## Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>3</td>
</tr>
<tr>
<td>Preface</td>
<td>3</td>
</tr>
<tr>
<td>The Diesels and their Competitors</td>
<td>4</td>
</tr>
<tr>
<td>Diesel Engines in Stationary Applications</td>
<td>5</td>
</tr>
<tr>
<td>Load Flexibility</td>
<td>6</td>
</tr>
<tr>
<td>Fuel Linkage</td>
<td>6</td>
</tr>
<tr>
<td>Fuel Flexibility</td>
<td>8</td>
</tr>
<tr>
<td>Emissions</td>
<td>9</td>
</tr>
<tr>
<td>Two-stroke Engine Driven Plants</td>
<td>9</td>
</tr>
<tr>
<td>The Bahamas Project</td>
<td>10</td>
</tr>
<tr>
<td>Conclusion</td>
<td>12</td>
</tr>
<tr>
<td>Literature</td>
<td>12</td>
</tr>
</tbody>
</table>
Abstract

During recent years, an increasing demand has been experienced in the stationary diesel engine market for large diesel units for reliable and fuel efficient power plants in the range of 30-250 MW, based on cost effective refinery residuals.

This demand is being met by modern marine-derivative medium speed diesel GenSets and, for the larger units, by two-stroke low speed crosshead uniflow scavenged diesel engines, the latter capable of burning almost any fuel available on the market, whether liquid or gaseous.

This paper will deal with service experience gained from two-stroke low speed diesel engines and their fuel capability, as well as describe the latest 30 MW extension of the Clifton Pier plant on the Bahamas, owned by the Bahamas Electricity Corporation (BEC).

Preface

Diesel engines for power generation from MAN B&W Diesel are offered in the following categories, see Fig. 1:

- High speed and medium speed engines, ranging from 0.5 to 22 MW per unit, from MAN B&W Diesel’s companies in Germany, Denmark, France and the UK.

- Two-stroke MC engines from MAN B&W Diesel, Copenhagen, Denmark. These are low speed engines with unit outputs of up to 68 MW. The engines are built by MAN B&W licensees as listed in Fig. 2.

Fig. 2: MAN B&W two-stroke licensee family
The low speed two-stroke engines match any requirements of medium to large size projects, whether for island utilities or large IPP or captive plants, up to say 250-300 MW, Fig. 3.

Guam, Enron units D8 D9
Availability % 96.3 95.1
Reliability % 99.0 97.6
Scheduled outage hrs. 234 217
Unscheduled outage hrs. 84 207
Load factor % 82 83

Low speed engines are particularly suited to digest any fuels with high efficiency and good reliability. Engineers are well acquainted with the technology through wide experience from the world merchant fleet, which is dominated by MAN B&W low speed two-stroke engines.

The Diesels and their Competitors

Looking at the prime mover options available to the end-user today, and comparing their efficiencies, we can see that in the relevant range, say 12-68 MW per unit, Fig. 4, the two-stroke diesel engine is unrivalled as the most fuel efficient prime mover, whether compared with medium speed engines, steam turbines or single-cycle or combined cycle gas turbines.

Fig. 4: Power efficiency comparison at ISO 3046
Diesel Engines in Stationary Applications

The MAN B&W Diesel engines are always matched to the actual climatic conditions of the site, with due allowance for seasonal variations. With demanding site conditions, medium speed engines sometimes call for slight derating, whereas this is not required for low speed diesels in which an acceptable combustion chamber heat load is maintained by modification of the heat rate of the engine.

A comparison of deratings, as a function of ambient conditions for the various combustion engines on the market, is shown in Fig. 5, revealing the insensitivity of the low speed diesel engines to ambient conditions, when compared with other internal combustion machines. When one is comparing the various prime movers, differences in the various ISO standards should be considered, Fig. 6.

---

**Fig. 5: Influence of ambient conditions on rating of internal combustion engines**

<table>
<thead>
<tr>
<th>Air temperature °C</th>
<th>Gas turbines ISO 3977</th>
<th>Diesel engines ISO 3046</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coolant temperature °C</td>
<td>15</td>
<td>25</td>
</tr>
<tr>
<td>Barometric pressure mbar</td>
<td>1013</td>
<td>1000</td>
</tr>
<tr>
<td>Relative humidity %</td>
<td>60</td>
<td>60</td>
</tr>
</tbody>
</table>

*) If applicable

**Fig. 6: Comparison of ISO conditions**
Load Flexibility

To cater for load variation in plants, say up to 300 MW, it is quite common to install a number of equally-sized units. The load fluctuations called for by users are then managed by sequential starting and stopping of the units.

This configuration and running principle is very often seen with the traditional gas turbines, because of their poor part-load efficiency behaviour.

As shown in Fig. 7, the efficiency of diesel engines, and especially of two-stroke low speed diesels, is almost independent of load over a wide load range. Furthermore, low load running without any limitation is possible down to approx. 20% of Maximum Continuous Rating (MCR), and the engines are able to run at 10% overload for one hour every 12 consecutive hours. It is therefore fully feasible to install the largest two-stroke diesel units applicable, i.e. as few units as possible for a given plant size, thereby shortening plant construction time, reducing the space requirement, as well as reducing first cost, running cost and maintenance load, while still ensuring high efficiency and reliability, irrespective of the plant running programme.

