for example, a particular ship requires frequent manoeuvring or part load operation.

Looking towards the future, do you see that we may ultimately reach a stage where ships' engineers will simply pour a small sample of bunkered fuel into a micro-chip analyser which, in turn, will be linked to an engine combustion control computer to regulate all the parameters automatically.

It has yet to be proved whether electronic injection will be the solution for some or all of the problems facing the diesel engine. However, any method which may contribute to their efficiency and reliability must be fully evaluated.

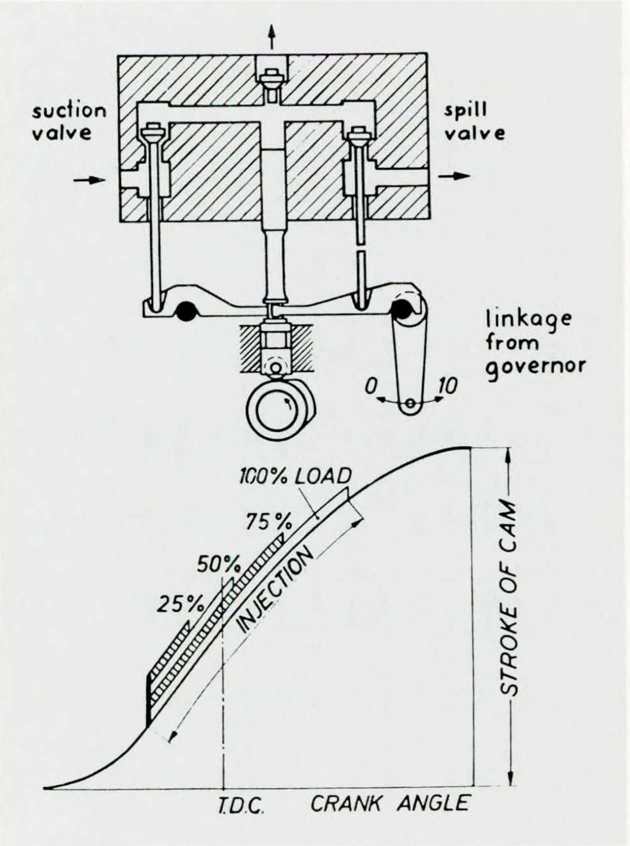

FIG D1 Sulzer type fuel injection pump; double-controlled, constant beginning of injection.

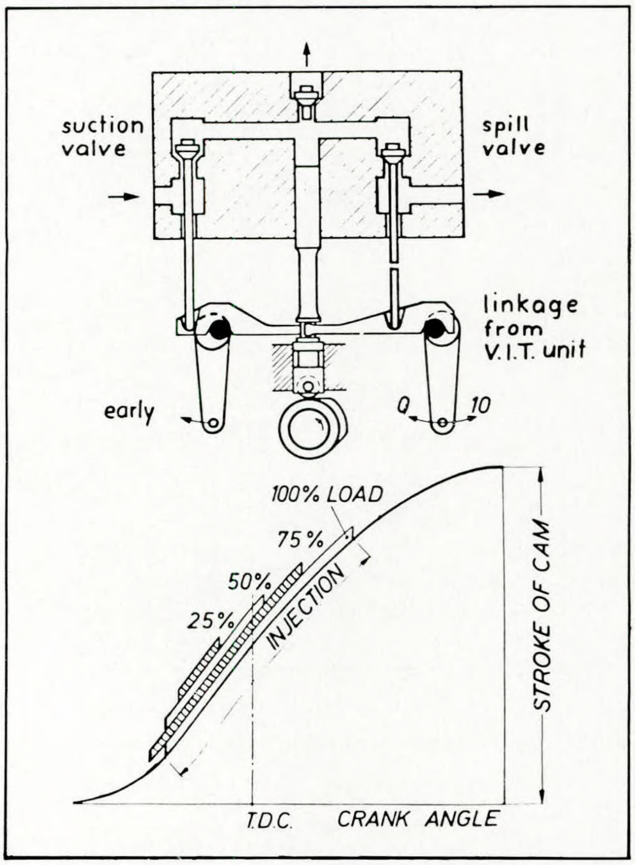

FIG D2 Double-controlled injection pump with VIT mechanism

DR M.K. EBERLE (Sulzer Bros.):

I fully agree with the author about the desirability of controlling maximum firing pressure in order to minimize specific fuel consumption. I certainly appreciate the concluding remark, that quite a bit of control can be achieved by mechanical means.

