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Closed cycle diesel propulsion systems

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SYNOPSIS

The search for alternative underwater power sources has attained prominence in recent times as both military and civilian authorities seek to extend their operational capabilities. This paper traces the development of the Argo-diesel closed cycle engine concept, pioneered at the University of Newcastle upon Tyne, and now being developed by Cosworth Deepsea Systems, in association with partners in Europe.

The paper describes the various stages of development including the exhaust gas processing plant and water management system. Typical operating characteristics are also presented and discussed. The system is ultimately intended to provide propulsion for submarines, submersibles, and other underwater vehicles.

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INTRODUCTION

Airless underwater power generation systems have aroused considerable interest since the years of World War II when the Germans pioneered work with both Walther turbine and diesel engine systems. Initially, the application of this technology was directed towards military applications. More recently, developments in offshore technology have led to a surge of interest in some particularly exciting projects as typically encapsulated by the submarine support vessel concept.[1,2]

The potential advantages of deploying submarines, rather than the currently conventional surface based multipurpose support vessels, is increasingly recognised. Concepts of complete subsea production systems are ultimately envisaged, and the question of powering submarines and other systems associated with these requirements is becoming significantly more urgent.

It may be argued,[3] that the combination of hydrocarbon fuel and oxygen remains the most appropriate choice of energy source for subsea operation. A number of options for harnessing this source are currently under investigation as evidenced by the current literature. The purpose of the present paper is to review one particular line of approach, as followed at Newcastle University in the Department of Marine Engineering, leading to the evolution of what has come to be known colloquially as the Argo-diesel system. This paper presents an historical perspective of what has been achieved, concentrating on the practical significance of the most recent developments.

PRELIMINARY RESEARCH

The initial research at Newcastle aimed to develop a closed cycle diesel engine system which would in principle be completely autonomous and depth independent. A fundamental aim was to keep the system as simple as possible, utilising 'off the shelf' technology wherever possible, and capitalising on the acknowledged advantages of conventional diesel engines. This work was funded by the Marine Technology directorate of the SERC between 1979–1983. The resulting Nitro-diesel concept is illustrated schematically in Fig 1. The Nitro-diesel engine essentially comprises a closed thermodynamic circuit with recirculated nitrogen constituting the inert diluent gas (as is the case of course in the conventional air breathing engine). The concentration of oxygen is maintained at approximately atmospheric conditions while CO_2 is contained at typically 2–4% by the action of a chemical absorber.

Overall, this preliminary research programme was extremely successful, fully vindicating the original promise of the system and providing useful validation of the simulation model.[4,5]

From the results obtained it was projected that the total weight and volume characteristics of the system plus consumables, for a typical diving mission, even allowing for the bulky KOH absorption system, would still show a significant advantage compared to the conventional lead acid battery. However, considering the relative complexity and development cost compared to conventional systems, it was considered necessary to secure additional improvements in power to weight and volume, to make the system more commercially attractive.

RESEARCH OBJECTIVES AND CONSTRAINTS

A brief review of the fundamental requirements of closed cycle engine operation is outlined as follows. In principle, the engine is intended to operate with a performance specification virtually identical to a conventional naturally aspirated engine. However, since the working fluid is to be recycled, the following essential features need to be incorporated into the gas reprocessing system:

1. Thermal energy associated with the exhaust must be dissipated.

2. Oxygen consumed during the combustion process must be replenished.
3. Unwanted products of combustion must be removed.
4. The working fluid must retain acceptable thermodynamic properties.

From the Nitro-diesel research it was apparent that the main thrust of subsequent effort should be directed towards the problem of reducing the bulk of consumables used. An obvious area in which to investigate weight and space reduction was in the absorption system. In particular, it was evident that a radical saving in space and weight of consumables would be obtained if it were possible to eliminate the bulk associated with the KOH chemical absorption system, as used in the Nitro-diesel.

REGENERATIVE ABSORPTION

One possibility, which formed the basis of a proposal made jointly in 1984 by the Department of Marine Engineering and the Department of Chemical Engineering at Newcastle University, is to resort to the use of regenerative chemical absorbents, such as MEA (monoethanolamine) or DEA (diethanolamine) to replace the KOH absorber. This could be achieved using a batch system, as in the case of the Nitro-diesel. This scheme would offer some benefit in terms of operating cost as the absorbent could be regenerated 'off-line' and then used again. However, when used in this mode, the bulk of absorbent carried per mission would actually exceed the equivalent KOH overhead, since MEA has relatively poorer absorption capabilities.

A more practical proposition is to carry a limited quantity of the regenerative absorbent and perform regeneration on-line, using waste heat from the engine. A schematic representation of the proposed system is illustrated in Fig 2.

