INVESTIGATION OF THE POTENTIAL REDUCTION OF NO_x EMISSIONS FROM A MARINE DIESEL ENGINE

BY

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ABSTRACT

With increasing concern for the state of our environment, governments and international legislative organisations are expected to impose strict emission restrictions on marine diesel engines within the next decade. The PAXMAN Valenta 12RP200E engine is used on board Royal Navy Type 23 frigates for electrical power generation, and therefore will be subject to future emission legislation. The Royal Naval Engineering College is investigating various techniques for the reduction and/or the elimination of exhaust gas constituents that are of particular concern. This article describes the generation of an engine model, and its validation against real engine data emissions levels. The primary methods of emission reduction investigated include variable valve timing, retarded fuel injection, pilot or split injection and enhanced intercooler performance. With these methods, potential reductions in NO_x emissions by up to 60% of current levels were predicted.

Introduction

Although not currently constrained by any external legislation regarding marine engine exhaust emissions, the Royal Navy is increasingly aware of the environmental necessity of such measures. However, legislation proposed by the International Marine Organisation on a global scale and more locally by the UK Environmental Protection Act is expected to embrace naval vessels[1,2].

In anticipation of future legislation, the Royal Naval Engineering College (RNEC) has established a programme of research to investigate the exhaust gas emission characteristics of marine engines. Although concentrating primarily on diesel engines, this research programme embraces a wide range of aspects likely to influence exhaust emissions. The aspects under consideration can be categorized under the three main headings of:

- Fuel conditioning.
- Engine design.
- Exhaust gas conditioning.

The research effort includes actual engine testing as well as computer simulation work.

In the long term, reduction of all the major pollutants in engine exhaust gas will need to be addressed. Those exhaust gas constituents of particular concern are the Oxides of Nitrogen (NO_x) and Sulphur (SO_x), unburnt Hydrocarbons (UHC's) and Carbon Dioxide (CO_2)—the 'greenhouse' gas. Reduction of SO_x levels can primarily be achieved by reducing the sulphur content of the fuel used. The primary means of reducing the other constituents is through improvements to the combustion process within the engine.

Current effort at the RNEC is concentrating on NO_x reduction techniques for diesel engines since the forthcoming regulatory limit on this constituent, together with particulate matter, is likely to present the first legislative obstacle in 1995/96.

This article discusses some preliminary simulation work aimed at investigating the potential of some primary methods for improving the NO_x characteristics of the PAXMAN Valenta 12RP200 engine. These engines are used by the Royal Navy in the Type 23 frigates for onboard electrical power generation, and will be subject to future emission legislation. The methods investigated were:

- Retarded fuel injection.
- Pilot (or split) injection.
- Variable valve timing.
- Enhanced intercooling

Bath University's Simulation Program for Internal Combustion Engines (SPICE), was used to model the engine characteristics. Model validation was achieved against basic engine test data supplied by PAXMAN.

Engine Specifications

The generation of an engine model was based on real engine geometrical and operational data from the PAXMAN Valenta 12RP200 engine series. Specifications for this engine are:

Engine Type:	PAXMAN Valenta 12RP200E
No of Cylinders & Configuration	12 60° Vee
Cycle:	4 Stroke, intercooled & turbocharged
Compression Ratio:	13:1
Operating Speed Range:	600–1600 rev/min
Combustion System:	Direct Injection
Max Continuous Propulsion Ratings:	1510 kWb (2024 bhp) at 1460 rev/min
Intercooler Capacity:	0.027m^3 (6.0 imp gal)

Simulation

The testing and development of emission reducing modifications to an existing engine is expensive and time consuming. The production of an accurate simulation package, to aid the optimisation of emission reduction techniques before they are implemented, is crucial to the economic and technical success of this