Fuel Linkage

As most diesel plants are installed in areas which depend on liquid fuels with scarce and unstable supplies of high quality fuels, it is of paramount importance for the feasibility of a project that the acceptable range in the guideline fuel oil specifications of the various prime movers is considered at a very early stage. Fig. 8 shows the difference in fuels that can be used in gas turbines and diesel engines in general.

Essentially, diesel engine combustion comprises a series of batch processes, whereas the gas turbine uses continuous combustion. In the batch process, higher initial temperatures and pressures can be used than in the gas turbine, since the exposed components are cooled at the end of each process and between processes. The thermal

---

**Fig. 7: Typical part load efficiencies of prime movers**

<table>
<thead>
<tr>
<th>Designation</th>
<th>Diesel engines CIMAC-H55</th>
<th>Gas turbines ASTM 2880</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density at 15 °C</td>
<td>1010</td>
<td>876</td>
</tr>
<tr>
<td>Kinematic viscosity at 100 °C</td>
<td>55</td>
<td>50</td>
</tr>
<tr>
<td>Flash point °C</td>
<td>≥ 60</td>
<td>66</td>
</tr>
<tr>
<td>Carbon residue % (mm)</td>
<td>22</td>
<td>0.35 ***</td>
</tr>
<tr>
<td>Ash % (mm)</td>
<td>0.15</td>
<td>0.03</td>
</tr>
<tr>
<td>Water % (mm)</td>
<td>1.0</td>
<td>1.0 **</td>
</tr>
<tr>
<td>Sulphur % (mm)</td>
<td>5.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Vanadium ppm (mm)</td>
<td>600</td>
<td>0.5-2</td>
</tr>
<tr>
<td>Aluminium + Silicon mg/kg</td>
<td>80</td>
<td>(10)</td>
</tr>
<tr>
<td>API gravity (min)</td>
<td>* API</td>
<td>35</td>
</tr>
<tr>
<td>Sodium plus potassium ppm (mm)</td>
<td>200</td>
<td>1</td>
</tr>
<tr>
<td>Calcium ppm (mm)</td>
<td>200</td>
<td>1</td>
</tr>
<tr>
<td>Lead ppm (mm)</td>
<td>10</td>
<td>1</td>
</tr>
</tbody>
</table>

* experience, no limitations in official specification  
** Incl. sediment  
*** on 10% destillation

**Fig. 8: Diesel engine and gas turbine liquid fuel guideline specification**
efficiency can therefore be higher in the diesel than in the gas turbine. Each piston stroke constitutes a batch process, and the slower it can be while still maintaining its adiabatic thermodynamics, the more efficient it can be.

An added advantage of the slow process that takes place in a low speed engine is that the ignition delay which may occur, depending on fuel quality and engine geometry, has less impact on a low speed engine.

While a low speed engine often gives a longer ignition delay than its medium speed counterpart with the same fuel, the ignition delay is still proportionally shorter in a low speed engine, in terms of degrees crankshaft angle.

Fig. 9: Fuel acceptance

As illustrated in Fig. 9, the typical fuel injection period in terms of milliseconds is 3-4 times longer in a low speed engine, i.e. up to 35 msec. Typical ignition periods are up to 10 msec in a medium speed engine and up to 20 msec in a low speed engine.

Hence, in a worst-case situation using a fuel with a tendency towards long ignition delay, all the fuel for a stroke may have been injected in a medium speed engine before ignition takes place. Ignition can then take the form of a detonation which harms the piston, piston rings and bearings. In the low speed engine, even with a long ignition delay, less fuel is injected before ignition. Thus, the risk of detrimental detonation is over.

This is one of the reasons why a low speed engine is considered more forgiving than other types of machinery when low-quality, low-cost fuels are used, as outlined later.

Fig. 10: Examples of liquid fuels burned in MAN B&W two-stroke low speed diesel engines
Fuel Flexibility

Most power plants built today are based on the use of one or two fuels. Such fuels are typically natural gas or light fuels for gas turbines, coal or heavy fuel for steam turbines, and diesel oil, heavy fuel oil or natural gas for diesel engines.

The two-stroke low speed diesel engines of MAN B&W design are able to run on virtually any commercially available liquid or gaseous fuel.

Fig. 8 shows a typical guideline fuel oil specification of today for such engines. The basic data are dictated by the logistics of the marine market, which require that the fuel can be transported to the ship. This requirement, in principle, does not apply to stationary plants which can be placed close to the source of energy and connected to it by a pipe that is heated by waste heat from the engine.

Various types of refinery waste can thus be used in low speed diesels.

Such fuel oil specifications are normally quoted by the majority of diesel engine designers on the market, regardless of the number of strokes. Nevertheless, in this connection it should be noted that most medium speed designers specify a max. design temperature of HFO at injection in the range of 130-150 °C, resulting in a max. fuel viscosity of 700 cSt at 50 °C.

