

NINTH EDITION

POUNDER'S MARINE DIESEL ENGINES AND GAS TURBINES

DOUG WOODYARD



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Ninth edition

Edited by

Doug Woodyard



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Pounder's Marine Diesel Engines and Gas Turbines

Preface

Major developments in two-stroke and four-stroke engine designs for propulsion and auxiliary power drives in the 5 years since the publication of the eighth edition of *Pounder's Marine Diesel Engines* call for another update.

This ninth edition reflects the generic and specific advances made by marine engine designers and specialists in support technologies—notably turbocharging, fuel treatment, emissions reduction and automation systems—which are driven by: ship designer demands for more compactness and lower weight; ship-owner demands for higher reliability, serviceability and overall operational economy; and shipbuilder demands for lower costs and easier installation procedures.

A historical perspective logs the nautical milestones over the first century of marine diesel technology, which closed with the emergence of electronically controlled low-speed designs paving the path for future so-called 'Intelligent Engines'. Development progress with these designs and operating experience with the escalating number in service are reported in this new edition.

Since the last edition, increasing interest in dual-fuel (DF) and gas engines for marine and offshore industry applications is reflected in an expanded chapter. The specification of DF medium-speed diesel machinery for LNG carrier new-building projects in 2002 marked the ousting of steam turbine propulsion from its last bastion in commercial shipping. A growing number of these DF–electric installations are now entering service, alongside direct-coupled low-speed engine-powered LNG carriers equipped with boil-off gas reliquefaction plant.

Controls on exhaust gas emissions—particularly nitrogen oxides, sulphur oxides and smoke—continue to tighten regionally and internationally, dictating further responses from engine designers exploiting common rail fuel systems, emulsified fuel, direct water injection and charge air humidification. These and other solutions, including selective catalytic reduction and exhaust gas recirculation systems, are detailed in an extended chapter.

Also extended is the chapter on fuels, lube oils and the problems of contamination, which includes information on low sulphur fuels, new cylinder and system lubricants, and cylinder oil-feed system developments.

Marine gas turbines, specified for some cruise ship and fast ferry propulsion projects from the late 1990s, have seen their competitiveness undermined by rising fuel prices in recent years. The relevant chapter, introduced in the last edition, has been revised to cover design refinements and significant installations.

The traditional core of this book—reviews of the current programmes of the leading low-, medium- and high-speed engine designers—has been thoroughly updated. Details of all new designs and major modifications to established models

introduced since the last edition are provided, along with service experience with the most popular designs. Technically important engines no longer in production but still encountered at sea justify their continued coverage.

In preparing the new edition the author expresses again his gratitude for the groundwork laid by the late C.C. Pounder and to the editors of the sixth edition, his late friend and colleague Chris Wilbur and Don Wight (whose contributions are respectively acknowledged at the end of sections or chapters by C.T.W. and D.A.W.).

In an industry generous for imparting information on new developments and facilitating visits, special thanks are again due to MAN Diesel, Wärtsilä Corporation, Caterpillar Marine Power Systems, ABB Turbo Systems, the major classification societies, and the leading marine lube oil groups. Thanks again also to my wife Shelley Woodyard for her support and assistance in this project.

Finally, the author hopes that this edition, like its predecessors, will continue to provide a useful reference for marine engineers ashore and at sea, enginebuilders and ship operators.

Doug Woodyard

Introduction: A Century of Diesel Progress

Close to a century after the entry into service of *Selandia*, generally regarded as the world's first oceangoing motor vessel, the diesel engine enjoys almost total dominance in merchant ship propulsion markets. Mainstream sectors have long been surrendered by the steam turbine, ousted by low- and medium-speed engines from large container ships, bulk carriers, VLCCs and cruise liners. Even steam's last remaining bastion in the newbuilding lists—the LNG carrier—has been breached by dual-fuel medium-speed diesel engine designs arranged to burn the cargo boil-off gas as well as by direct-coupled low-speed diesel engines.

The remorseless rise of the diesel engine at the expense of steam reciprocating and turbine installations was symbolized in 1987 by the steam-to-diesel conversion of Cunard's prestigious cruise liner *Queen Elizabeth 2*. Her turbine and boiler rooms were ignominiously gutted to allow the installation of a 95 600 kW diesel–electric plant.

The revitalized *QE2*'s propulsion plant was based on nine 9-cylinder L58/64 medium-speed four-stroke engines from MAN B&W Diesel which provided a link with the pioneering *Selandia*: the 1912-built twin-screw 7400 dwt cargo/passenger ship was powered by two Burmeister & Wain eight-cylinder four-stroke engines (530 mm bore/ 730 mm stroke), each developing 920 kW at 140 rev/min. An important feature was the effective and reliable direct-reversing system.