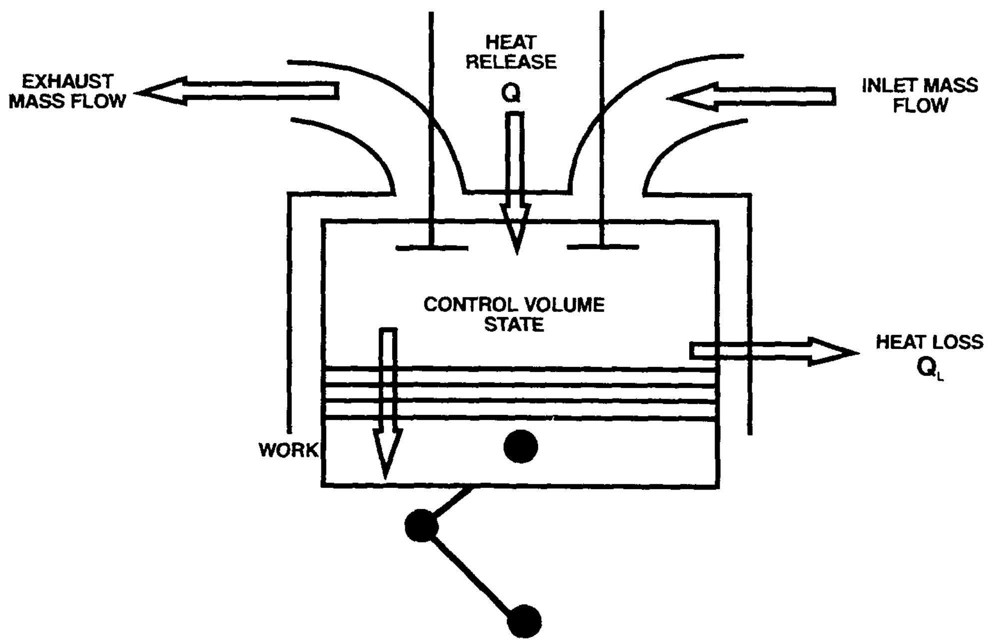

FIG. 1—SIMPLE CYLINDER MODEL

particular work. The emissions prediction package incorporated into SPICE, is one such simulation. In its basic form SPICE is a single zone model simulation program. The single zone is the combustion chamber volume (or the control volume) through which mass and energy are conserved, (FIG. 1). Combustion is represented by a rate of heat release function.

The program performs its simulation by representing the system with combinations of discrete:

- Thermodynamic control volumes.
- Flow junctions.
- Shafts.
- Controllers.

The basic configuration of the quarter scaled (or 3 cylinder) 12RP200 model developed for the RNEC study is shown at (FIG. 2).

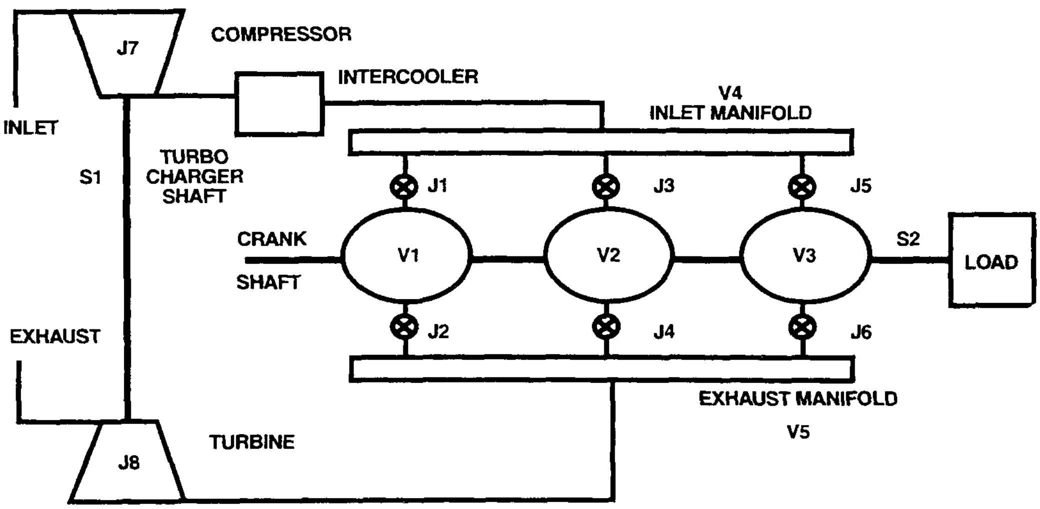

FIG. 2—SIMPLE MODEL CONFIGURATION
J: Junction S: Shaft
V: Volume

In its advanced form, SPICE incorporates an emission prediction capability. This capability is primarily aimed at predicting actual Nitric Oxide (NO) emissions, with other gaseous emissions based on cylinder equilibrium values (NO_x is currently considered to be the most important emission to control). The emissions prediction is a multi zone model and differs considerably from its single zone counterpart. However, in the simulation both models are run, with the single zone model providing inputs such as initial cylinder pressures and temperatures for the multi zone model. Equivalence ratio, crank angle (CA) integration step and the heat release pattern, amongst others, can be user defined as in the current study.

The emissions model assumes that fuel burns over a range of equivalence ratios around the stoichiometric ratio. The numerical methods used to solve the defining equations use a discrete time base or CA step, and thus the heat release takes place as a series of increments. Each increment is assumed to burn at a number of discrete equivalence ratios, and is represented as six packets at each integration step. The final composition of each packet after heat release is determined from a 11 species equilibrium analysis. The simulation then advances by one integration step and 6 new active packets are generated. Existing packets from the previous integration step are supplied with more air by introducing a mixing rate factor for the interaction of excess air and the old, but still active packets. Should a packet temperature fall below 1700°K then it is assumed to be inactive for NO production. To reduce computational time packets of similar mass and temperature are amalgamated to form 1 packet. Once all the packet temperatures fall below 1700°K, the NO formation threshold, then the emissions calculations are complete.