It will be noted that, relative to the Nitro-diesel, an additional component, in the form of an absorbent-regenerator/exhaust-gas cooler, has been installed in the closed system. The relatively cold, CO_2 laden absorbent recycling from the absorber, is now heated by the exhaust gas from the engine, whereupon the CO_2 gas is partly desorbed due to the increased temperature. The free CO_2 can then be collected and either compressed and stored on board, or discharged overboard. The MEA absorbent is cooled and returned to the absorber to complete the liquid cycle.

Although this proposal was unsuccessful in attracting funding at that time, it is interesting to note that such a system has now been built and apparently operated successfully by the Japanese.[6]

SEA WATER ABSORPTION

Another proposition, which arose at approximately the same time as the regenerative absorber concept, was to use water as the CO_2 absorbent, since this is obviously in virtually infinite supply in the marine environment. However, this scheme inevitably introduces potential penalties since water is a much poorer absorber of CO_2 than any of the chemical absorbents considered. This problem can be partly offset by performing the absorption process at a higher partial pressure of CO_2, which facilitates high mass transfer rates without requiring unrealistically high water flowrates. However, this does imply the establishment of a high total pressure, or a high percentage CO_2 concentration, or a combination of both these options.

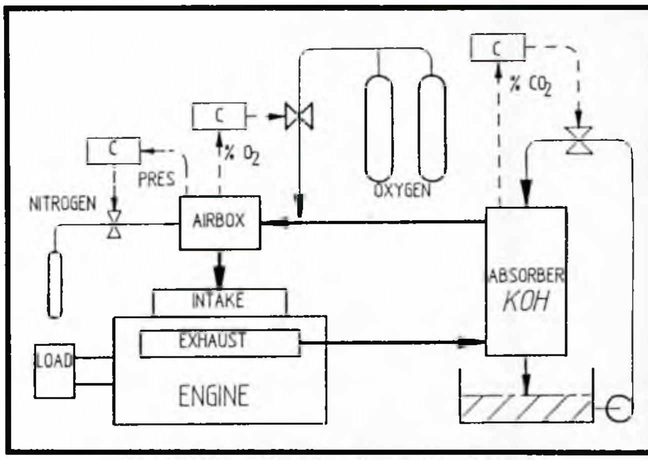

Fig 1: Nitro-diesel schematic diagram

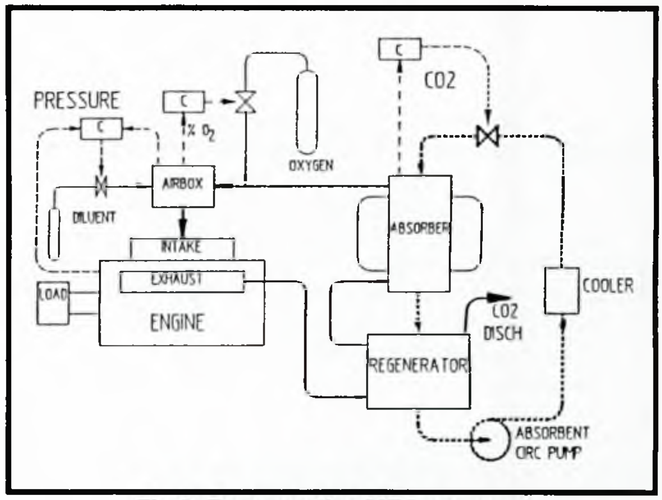

Fig 2: Regenerative MEA proposal

Unfortunately however, restrictions are imposed with respect to both pressure and constituency, by the operating requirements of the engine. High total pressure ultimately reflects in a correspondingly high cylinder peak-pressure for a given compression ratio and combustion conditions. Engines designed to operate with high levels of boost pressure are therefore potentially most adaptable in this respect, although finite limits dominated by design considerations obviously exist.

There is also a significant limitation with respects to the concentration of CO_2 which is acceptable. Being a triatomic gas, CO_2 has a relatively low ratio of specific heats (gamma) and this has important consequences for the temperature and pressure at the end of the compression stroke. This, in turn, implies degradation in combustion efficiency for a conventionally designed engine.

Rather than resort to redesigning the diesel, it was decided to seek alternative solutions to this problem.

Pressurised absorption

One potential solution to the problem is to pressurise the absorber. In such a system a compressor would be used to raise the pressure of the exhaust gas stream before entry to the absorber. Partial recovery of the compression energy would be achieved by utilising a mechanical 'air-motor' device to expand the high pressure gas leaving the absorber.