Progress in raising specific output over the intervening 70 years was underlined by the 580 mm bore/640 mm stroke design specified for the *QE2* retrofit: each cylinder has a maximum continuous rating of 1213 kW.

Selandia was built by the Burmeister & Wain yard in Copenhagen for Denmark's East Asiatic Company and, after trials in February 1912, successfully completed a 20 000 mile round voyage between the Danish capital and the Far East (Figure I.1). The significance of the propulsion plant was well appreciated at the time. On her first arrival in London, the ship was inspected by Sir Winston Churchill, then First Lord of the Admiralty; and *Fiona*, a sister ship delivered four months later by the same yard, so impressed the German Emperor that it was immediately arranged for the Hamburg Amerika Line to buy her.

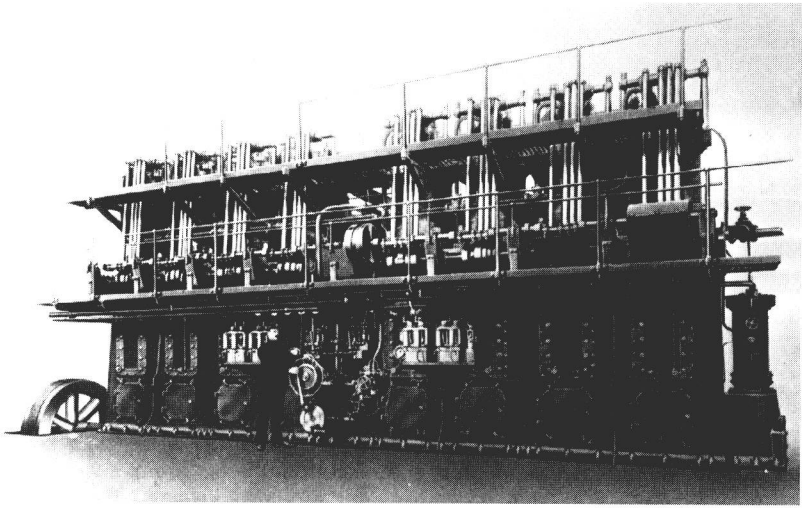


FIGURE I.1 One of two Burmeister & Wain DM8150X engines commissioned (1912) to power the first *Selandia* (MAN B&W Diesel)

A third vessel in the series, *Jutlandia*, was built by Barclay, Curle, in Scotland and handed over to East Asiatic in May 1912. The Danish company's ocean-going motor ship fleet numbered 16 by 1920, the largest being the 13 275 dwt *Afrika* with twin six-cylinder B&W engines of 740 mm bore/1150 mm stroke developing a combined 3300 kW at 115 rev/min. Early steam-to-diesel conversions included three 4950 dwt vessels built in 1909 and repowered in 1914/1915 by the B&W Oil Engine Co. of Glasgow, each with a single six-cylinder 676 mm bore/1000 mm stroke engine developing 865 kW at 110 rev/min.

Selandia operated successfully for almost 30 years (latterly as *Norseman*) and maintained throughout a fully loaded service speed of 10.5 knots before being lost off Japan in 1942. The propulsion plant of the second *Selandia*, which entered service in 1938, demonstrated the advances made in diesel technology since the pioneering installation. The single, double-acting two-stroke, five-cylinder engine of the 8300 dwt vessel delivered 5370 kW at 120 rev/min: three times the output of the twin-engined machinery powering the predecessor.

The performance of *Selandia* and other early motor ships stimulated East Asiatic to switch completely from steamers, an example followed by more and more owners. In 1914 there were fewer than 300 diesel-powered vessels in service with an aggregate tonnage of 235 000 grt; a decade later the fleet had grown to some 2000 ships of almost two million gross register tonnage; and by 1940 the total tonnage had risen to 18 million gross register tonnage embracing 8000 motor ships (Figure I.2).