EMISSION REDUCTION

NO_x Emissions

Atmospheric nitrogen is oxidised during the combustion process, and emitted by the engine as NO and Nitrogen Dioxide (NO_2). These compounds are generally treated as NO_x. At the end of the combustion stage it is estimated that 98% of the NO_x emissions are NO. However once exhausted from the engine NO rapidly oxides to NO_2. Levels of NO_x emissions are dependent on temperatures achieved during combustion and the length of time spent at these temperatures. Conditions favouring low NO_x formation, ie lower combustion temperatures and shorter reaction times, are generally opposed to the requirements of good fuel economy, low smoke and low exhaust temperatures.

Validation of Engine Emissions

General engine performance characteristics and predicted engine emissions were validated against actual engine data from PAXMAN. Table 1 shows the SPICE errors based on the mean values from PAXMAN engine results at standard injection timing.

	% Error at 100% LOAD	*% Error at 75% LOAD*	*% Error at 50% LOAD*	*% Error at 25% LOAD*
BRAKE POWER (kW)	−1.99	−1.32	−2.62	−6.51
INLET MANIFOLD (bar)	−2.52	−2.80	2.71	2.20
BFSC (g/kWh)	−3.01	−3.82	−1.49	−1.27
MCFP (bar)	−5.51	−0.95	−3.37	−12.09
AFR (TRAPPED)	1.51	1.55	−0.92	−6.08
INLET TEMPERATURE (K)	0.00	−2.30	−0.06	−0.33
EXHAUST TEMPERATURE (K)	1.45	1.55	2.16	3.48
T/C SPEED (rpm)	−4.49	−6.27	−5.68	−3.46
NO EMISSIONS (ppm(v))	2.28	−5.90	−7.40	−0.80

TABLE 1—*Validation of SPICE Engine and Emissions Results*
MCFP: Maximum Cylinder Firing Pressure

SPICE NO predictions were compared to real engine emissions for standard fuel injection timing and for the injection timing retarded by up to 5°. The emissions values calculated by SPICE were initially compared using volumetric units of ppm(v). Across an engine load range from 25% to 100% of full load, the SPICE predicted emissions were within a maximum of 7.7% of those recorded from a comparable PAXMAN engine. A selection of these results are shown in Table 2.

	SPICE NO EMISSIONS PREDICTED (ppm(v))	*PAXMAN NO EMISSIONS OFF ENGINE (ppm(v))*	*ERROR*
STANDARD INJECTION TIMING			
100% LOAD	1114	1143	2.5
75% LOAD	1048	1114	5.9
50% LOAD	1000	1080	7.4
25% LOAD	868	875	0.7
INJECTION TIMING RETARDED 1.5°			
100% LOAD	1020	1052	3.1
25% LOAD	776	806	3.7
INJECTION TIMING RETARDED 3°			
100% LOAD	915	913	−0.2
25% LOAD	689	697	1.1
INJECTION TIMING RETARDED 5°			
100% LOAD	822	802	−2.6
25% LOAD	581	598	2.9

TABLE 2—*SPICE NO Emissions and Actual Engine Data*

Retarded Fuel Injection

Retarding the point of fuel injection is the most effective primary means of reducing NO emissions. Injecting fuel later in the combustion cycle limits the amount of fuel-premixing, and in doing so lowers cylinder pressures and temperatures. However, these conditions will increase emissions of Carbon Monoxide (CO), UHC's and Smoke, whilst reducing engine output and increasing Brake Specific Fuel Consumption (BSFC). Investigations into the retardation of fuel timings of up to 10° CA, showed a reduction in NO emissions by between 32 and 48%. The penalties for this decrease in NO emissions are an increase in BSFC of 6%, a reduction in engine power of 6% and a 20% increase in CO emissions. Utilising higher compression ratios and higher injection pressures will aid the reduction of the fuel economy penalty associated with retarded fuel injection.

Variable Valve Timing (VVT)

The reduction in engine power with retarded fuel injection timing suggested that alternative means were required to boost engine power and reduce specific fuel consumption, in order to offset the penalties imposed for reduced NO emissions. The following areas have been investigated:

1. *Exhaust Valve Opening (EVO).* The effect of advancing the exhaust valve timing by up to 15°CA across the engine load range, showed a decrease in specific NO emissions of up to 2.6%. At very low loads there is no improvement in emissions because there is little change in volumetric NO emissions and engine power.