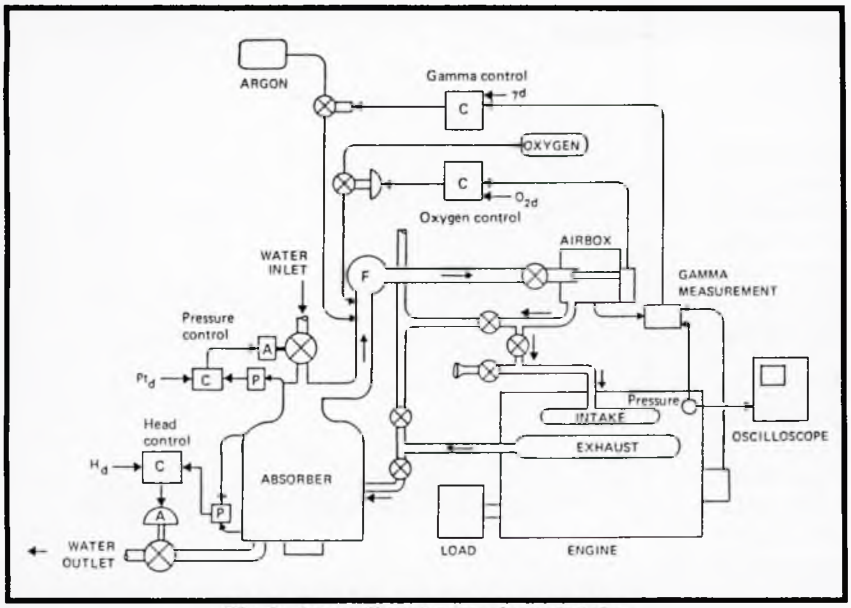

Fig 3: Argo-diesel experimental rig

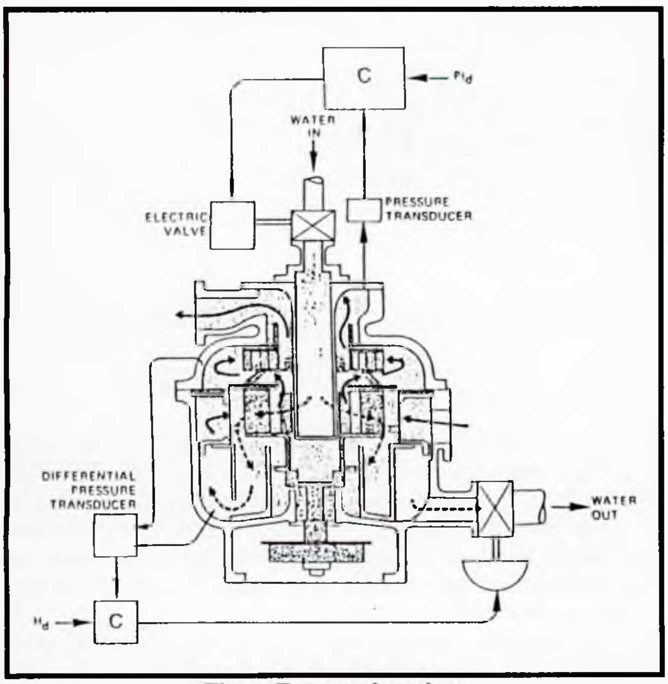

Fig 4: Rotary absorber

Heat exchangers and coolers would also be necessary since absorption must occur at low temperature, to minimise the water requirement. It will also be apparent that maximisation of energy recovery will be subject to the normal constraints of the thermodynamic laws. Such considerations rapidly lead into a range of practical design trade-offs as the system becomes progressively more complex. Although preliminary computer simulation studies of this system were conducted at Newcastle, this proposal did not in fact progress beyond the conceptual study phase.

Argon injection

In response to a perceived requirement to achieve a mechanically simplified system it was decided to revert to a uniform, nominally 'low pressure' cycle, into which a quantity of monatomic gas (in this case Argon) is added, with the objective of restoring the mean ratio of specific heats for the gas mixture (gamma) to a value of approximately 1.4 (at atmospheric pressure and temperature). By this means, it is intended that the thermodynamic qualities of the working fluid will be consistent with those of air, even when the CO_2 partial pressure is relatively high.

Gas constituency

The concentrations of CO_2 and argon were therefore targeted for selection by a process of compromise between the absorber and engine operating conditions.

Unlike the prevailing situation in a conventional air breathing engine, oxygen concentration in the gas stream of a closed system of this type can be selected, subject to optimisation, allowing for certain constraints. Nominally oxygen should be at 21% by volume which brings the system as near to standard as possible.