Between the two world wars the proportion of oil-engined tonnage in service thus expanded from 1.3 per cent to 25 per cent of the overall ocean-going fleet. By 1939 an estimated 60 per cent of the total tonnage completed in

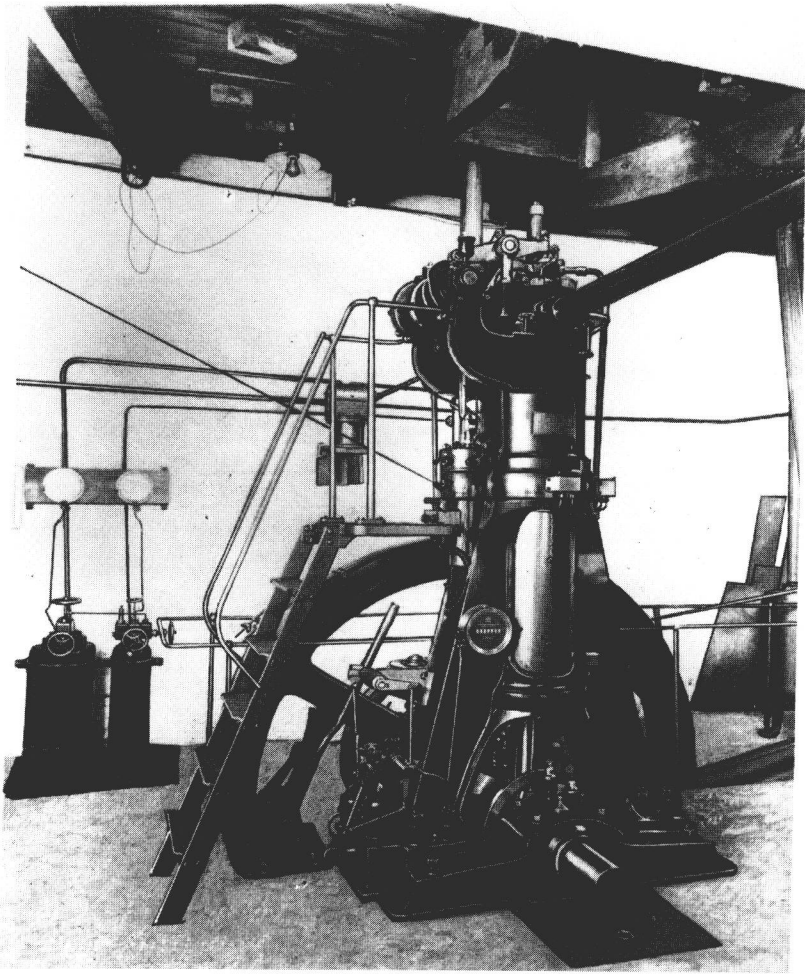


FIGURE I.2 A 20 bhp engine built in 1898 by Burmeister & Wain to drawings supplied by Dr Diesel, for experimental and demonstration purposes. MAN built the first diesel engine—a 250 mm bore/400 mm stroke design—in 1893

world yards comprised motor ships, compared with only 4 per cent in 1920 (Figure I.3).

In outlining the foundations of the diesel engine's present dominance in shipping other claimants to pioneering fame should be mentioned. In 1903 two diesel-powered vessels entered service in quick succession: the Russian naphtha carrier *Vandal*, which was deployed on the Volga, and the French canal boat *Petit Pierre*. By the end of 1910 there were 34 trading vessels over 30 m long worldwide with diesel propulsion, and an unknown number of naval vessels, especially submarines.

The earliest seagoing motor vessel was the twin-screw 678 ton *Romagna*, built in 1910 by Cantieri Navali Riuniti with twin four-cylinder port-scavenged