Sulzer in the early sixties introduced for its low-speed, two-stroke diesel engines the double-controlled valve pump. The beginning of delivery is determined by the closing of the suction valve and terminated by the opening of the spill valve. By the use of two independent valves for the control of fuel delivery, various arrangements for the timing of the injection may be achieved.

RND, RND-M as well as RL type engines (the latter up to spring 1980) were operated with constant beginning fuel injection (Fig D1).

Responding to the extreme increase in fuel prices, Sulzer early in 1980 introduced the VIT (variable injection timing) mechanism, which allows the maintenance of maximum firing pressures down to engine loads of approximately 85 per cent (propeller law), improving brake specific fuel consumption by roughly one per cent at loads between 85 and 90 per cent (Figs D2, D3). At low loads, injection is retarded and a smoother engine operation is possible, again with an improvement in specific fuel consumption.

The necessary variation in suction and spill valve timing is achieved by a simple and reliable mechanism linked through a built-in cam to the governor's load setting (Fig D4).

Hence, the fuel injection timing (combustion pressure) and the fuel delivery to the injectors (determined by the timing difference of both valves) are controlled load dependently.

A separate lever of the VIT-mechanism allows for a manual adjustment of the fuel injection timing — the "fuel quality setting" — the automatic timing device (cam) always being engaged.

Burning heavier fuels can result in an ignition lag and, consequently, a drop in maximum combustion pressure which increases the fuel consumption. While the engine is running, the combustion pressure can easily be adjusted to its normal permissible value by a simple

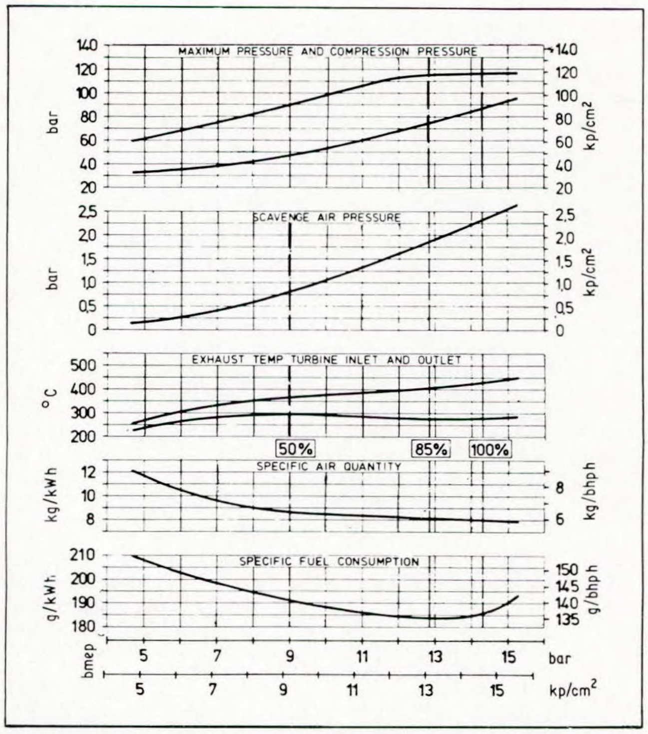

FIG D5 Performance curves of 6RLB90 engine: 2940 kw/cyl (400 bhp/cyl) at 102 rev/min (propeller law)