The recirculating gas stream will also contain nitrogen in addition to O_2, CO_2 and Ar, since a certain quantity of N_2 will be retained in the system at the time of changing over from open to closed cycle. Over a period of time, the nitrogen partial pressure will assume equilibrium with the sea water flowing in the absorber. The equilibrium level will depend on the degree of nitrogenisation of the water and would normally be expected to correspond to about 0.79 bar assuming the water had at some stage in its history been in equilibrium with the atmosphere.

THE LABORATORY BASED ARGO-DIESEL TEST-RIG

The physical test-rig which was subsequently built as the basis for the experimental work undertaken at Newcastle, is illustrated schematically in Fig 3. By this time the University research workers had been joined by Cosworth Engineering, whereupon the project proceeded under funding provided jointly by the Marine Technology Directorate (MTD) of the SERC, with equal funding and technical assistance provided by Cosworth.

A key contribution from Cosworth was the introduction of a centrifugal absorber designed and manufactured by them as shown schematically in Fig 4. A key design objective was to reduce the size of the absorber relative to the original packed column system as used on the Nitro-diesel rig.

The laboratory based system was configured so that the engine could be operated in either open cycle mode (necessary for baseline data retrieval and calibration of instrumentation, etc) or closed cycle. This facility is clearly shown in Fig 3 upon considering the arrangement of the various pipework isolation valves. There is also an intermediate position in which the engine breathes from the atmosphere and discharges through the reprocessing system and ultimately back to the atmosphere. This condition is experienced during the changeover sequence between open and closed cycle modes, but also provides a useful facility for partial checking of various subsystems prior to going into the completely closed cycle mode of operation.

The exhaust gas leaving the engine is spray cooled when it exits from the manifold before passing into the outer annulus of the absorber.

After passing through the mass transfer elements of the rotor and the demisting element located at the upper end of the rotor, the gas stream leaves the scrubber and passes through a conventional paper element/cyclone type air filter before entering the gas reservoir volume (the 'airbox').

The replenishment oxygen stream is admitted to the system at a union in the pipework preceding the airbox, and mixing is achieved by turbulence in the pipe before the gas stream enters the airbox. A small quantity of argon is injected at the same location, to replace the relatively small quantities which are dissolved in the water flowing through the absorber.

From the airbox the reconstituted gas stream flows back to the engine intake, thereby closing the cycle.

The flow of water into the absorber is controlled by a motorised ball-valve. Discharge of water from the absorber is through a high response pneumatically controlled valve. The method of control used in the first series of tests was to regulate the rate of flow into the absorber in response to the partial pressure of CO_2 in the system; increasing water flow to reduce CO_2 and vice versa. The drain valve was then arranged to control the discharge rate to maintain an appropriate level in the absorber as measured by a differential pressure transducer. This arrangement is clearly illustrated in both Figs 3 and 4.

The benefit of experience derived during the development, analysis and test phases associated with the Nitro-diesel programme, was harnessed in several features of the new Argo-diesel rig. The engine used was a Perkins D3152 three-cylinder direct injection diesel, built to a turbocharged specification to accommodate the high cylinder loading associated with the pressurised cycle operated in the new system.

Scavenging of the engine crankcase was also required to remove gases leaking past the piston rings. This was achieved by sealing the engine crankcase and introducing a small compressor to draw gas from the crankcase and discharge it back into the closed gas system. A simple vacuum prevention valve was utilised on the compressor suction side with the compressor crankcase being connected in common with the engine crankcase to prevent possible leakages from this source.

The engine was fitted with manual control of the speed demand set point, and engine loading was effected by a hydrostatic dynamometer similar to the device which had been used very successfully in the original Nitro-diesel rig. This cheap and simple dynamometer provided responsive and accurate steady-state load control independent of speed variations, and also provided a capability for high response dynamic loading of the engine, as required.

CONTROL SYSTEMS AND DYNAMIC PERFORMANCE

Control engineering aspects are critical in the achievement of well integrated closed cycle power-plant of the types described. In order to achieve satisfactory control of the recirculated gas constituency it will be apparent that a relatively sophisticated control system, involving several interactive variables, will be required. Essentially the main control loops are:

1. oxygen control;
2. total pressure control;
3. gamma control;
4. level control in the absorber.