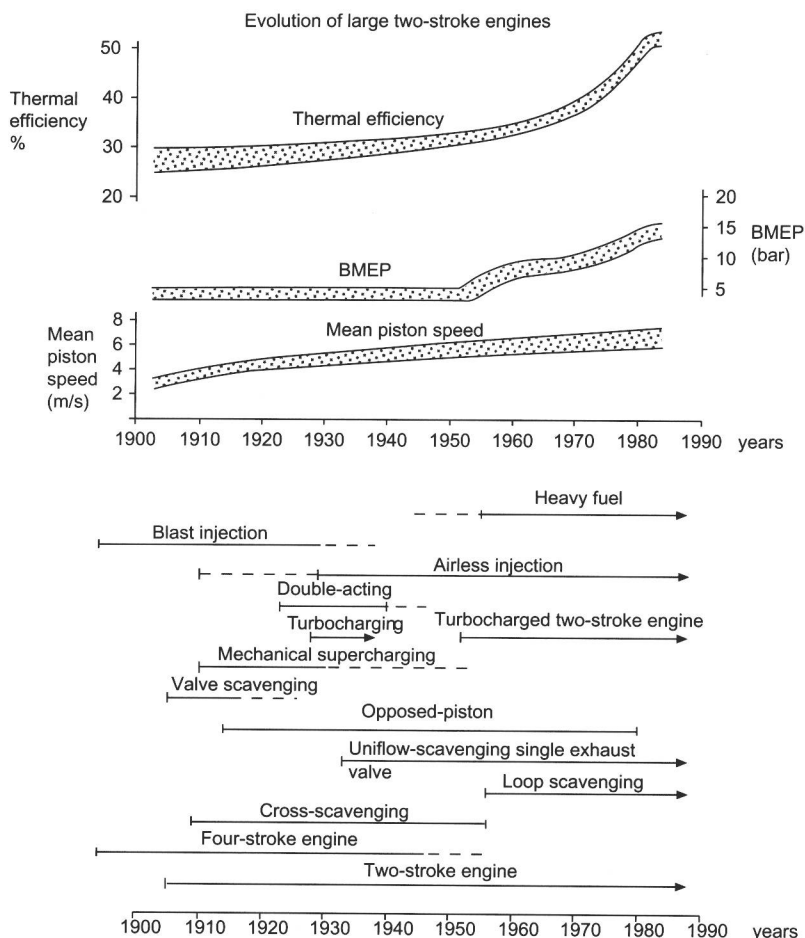


FIGURE I.3 Main lines of development for direct-drive low-speed engines

trunk piston engines supplied by Sulzer. Each 310 mm bore/460 mm stroke engine delivered 280 kW at 250 rev/min.

The year 1910 also saw the single-screw 1179 dwt Anglo-Saxon tanker *Vulcanus* enter service powered by a 370 kW Werkspoor six-cylinder four-stroke crosshead engine with a 400 mm bore/600 mm stroke. The Dutch-built vessel was reportedly the first oceangoing motor ship to receive classification from Lloyd's Register.

In 1911 the Swan Hunter-built 2600 dwt Great Lakes vessel *Toiler* crossed the Atlantic with propulsion by two 132 kW Swedish Polar engines. Krupp's first marine diesel engines, six-cylinder 450 mm bore/800 mm stroke units developing 920 kW at 140 rev/min apiece, were installed the same year in the twin-screw 8000 dwt tankers *Hagen* and *Loki* built for the German subsidiary of the Standard Oil Co. of New Jersey.

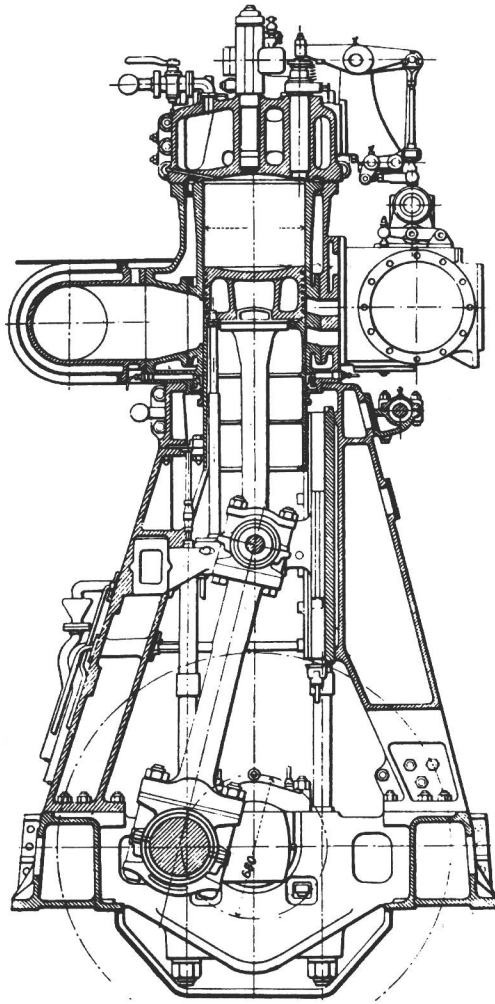


FIGURE I.4 Twin Sulzer 4S47 type cross-flow scavenged crosshead engines served the *Monte Penedo*, the first large oceangoing vessel powered by two-stroke engines (1912). Four long tie-rods secured each cylinder head directly to the bedplate, holding the whole cast iron engine structure in compression

The following year, a few months after *Selandia*, Hamburg-South Amerika Line's 6500 dwt cargo/passenger ship *Monte Penedo* entered service as the first large oceangoing vessel powered by two-stroke diesel engines. Each of the twin four-cylinder Sulzer 4S47 crosshead units (470 mm bore/680 mm stroke) delivered 625 kW at 160 rev/min (Figures I.4–I.6).