2. *Inlet Valve Closure (IVC)*. Retarding the inlet valve closure increases engine power output due to the increased ram effect, which improves cylinder filling, a higher baseline pressure at the start of combustion and results in a higher thermal efficiency. A 15°CA retardation of IVC gave reductions of up to 1.9% in NO emissions across the engine range. This is primarily from increased engine power output which is due to a reduced ignition delay, higher cylinder pressures and temperatures.
3. *Inlet Valve Open Duration (IVDUR)*. Maximum reductions in specific NO emissions were achieved with an increase in IVDUR of between 15 and 20%. At +20% IVDUR, results showed a 6.3% maximum reduction in NO emissions.
4. *Exhaust Valve Open Duration (EVDUR)*. Significant reductions in No emissions can be achieved by shortening EVDUR by up to 35%, but at the expense of increased BSFC and reduced Brake Power. However, the results for a reduction in EVDUR of 15% show a reduction of 9% in NO emissions, and a correspondingly small change in engine power output or fuel consumption.
5. *Exhaust Valve Lift (EVLIFT)*. Investigations found that reductions in NO emissions were less than 0.6% for an increase in EVLIFT of +15%.
6. *Inlet Valve Lift (IVLIFT)*. Increases in IVLIFT were evaluated for up to +20%. The maximum reduction of specific NO emissions by increasing the valve lift was 2.2% for an increase of +15%.

Results of the investigations showed that VVT will not reduce volumetric NO emissions. But its use will in general increase engine power and reduce fuel consumption will reduce specific NO emissions. The fitting of fully variable timing to the PAXMAN engine can not be justified due to the small reduction of NO emissions available. Alternatively a selected fixed alteration to the valve timing combined with a retardation in the point of heat release could be implemented during engine rebuild to help reduce specific NO emissions and other gas flow problems of the engine.

Enhanced Intercooling

Enhanced intercooling is a recognised means of reducing NO emissions. This can be achieved by either reducing the temperature of the cooling water to the intercooler or by increasing the intercooler effectiveness. These techniques give a reduction in charge air temperature which in turn will give a corresponding reduction in peak combustion temperatures, hence the decrease in NO emissions.

Investigations into the effect of reducing cooling water temperature showed a 10% reduction in NO emissions. Improving intercooler efficiencies reduced NO emissions by 6%. Combined with a 10° retardation for the main fuel injection, a reduced cooling water temperature of 293°K (20°C) gave reductions of NO emissions of up to 61%. Simulation of the same retardation in the point of fuel injection, together with an intercooler effectiveness of 90% across the engine load range, showed a decrease in NO emissions of 60–63%. These reductions are due to a combination of reduced volumetric NO emissions coupled with an increase in engine power from the reduced charge air temperature and consequent density increase.

Pilot or Split Injection

Pilot or split injection has been suggested as a method of balancing the trade off between NO emissions reductions and increasing UHC emissions. This was based on the premise that split injection reduces the peak rates of cylinder pressure rise, giving lower peak pressures and cylinder temperatures, thus giving reduced NO emissions. The main advantage of pilot injection is to reduce the ignition delay period, with a subsequent reduction in engine noise. Initial results showed that introducing pilot injection at standard fuel injection timings was not reducing NO emissions from the engine. These emissions were up because although the pilot injection reduced that rate at which pressure increased, generally peak temperatures were higher, thus increasing NO emissions.

Pilot injection with retarded fuel injection timing improved both power and fuel BSFC against the purely retarded case, whilst still significantly cutting NO emissions by 28.4% at full load. Therefore there exists the possibility of reducing fuelling at full load to further reduce emissions and fuel consumption. The trends in fuel consumption and NO emissions are similar at reduced loads.

The pilot acts as a catalyst during the pre-mixed burning phase with increased peak pressure and hence increased power. At lower powers there is obviously a greater ignition delay between pilot injection and main heat release. The major effect of the pilot at 50% load is the 2°CA in ignition delay. At 25% load, the pilot has increased the peak pressure in heat release during pre-mixing burning and reduced ignition delay by 6°CA.

Concluding Remarks

The results of investigations into the possibilities of reducing noxious emissions from marine diesel engines, have shown that substantial reductions can be achieved using combinations of primary methods. Pilot or spilt injection has proved most effective with retarded main injection, and will reduce the associated penalties of excessive fuel consumption, power reduction and increased CO emissions. Retarded fuel injection reduced the peak of heat release thus reducing NO emissions but also reducing engine power output. Less productive methods of controlling NO emissions, such as variable valve timing, will benefit the performance of the engine, and therefore reduce specific NO emissions.

Continuing development of the emissions package and engine model might in future allow further investigations to be carried out regarding the effects on exhaust emissions from water injection, and fuel emulsification.

References

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2. Findlay, R. F. A.: Exhaust Emissions from Marine Prime Movers, *Journal of Naval Engineering* June 1993 Vol 34 No 2