The oxygen control system technology was transferred directly from the earlier nitro-diesel research. This aspect had initially been considered to be potentially problematic particularly under dynamic 'load change' situations and had consequently warranted a detailed level of analysis and testing including a comprehensive computer simulation.[7]

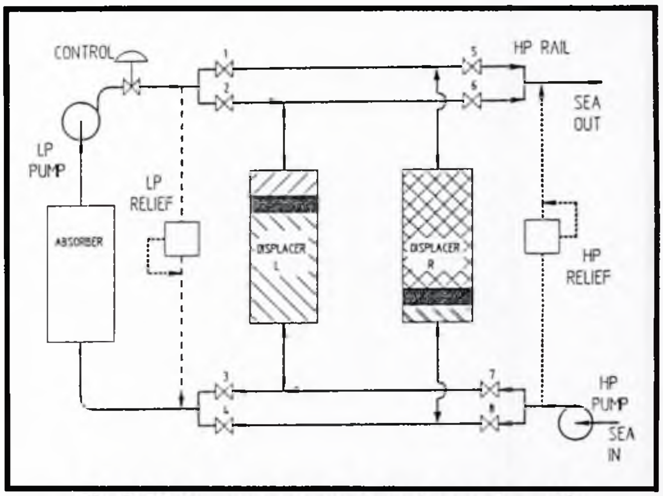

Fig 5: Water management system schematic

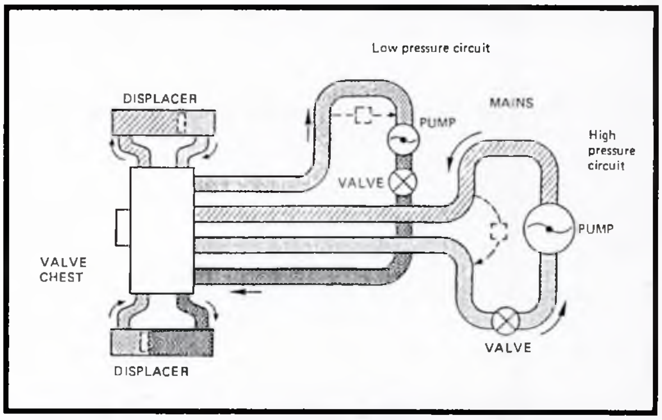

Fig 6: High pressure testing of water management system

The device developed for measuring gamma was based on the application of fundamental thermodynamic principles associated with compression of a sample of process gas in an engine cylinder.[8]

The pressure control loop facilitates regulation of water flow to the absorber which in turn controls the CO_2 absorption rate. The interaction between the total system pressure control and the absorber level control systems is clearly apparent upon consideration of Fig 3.

Collectively, these systems required careful design in order to combine acceptable stability margins with fast response rates, during both steady-state and dynamic loading of the engine.

INTRODUCTION OF THE WATER MANAGEMENT SYSTEM

During the initial phases of the experimental testing at Newcastle the engine was operated with water drawn directly from the town mains. The water flowrate was controlled and throttled down to absorber pressure through the flow control valve as shown in Fig 3. The carbonated water leaving the

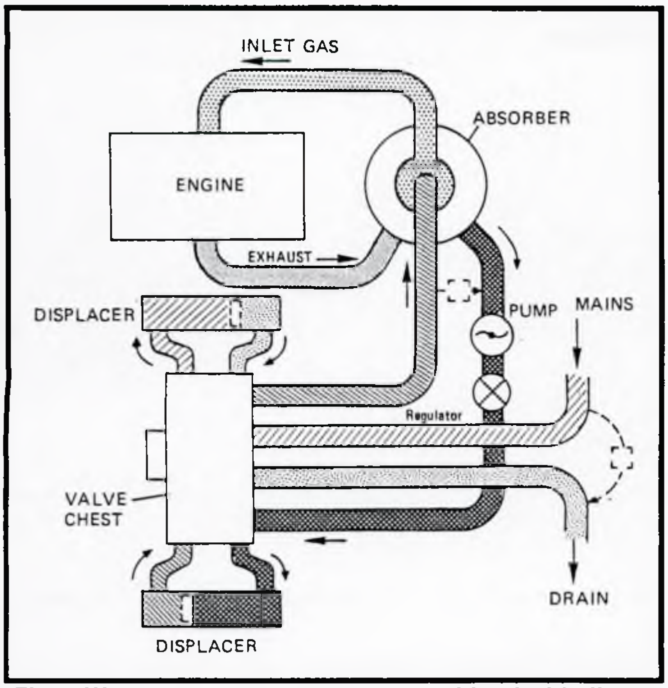

Fig 7: Water management system combined with diesel engine

absorber was then discharged directly to the drain after throttling down through the head control valve.

While this method of operation is entirely adequate when operating at near atmospheric pressure conditions, it is not suitable for operation at great depth. This is because significant potential energy losses would occur when throttling down sea water from ambient hydrostatic pressure conditions to engine exhaust gas pressure conditions. This energy would then require to be restored before the carbonated water could be discharged overboard against the external seawater pressure. Since significant water flowrates are necessary in this system, it is necessary to incorporate some form of energy recovery device if the pumping losses are to be retained at an acceptable level.