For the two-stroke engines of MAN B&W design, the max. design temperature of the fuel preheating is 250 °C, corresponding to a specific fuel viscosity of approx. 70,000 cSt at 50 °C, i.e. a factor of 100 in admissible fuel viscosity.

Fig. 10 shows examples of liquid fuels burnt or tested successfully in MAN B&W two-stroke low speed diesels, while Fig. 11 shows similar data for gaseous fuels.

Fig. 12 shows the fuel flexibility of the MAN B&W MC-GI-S type high-pressure gas injection, dual fuel, two-stroke engines, which are able to burn both liquid and gaseous fuel in almost any ratio without influencing their power rating or efficiency.
Emissions
In response to the increasing demand for environmental protection, the two-stroke low speed diesels can be delivered with internal and external controls to comply with virtually any emission restriction requirements, including the 1998 World Bank Guideline for diesel-driven plants.

Two-stroke Engine Driven Plants
An example of a 40 MW medium-load high-injection pressure two-stroke crosshead diesel engine plant is the Chiba plant in Tokyo (Fig. 13). This plant is based on a 12K80MC-S engine, developing 40 MW at 102.9 rpm at an ISO efficiency of 49.3%. The plant is equipped with extensive SCR control of NOx emission in order to fulfil the local NOx limit of 13 mg/Nm³.

Main particulars
Prime mover: MAN B&W 12K80MC-GI-S
Dual fuel high-pressure gas injection engine
MCR: 40 MW
Engine speed: 103.4 r/min
Main effective pressure: 17 bar
Cylinder bore: 800 mm
Stroke: 2300 mm
Number of cylinders: 12
Fuels: Main fuel: LNG
Pilot fuel: Low-sulphur diesel oil
Gas compressor: Thomassen recipro. four-stage
Pressure: Suction: 4.5 bar
Delivery: 300 bar
Generator: Meidensha
Output: 40,000 kW
Voltage: 3.2 kV
Frequency: 50 Hz
De-NOx: Ammonia SCR
NOx limit: 13 mg/Nm³

Main data 1994-1999
Average reliability: 97%
Average availability: 97%
Average load factor: 71%
Average efficiency, gross: 46.1%
Average efficiency, net: 42.6%

Fig. 13: 40 MW Chiba plant in Japan
The Bahamas Project

At the beginning of the seventies, four 10 MW two-stroke units were installed at the Clifton Pier power plant by Bahamas Electricity Corporation.

In 1992 the plant was extended with two 9K80MC-S engines (units DA 9 and DA 10), built by MAN B&W Diesel’s Japanese licensee Mitsui Engineering & Shipbuilding Co. Ltd and supplied by Burmeister & Wain Scandinavian Contractor A/S, Mitsui’s contracting division.

In November 1996 after an extensive international call for tenders, Bahamas Electricity Corporation, decided to extend the plant with a new 30 MW unit, Figs. 14 and 15.

The prime mover selected was an MAN B&W type 10K80MC-S diesel engine, developing 33.5 MW at 102.9 r/min at an ISO efficiency of 49%. The engine was built by Manises Diesel Engine Company S.A., Spain, and the plant order was awarded to a group of companies led by Alstom Power S.A., Madrid, Spain (Fig. 16).

The project was financed by the Inter-American Development Bank and the European Investment Bank.

The new plant, called unit DA 11, was successfully commissioned and handed over to the owner, Bahamas Electricity Corporation, in October 1999.

The plant is equipped with a large exhaust gas boiler, utilising the exhaust gas waste heat energy down to some 180 °C. The energy is utilised for the production of 10-bar steam, partly used for heating the fuel oil, and mainly

Fig. 15: Bahamas, single-line diagram
for the production of drinking water, which is being supplied to the local municipality (Fig. 17).

The main data of the engine and Alstom generator are shown in Fig. 18.

During commissioning, extensive measurements were taken of all guaranteed plant values, and fulfillment has been ascertained, ref. Fig. 19, comparing the guaranteed and the actually obtained data.

Of course, no plant of such size has been commissioned without teething troubles. In connection with the engine itself, tear of compensators between turbocharger and air cooler was experienced, as well as repeated accelerated wear on two out of ten cylinders. The difficulties have been investigated in detail, resulting in realignment of the compensators and the introduction of the latest development of ceramic-coated piston rings. Since these modifications were carried out, the engine has been running without any unplanned stoppage.
From its commissioning in October 1999 until 31 December 2000, the engine has accumulated 9500 running hours, and a total of 280 hours have been spent on scheduled and unscheduled maintenance, resulting in a total plant availability of 90% in the period.

In February 2001, BEC awarded an order for an identical diesel generator unit to the same group of companies for delivery in 2002.

**Conclusion**

As shown, the two-stroke low speed diesels of MAN B&W design are a viable option to be investigated and chosen by owners anywhere where reliable, fuel-efficient diesel plants are required, especially if the fuel is of a poor quality and available in scarce amounts.

The future development of such engines will be dictated by the market, in particular by the future fuel oil prices and qualities, and the trend seems to point in the direction of even more efficient and ever larger units.

**Literature**