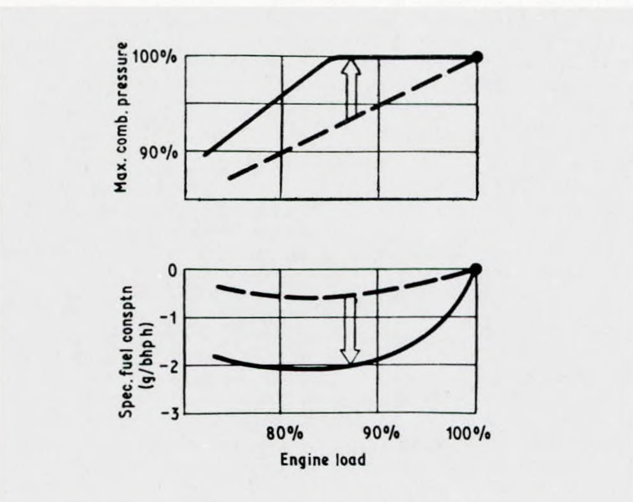

FIG D3 Improvement in specific fuel consumption due to VIT

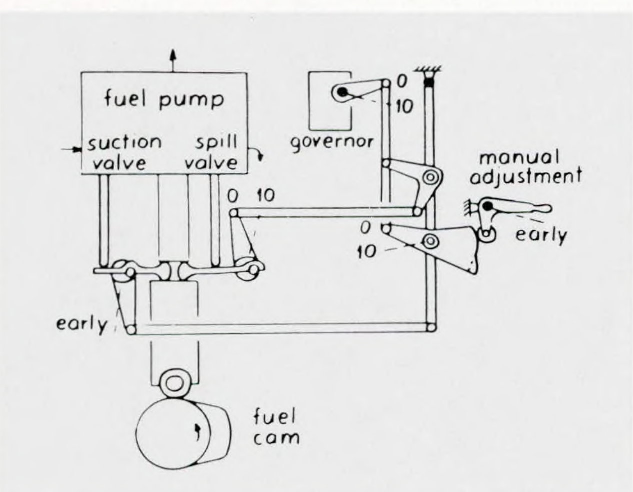

FIG D4 Variable Injection Timing mechanism

readjustment of the fuel quality lever towards earlier ignition. Consequently, the fuel consumption is lowered to its best possible value. The same lever can be used in order to compensate for changed ambient conditions.

Together with any simple combustion pressure indicator, the reliable VIT-mechanism gives the chief engineer on board the flexibility to cope with all kinds of low quality fuels and to run his engine automatically at the lowest possible fuel consumption.

The next step would be to monitor the cylinder pressures on-line, taking into account engine load and speed, and set the separate lever automatically. Based on the Sulzer experience with engine diagnostics, this would be relatively simple. Fig D 5 shows the performance of a RLB90 engine, applying VIT.

In the early seventies Sulzer began designing a system which can be controlled either electronically or hydraulically: the company prefers to call these systems time-controlled. The electronically-controlled system was operational in 1976 and during the last couple of years was used on a single-cylinder, low-speed, two-stroke diesel engine with a bore of 760mm and a speed of 120 rev/min; quite a bit of fuel testing was done with this engine.

Originally, it was hoped that particularly at low loads, specific fuel consumption would be improved on account of increased fuel injection pressures. The question was raised, whether the different shape of the fuel pressure trace before injector might influence specific fuel consumption.

Comparing the engine performance data obtained with both fuel injection systems, conventional and time-controlled, indicated no difference in specific fuel consumption at full load maintaining maximum firing pressures. Also, there was hardly an improvement found at part load. With the extremely accurate fuel metering of a positive displacement pump as used for the Sulzer low-speed engines, low-speed running is not a problem which would ask for a time-controlled injection system.

Based on these findings, together with the possibilities of the double-controlled fuel pump equipped with VIT, for the time being the company is not going into electronics for the purpose of fuel injection. In the future, however, it is not outruling a time-controlled fuel injection system, particularly in its hydraulically-controlled version, for fuels such as coal slurries.