It was therefore necessary to design and construct a water management system (WMS) in order to overcome these operational problems. The system which was developed uses a piston displacement principle, such that a supply of low pressure water is made available to the absorber as a reasonably continuous flow.

This objective was achieved by the Cosworth design team using twin parallel displacer units. The displacers alternate between high and low pressure cycles, thereby utilising hydraulic balance to avoid the necessity for pumping overboard against high differential pressures.

An explanation of the working of the WMS may be obtained upon considering a complete sequence in the operating cycle, viewed in the context of the schematic diagram shown in Fig 5.

The absorber and all pipework to the left of valves 1, 2, 3 and 4 are permanently part of the low pressure side of the system. The seawater pump and all pipework and components to the right hand side of valves 5, 6, 7 and 8 are permanently associated with the high pressure system (ambient depth condition).

Starting with valves 2 and 3 open, while 1 and 4 are closed, the LP pump draws carbonated water from the absorber and discharges through the LP control valve and changeover valve 2 into the top of displacer cylinder L. The free floating piston moves downwards displacing a fresh charge of water through changeover valve 3 and into the absorber.

Simultaneously the HP pump discharges uncarbonated sea water through changeover valve 8 into the lower section of displacer cylinder R. The action of the piston then displaces a batch of carbonated water from the upper section of cylinder R out through changeover valve 5 and hence to the overboard discharge.

The capacity of the HP pump is in effect greater than the capacity of the LP pump and, upon completion of the stroke of the HP piston, the valve changeover sequence is activated whereby valves 2, 3, 8 and 5 close, and valves 1, 4, 7 and 6 open. The displacer L now becomes the high pressure unit, filling from the bottom through valve 7 and discharging carbonated water overboard through valve 6. The right hand unit is now at low pressure and provides a fresh charge of water to the absorber through changeover valve 1.

The design of the valve mechanism is based on a pair of interlocked spool valves which are actuated hydraulically. Since the valves are mechanically arranged so as to render impossible the temporary connection of the HP and LP sides, there is a momentary interruption in flow as the changeover takes place. Bypass relief valves are included in the piping arrangement, to relieve water hammer which might occur during the changeover sequence.

The WMS was originally commissioned and tested remotely from the engine and absorber test rig. This phase of the work was undertaken at BHRA, Cranfield. During this phase the WMS rig was configured such that the high-pressure side of the system was operated under conditions which physically simulated pressures of up to 35 bar, while the LP circuit was maintained at atmospheric pressure. A closed system with continuous water recirculation was used for this part of the test, since there was no requirement to remove CO_2 at this stage (Fig 6). The purpose of this series of tests was purely to evaluate the hydraulic performance of the WMS prior to incorporation with the engine and absorber at Newcastle.

Incorporation of the WMS on the Newcastle engine test rig required relatively straightforward modification to the existing pipework and control systems. Instead of taking water directly from the mains, access to the absorber was now arranged via the WMS. Similarly, the absorber drain was also connected into the WMS, from which a new connection to the lab drain was taken. This arrangement is illustrated in the simplified schematic diagram of Fig 7.

Mains pressure was utilised in what is, in effect, the high pressure side of the WMS, thereby avoiding the necessity of installing a separate pump. This was quite acceptable for the current series of laboratory based trials which were performed at near atmospheric pressure conditions.

A separate pump was installed in the low-pressure part of the system, between the absorber drain and the WMS. The original pneumatically-controlled absorber level control valve was moved to the pump discharge side and was thereafter used as the main water flow control device. In effect, this somewhat simplifies the water flow control system compared with the original arrangement as shown in Fig 4, since the net flow of water into the absorber is now nominally constrained by the geometry of the WMS to be identical to the net flow out. This means that the high response head control system was no longer required, and could now be replaced by simple manual filling and dumping valves whose main function is reduced to the establishment of a specified water head, prior to starting the rig.

In this configuration the absorber inlet valve shown in Fig 4 becomes redundant and pressure control now operates the

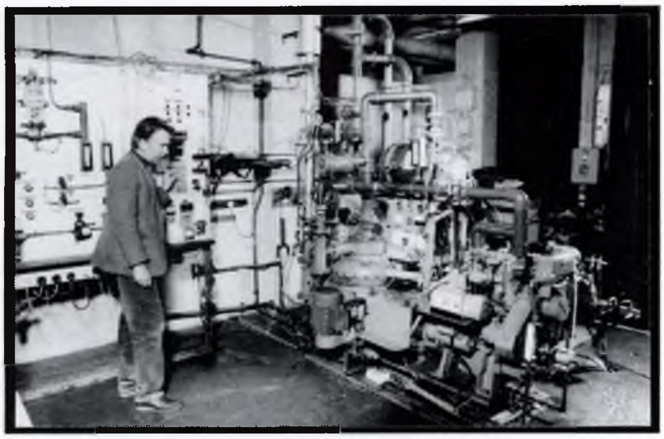

Fig 8: Photograph of Newcastle based test-rig

pump discharge valve. However, the water pipework and control systems were arranged so that the option of operation in the original configuration, independent of the WMS, was retained. A photographic reproduction showing the laboratory based system is provided in Fig 8.