(The adoption of the two-stroke cycle by Sulzer in 1905 greatly increased power output and fostered a more simple engine. Port-scavenging, introduced in 1910, eliminated the gas exchange valves in the cylinder cover to create a simple valveless concept that characterized the Sulzer two-stroke engine for 70 years: the

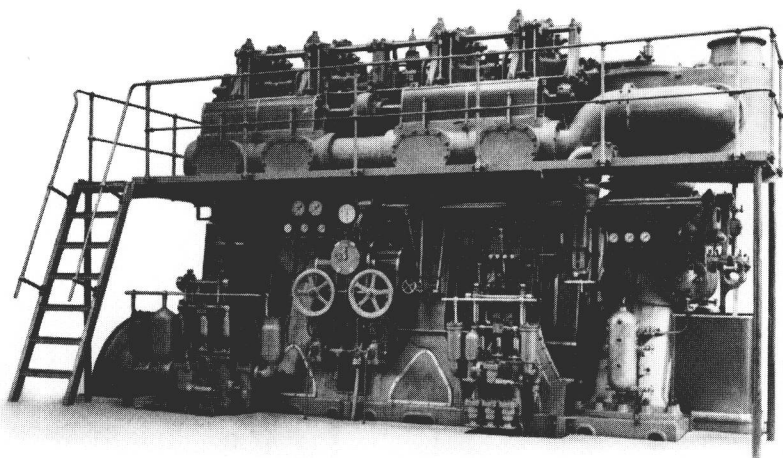


FIGURE I.5 One of the two Sulzer 4547 engines installed in the *Monte Penedo* (1912)

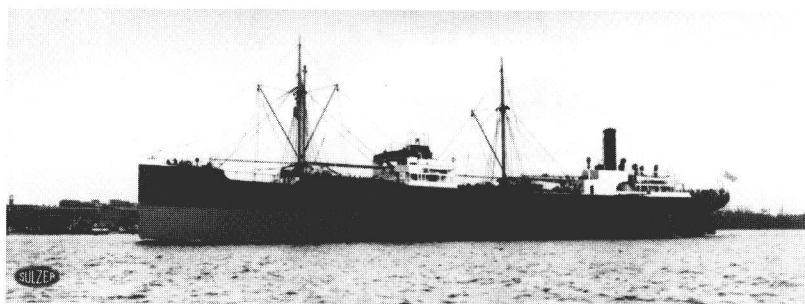


FIGURE I.6 The 6500 dwt cargo liner *Monte Penedo* (1912)

change to uniflow scavenging only came with the RTA-series engines of 1982 because their very long stroke—required for the lower speeds dictated for high propeller efficiency—was unsuitable for valveless port scavenging.)

Another important delivery in 1912 was the 3150 dwt Furness Withy cargo ship *Eavestone*, powered by a single four-cylinder Carels two-stroke cross-head engine with a rating of 590 kW at 95 rev/min. The 508 mm bore/914 mm stroke design was built in England under licence by Richardsons Westgarth of Middlesbrough.

There were, inevitably, some failures among the pioneers. For example, a pair of Junkers opposed-piston two-stroke engines installed in a 6000 dwt Hamburg-Amerika Line cargo ship was replaced by triple-expansion steam engines even before the vessel was delivered. The Junkers engines were of an unusual vertical tandem design, effectively double-acting, with three pairs of cylinders of 400 mm bore and 800 mm combined stroke to yield 735 kW at 120 rev/min. More successful was Hapag's second motor ship, *Secundus*,

delivered in 1914 with twin Blohm + Voss-MAN four-cylinder two-stroke single-acting engines, each developing 990 kW at 120 rev/min.

After the First World War diesel engines were specified for increasingly powerful cargo ship installations and a breakthrough made in large passenger vessels. The first geared motor ships appeared in 1921, and in the following year the Union Steamship Co. of New Zealand ordered a 17 490 grt quadruple-screw liner from the UK's Fairfield yard. The four Sulzer six-cylinder ST70 two-stroke single-acting engines (700 mm bore/990 mm stroke) developed a total of 9560 kW at 127 rev/min—far higher than any contemporary motor ship—and gave *Aorangi* a speed of 18 knots when she entered service in December 1924.

Positive experience with these engines and those in other contemporary motor ships helped to dispel the remaining prejudices against using diesel propulsion in large vessels.

Swedish America Line's 18 134 grt *Gripsholm*—the first transatlantic diesel passenger liner—was delivered in 1925; an output of 9930 kW was yielded by a pair of B&W six-cylinder four-stroke double-acting 840 mm bore engines (Figure I.7). Soon after, the Union Castle Line ordered the first of its large fleet of motor passenger liners, headed by the 20 000 grt *Caernarvon Castle* powered by 11 000 kW Harland & Wolff-B&W double-acting four-stroke machinery.