I would like to ask a few questions:

(1) In Fig. 2 of the paper an extremely high spread of the maximum firing pressures on account of different fuel qualities is shown. My company is still doing quite a bit of test work with different fuel qualities, but has not been able to find anything coming close to the data indicated. Would the author be kind enough to provide some analysis data of the fuels investigated?

(2) How does one compare the reliability of the new system with that of the conventional system?

(3) Does MAN sell its low-speed engines today depending on electronically-controlled fuel injection alone?

(4) How do engine costs compare between electronically controlled fuel injection and the conventional system?

MR A.J.S. BAKER CEng, FIMarE:
I congratulate the author for a progressive advance in the development of the oil engine. However, I am surprised that more has not been made of the potential use of electronic control to tailor the shape of the heat release diagram in the combustion chamber, since the author's colleague, Dr Woshni's studies (including three zone modelling of heat release diagrams) has hinted strongly that this route offers a potential way to improved thermal efficiency.

I assume that this must be under consideration at Augsburg, and ask how this might be done with the system described by the author since his work indicated that some of the poor fuels arriving on the marine bunker market could well respond significantly to optimised rate of injection, as well as modification to injection phasing.

Would the first engine to be sold with the new fuel injection system be equipped with a fuel-pump camshaft? Clearly, the cost saved by omitting the splendid MAN camshaft and its associated equipment must go a long way to offsetting the difference in costs of the old and new systems.

MR R.C. HASLAM-JONES BSc, CEng, MIMarE (Blue Star Line Ltd).
Firstly, why not use a single constant fuel pressure which would dispense with the need to control the fuel pressure according to engine load, and remove a control loop from a system which already appears to have to overcome a large number of problems?

Secondly, the scavenge air pressure is not used as a measured variable for control, and I would ask the author to comment on the reasons for not including the measurement of this variable, which could be used to give a more precise fuel to air ratio, despite the predictability of scavenge pressure in software, and the knowledge that the scavenge air pressure does fall off in service for a number of reasons.

Thirdly, the fuel valve differs considerably from those that marine engineers are more familiar with. Would the author describe the methods envisaged for testing and maintaining the fuel valve on board the ship, where it would appear that a complex testing procedure would be required under skilled supervision?

I understand that the crankshaft position resolver measures the crankshaft position to within one third of a degree. The unit which is furthest from the resolver will tend, under load, to deflect the crankshaft by more than one degree relative to the measuring point. I would like to know how much consideration was given to this and how the crankshaft twisting is compensated for in the fuel valve timing.

I would also like to know how the fuel pressure in the accumulator is established prior to starting the engine.

Finally, I understand that about five per cent of the fuel consumption of a conventional engine is used in driving the timing gears and the camshaft. Has all of this five per cent been absorbed in driving the fuel pumps of this new engine, or, has a saving been made, and appeared as a reduction in fuel consumption?

Author's Reply

I thank the contributors for their interesting questions, which shall be answered in order of subject since some of them deal with the same areas.

The first production engines were put into operation on the testbed in November this year. The first engine is still based on the conventional injection system whereas the second one features a purely electronic injection system. This answers in part the question as to whether an older engine with a conventional injection system can be refitted with an electronic injection system: such a refit is technically possible.

The existing fuel injection pumps do the work of the high-pressure pumps of the electronically controlled engine and fill the high-pressure accumulator with the proposed pressure. From the high-pressure accumulator up to the nozzle orifices everything is the same as with purely electronic injection. However, such a conversion requires a great deal of design work and equipment. This confines application to engine types built more frequently than others and indicates the as yet little chance in terms of deadlines.

MAN have engines with a mechanical injection system as well as engines with an electronic injection system in their production programme. The former are identified by the letters KSZ and the latter by the letters KEZ. It is taken for granted that the demand for engines with purely electronic injection will rise quickly as the quality of fuels deteriorates.