The combined test-rig was operated in the mode described for the remainder of the experimental programme.

OVERALL SYSTEM PERFORMANCE

The evaluation of the system was progressed by physical test-bed trials and experimentation, backed by computer modelling and simulation. The latter has proved indispensable with respect to acquiring a deeper understanding of the physical characteristics and inter-relationships associated with the respective components of the system. Numerous trials have been conducted from which both steady-state and transient data have been acquired.

During the initial phases of engine testing under laboratory conditions, baseline results were obtained with the engine operating in open cycle. Additional trials were then implemented to achieve preliminary performance validation of the absorber and the various control systems and associated instrumentation.

The main phase of tests in closed cycle mode included:

1. characterisations of the engine performance on closed cycle with an emphasis on specific fuel consumption under a variety of speed and load conditions;
2. measurement of corresponding specific oxygen consumption over the same operating range;
3. measurement of argon topping up requirements;
4. analysis of gas constituency and investigation of the consequences of variations in respective constituent partial pressures;
5. characterisation of the absorber performance with respect to CO_2 absorption rate, specific water flow rate, mass transfer effectiveness, rotor power requirements and pressure head losses on both water and gas sides;
6. evaluation of the water management rig operation.

Engine performance

Figure 9 summarises a particular set of steady-state data which illustrates how the closed cycle Argo-diesel performance compares with baseline 'open cycle' engine operation.

A significant feature of the engine performance when operating in closed cycle mode is a slight improvement in specific

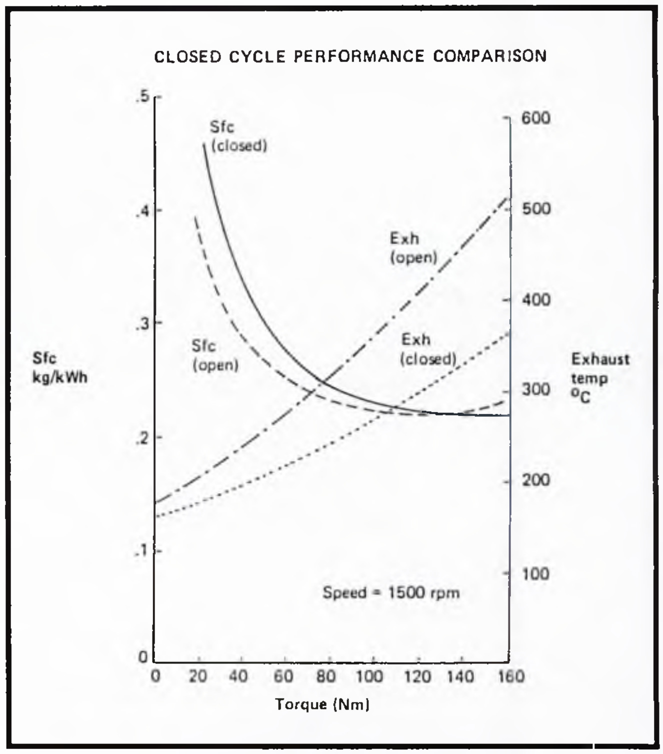

Fig 9: Steady state results

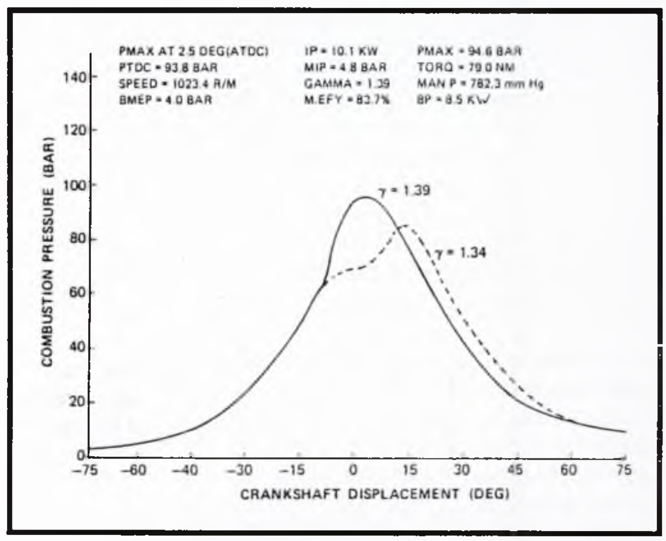

Fig 10: Cylinder conditions

fuel consumption (sfc) when operating at full load (relative to open cycle conditions). The sfc curve remains quite flat over the range 50%–100% load, with a minimum sfc of 0.23 kg/kW h being achieved. This can be attributed to the fact that a relatively abundant quantity of oxygen is present in the closed cycle mode due to the increased density of the cylinder charge. The characteristics are, in fact, very typical of conventional turbocharged engine practice.