Another power milestone was logged in 1925 when the 30 000 grt liner *Augustus* was specified with a 20 600 kW propulsion plant based on four MAN six-cylinder double-acting two-stroke engines of 700 mm bore/1200 mm stroke.

It was now that the double-acting two-stroke engine began to make headway against the single-acting four-stroke design, which had enjoyed favour up to 1930. Two-stroke designs in single- and double-acting forms, more suitable for higher outputs, took a strong lead as ships became larger and faster. Bigger bore sizes and an increased number of cylinders were exploited. The 20 000 grt *Oranje*, built in 1939, remained the most powerful merchant motor ship for many years thanks to her three 12-cylinder Sulzer 760 mm bore SDT76 single-acting engines aggregating 27 600 kW.

The groundwork for large bore engines was laid early on. Sulzer, for example, in 1912 tested a single-cylinder experimental engine with a 1000 mm bore/1100 mm stroke (Figure I.8). This two-stroke crosshead type 1S100 design developed up to 1470 kW at 150 rev/min and confirmed the effectiveness of Sulzer's valveless cross-scavenging system, paving the way for a range of engines with bores varying between 600 mm and 820 mm. (Its bore size was not exceeded by another Sulzer engine until 1968.)

At the end of the 1920s the largest engines were Sulzer five-cylinder 900 mm bore models (3420 kW at 80 rev/min) built under licence by John Brown in the UK. These S90 engines were specified for three twin-screw *Rangitiki*-class vessels of 1929.

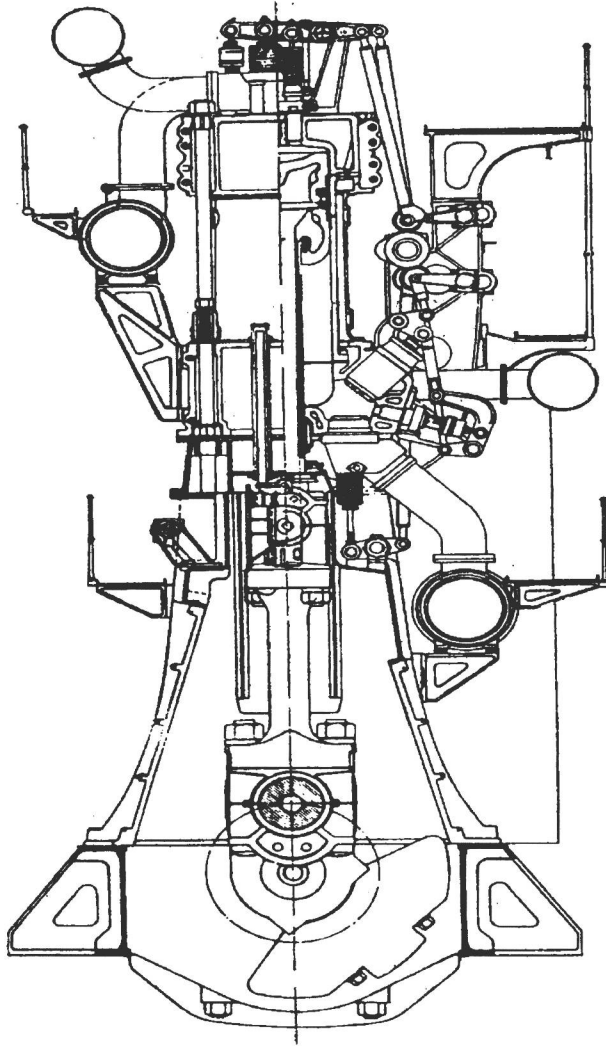


FIGURE I.7 A B&W 840-D four-stroke double-acting engine powered Swedish America Line's *Gripsholm* in 1925

GOODBYE TO BLAST INJECTION

It was towards the end of the 1920s that most designers concluded that the blast air–fuel injection diesel engine—with its need for large, often troublesome and energy-consuming high-pressure compressors—should be displaced by the airless (or compressor-less) type.

Air-blast fuel injection called for compressed air from a pressure bottle to entrain the fuel and introduce it in a finely atomized state via a valve needle into the combustion chamber. The air-blast pressure, which was only just slightly above the ignition pressure in the cylinder, was produced by a water-cooled compressor driven off the engine connecting rod by means of a rocking lever.