The two-stage flow control servo valve has been thoroughly tested with a view to the purpose for which it is to be used. Its two outputs control two independent valves so as to increase the redundancy of the system. After longer engine shutdown, the high-pressure accumulator is charged by means of a separate, small, high-pressure pump.

This process only takes a few minutes and the engine can be started thereafter. The power consumption of the engine-driven high-pressure pumps is more or less the same as that of normal injection pumps. It is more likely to be higher than lower because more energy is made available to the injection system, especially at part loads.

High reliability of electronic injection is ensured by the use of proven components for both the mechanical and the electronic system. The electronic system monitors itself and the response to the electronic pulses transmitted. Provision has been made for adequate redundancy. A product as reliable as this cannot be any cheaper. On the whole, the costs of electronic injection thus cannot be any lower than those of mechanical injection. However, the decisive point is that, in terms of controllability of the injection process and adaptability to varying fuel grades, the capacity of an electronic injection system is very high.

The fuel grades stated in the paper, which have a wide range of different combustion properties, do not feature any eye-catching peculiarities in the usual analysis values. Cetane numbers, etc, were not stated. The author does not believe that it will be possible in future to analyse the combustion properties of a fuel with sufficient accuracy by means of an automatic device.

It will therefore be impossible to match the electronic control system of an engine to such values. The author agrees with the opinion expressed by a previous speaker that it will be possible with the electronically-controlled injection system in future to monitor on-line the cylinder pressures and, taking into account engine load and speed, to set the injection commencement automatically. This process will lead to the engines responding automatically to the combustion characteristics of the fuel. At the moment this adjustment is still made by the operators who vary the injection commencement of the electronic injection systems in accordance with combustion pressure and temperature readings.

A great advantage of the electronic injection system is the ability to influence heat release. This is done, on the one hand, by optimal matching of the pressures available in the prechamber of the nozzles and, on the other, by additional pressure variation during injection. With electronic injection, the pressure in the injection nozzles is higher than with a purely mechanically-controlled injection system. This factor alone results in a somewhat lower fuel consumption, as atomisation is more efficient. With the materials of the mechanical components being exposed to the same stresses, more energy can also be made available in the prechamber of the nozzle at full load, this being the reason why the consumption figures measured at full load during the tests were lower than the ones with an optimised mechanical injection system.

Especially in part-load operation, the great advantage of electronic injection with a constant-pressure system and controllable pressure in this system comes to bear. Owing to the aforementioned availability of higher energy, fuel atomisation is better within the entire engine service range and, consequently, the desire to have one set of nozzles for full-load operation and another one for slow steaming is less pronounced. Since the pressures remain within limits with a constant-pressure injection system, even starting on incorrectly pre-heated fuel does not involve any mechanical hazards. Moreover, the high-pressure accumulator and the pipes downstream of it can be tracer-heated with relative ease. Consequently, pier-to-pier operation with an electronically-controlled, constant-pressure injection system, on heavy fuel oil, has even better characteristics than a conventional system.

THE CHAIRMAN, Mr H.E. TUNE, CEng, FIMarE (Blue Star Line Ltd) summed up as follows:
From the present plateau much yet remains to be done in the field. Mr Häfner has, however, said that his first engines in operational service will be coming along within the year and very obviously much has been done already. It is clear that we are approaching at least technical availability of practicable electronic injection.

Dr Eberle has made his points on the potential of established mechanical injection systems for further developments in injection modulation and we will have our options. From that point cost effect may be expected to assume the immediate significant role.

For the medium term presumably, in Mr Häfner's own claim, electronic injection will continue to be no cheaper. "Better" however may become its principal recommendation if the potential advantages he forecasts become over-riding factors in helping us towards the ultimate in reliable economic operation on the poorer fuels as these may come along.

In the event I think we can all agree at least at this stage that this is a most significant area of development and with the potential in every sense for major contribution to our forward progress. Mr Häfner and his colleagues are to be congratulated on the work that has been done.