However, it should be noted that part load performance deteriorates relatively, when running in closed cycle, even though the corresponding full load performance is slightly improved. For example, the closed cycle sfc rises to 40% above the naturally aspirated value when the load falls to 25%. It is assumed that this reflects the increased pumping loss associated with the closed cycle mode, since the engine must circulate by its own action a constant volume flowrate of gas around the system, nominally independently of load. Consequently, at low load, these losses represent a much higher proportion of the cylinder power.

Exhaust temperatures are also reduced in closed cycle mode, typically being 130°C lower than the corresponding open cycle values. This reflects the higher mass flowrate of gas available to remove a nominally fixed quantity of exhaust energy.

The theoretical stoichiometric ratio of oxygen to fuel is estimated to be about 3.45 although some oxygen does dissolve in the water (approximately 3% of the total flow). The rate of argon replenishment is typically about 4% of the oxygen flowrate, this also being explained by dissolution in the absorption water, since argon does not participate in any chemical reaction.

As anticipated from theoretical considerations, combustion, and consequently efficiency, are significantly affected by the value of gamma maintained in the system. With high concentration of CO_2 the ignition delay is increased and peak pressure correspondingly reduced. The resulting distorted combustion curve implies impaired engine performance which is reflected in increased sfc.

With higher concentrations of argon the ignition delay is barely discernible and a smooth combustion curve results. Peak pressure increases correspondingly, attaining the engine manufacturer's maximum level of 120 bar when the engine is operating at full power. The significance of gamma is illustrated by attention to Fig 10 which is reproduced from typical data retrieved from the engine.

Absorber performance

The absorber was estimated to be typically 70% effective in its capacity to remove CO_2 from the exhaust gas; this figure being derived by comparing the actual gas absorption rate with the maximum rate which would be predicted assuming effluent water left the absorber saturated with CO_2 at the particular partial pressure prevailing in the system. Typically, carbon dioxide volumetric concentration is reduced from 36% to 32% with the system at a total pressure of 2 bar g and the engine at full load of 25kW and 1500 rev/min. The total gas pressure drop from exhaust manifold to inlet is 40 mm Hg under these conditions.

It was estimated that typical parasitic losses on the rig, including the absorber drive, circulating pumps, the crankcase scavenge compressor and instrumentation requirements amounted to approximately 1.5 kW which is of the order of 6% of full engine power in this case. Obviously, this implies that the net part load performance tends to be relatively less economical as the parasitic losses are nominally independent of output shaft power.

CONCLUDING REMARKS AND CURRENT STATUS

The laboratory based trials on the Argo-diesel, as outlined in this paper, were highly successful with engine performance confirming the results obtained in the previous sequence of tests on the Nitro-diesel. The system was operated on full power and at intermediate loads for continuous periods up to 7h per day while test data was retrieved and logged for analysis. The system was also successfully subjected to step load changes, throughout the operating range, with steps of up to 50% of the full load value. Start-up and shut-down sequences were also investigated with the system in closed cycle mode.

WMS operational data was also retrieved during the experimental trials and subsequently fed back into the design process to improve future generations of closed cycle engines.

Sufficient confidence was established, as a result of experience with the pilot system at Newcastle, to promote the development of a full scale 150 kW system incorporating updated designs based on the principles described in this paper. Cosworth have subsequently established a separate company (Cosworth Deep-sea Systems), to develop, refine, manufacture and market the Argo-diesel system.

In collaboration with European partners Cosworth have now successfully demonstrated full scale operational plant. The system compares favourably with other technologies currently being promoted.[9] Further research is also being undertaken at Newcastle, with the objective of improving theoretical understanding of combustion behaviour in closed cycle engines. Dynamic behaviour and control of the total system also remains the subject of academic interest.

Current areas of practical development at Cosworth include optimisation of the absorber to improve effectiveness, reduction of noise levels and reduction of parasitic losses. Significant achievements are being made in all these areas and it is envisaged that a promising future awaits the Argo-diesel system.

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