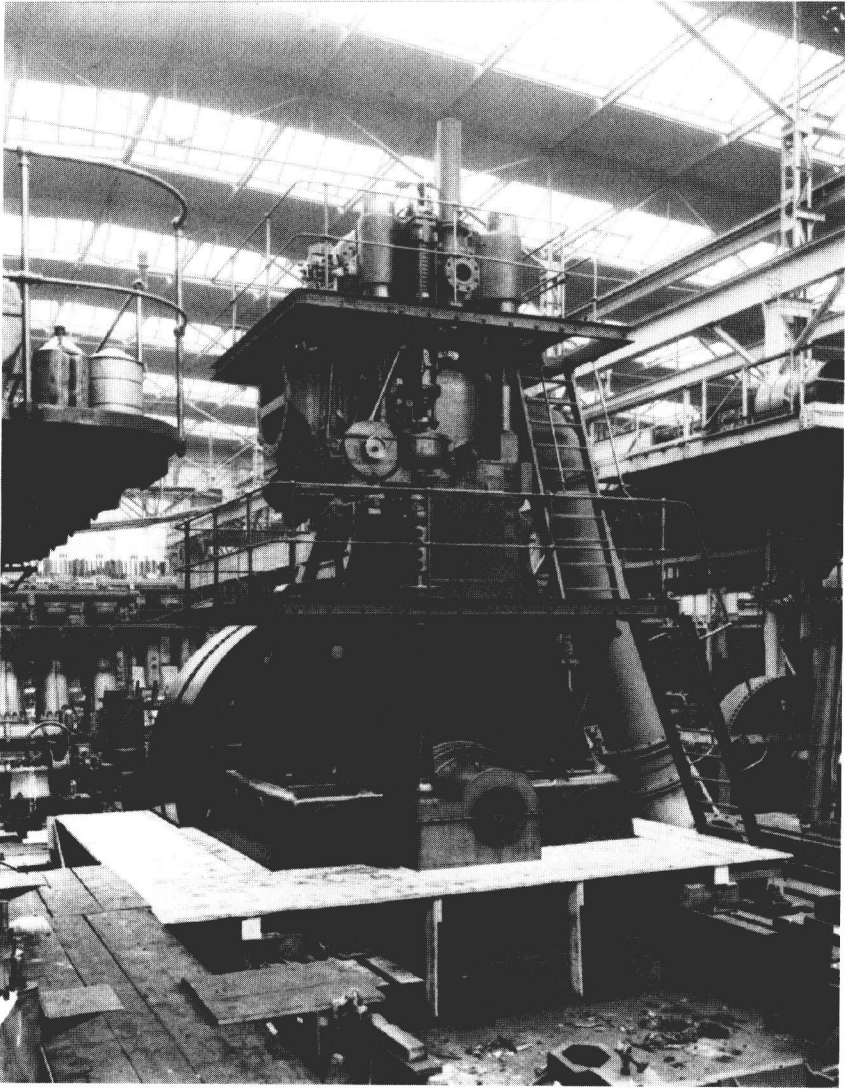


FIGURE I.8 Sulzer's 15100 single-cylinder experimental two-stroke engine (1912) featured a 1000 mm bore

Rudolf Diesel himself was never quite satisfied with this concept (which he called self-blast injection) since it was complicated and hence susceptible to failure—and also because the ‘air pump’ tapped as much as 15 per cent of the engine output.

Diesel had filed a patent as early as 1905 covering a concept for the solid injection of fuel, with a delivery pressure of several hundred atmospheres. A key feature was the conjoining of pump and nozzle and their shared accommodation in the cylinder head. One reason advanced for the lack of follow-up was that few of the many engine licensees showed any interest.

A renewed thrust came in 1910 when Vickers' technical director McKechnie (independently of Diesel, and six months after a similar patent from Deutz in Germany) proposed in an English patent an 'accumulator system for airless direct fuel injection' at pressures between 140bar and 420bar. By 1915 he had developed and tested an 'operational' diesel engine with direct injection, and is thus regarded as the main inventor of high-intensity direct fuel injection. Eight years later it had become possible to manufacture reliable production injection pumps for high pressures, considerably expanding the range of applications (Figure I.9).

The required replacement fuel injection technology thus had its roots in the pioneering days (a Doxford experimental engine was converted to airless fuel

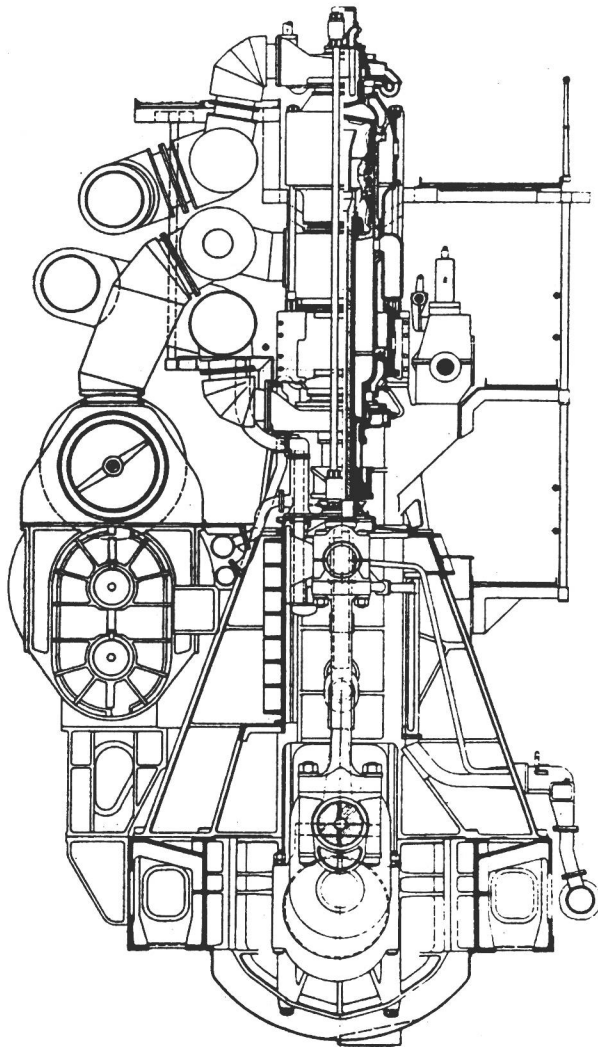


FIGURE I.9 A B&W 662-WF/40 two-stroke double-acting engine, first installed as a six-cylinder model in the *Amerika* (1929)

injection in 1911) but suitable materials and manufacturing techniques had to be evolved for the highly stressed camshaft drives and pump and injector components. The refinement of direct fuel injection systems was also significant for the development of smaller high-speed diesel engines.

A BOOST FROM TURBOCHARGING

A major boost to engine output and reductions in size and weight resulted from the adoption of turbochargers. Pressure charging by various methods was applied by most enginebuilders in the 1920s and 1930s to ensure an adequate scavenge air supply: crankshaft-driven reciprocating air pumps, side-mounted pumps driven by levers off the crossheads, attached Roots-type blowers or independently driven pumps and blowers. The pumping effect from the piston underside was also used for pressure charging in some designs.

The Swiss engineer Alfred Büchi, considered the inventor of exhaust gas turbocharging, was granted a patent in 1905 and undertook his initial turbocharging experiments at Sulzer Brothers in 1911/1915. It was almost 50 years after that first patent, however, before the principle could be applied satisfactorily to large marine two-stroke engines.

The first turbocharged marine engines were 10-cylinder Vulcan-MAN four-stroke single-acting models in the twin-screw *Preussen* and *Hansestadt Danzig*, commissioned in 1927. Turbocharging under a constant pressure system by Brown Boveri turboblowers increased the output of these 540 mm bore/600 mm stroke engines from 1250 kW at 240 rev/min to 1765 kW continuously at 275 rev/min, with a maximum of 2960 kW at 317 rev/min. Büchi turbocharging was keenly exploited by large four-stroke engine designers, and in 1929 some 79 engines totalling 162 000 kW were in service or contracted with the system.

In 1950/1951 MAN was the forerunner in testing and introducing high-pressure turbocharging for medium-speed four-stroke engines for which boost pressures of 2.3 bar were demanded and attained.

Progressive advances in the efficiency of turbochargers and systems development made it possible by the mid-1950s for the major two-stroke enginebuilders to introduce turbocharged designs.

A more recent contribution of turbochargers, with overall efficiencies now topping 70 per cent, is to allow some exhaust gas to be diverted to a power recovery turbine and supplement the main engine effort or drive a generator. A range of modern power gas turbines is available to enhance the competitiveness of two-stroke and larger four-stroke engines, yielding reductions in fuel consumption or increased power.

HEAVY FUEL OILS

Another important step in strengthening the status of the diesel engine in marine propulsion was R&D enabling it to burn cheaper, heavier fuel oils. Progress was spurred in the mid-1950s by the availability of cylinder lubricants able to neutralize acid combustion products and hence reduce wear rates to