Efficiency of MAN B&W two-stroke engines

MAN Energy Solutions
Future in the making

Stationary application
Future in the making

Contents

Definitions 05
Measuring heating values 06
Engine and generator heat rates and efficiency 07
Power consumption in auxiliary systems 09
Thermal efficiency 10
Engine control 12
Installation planning 12
References 13
Abbreviations (Definitions) 13
The purpose of this paper is to describe various terms used in connection with the installation of MAN B&W two-stroke low-speed diesel engines for stationary application, as there are differences compared to engines installed in vessels.

**Definitions**

MAN B&W two-stroke low-speed diesel engines are designed to provide optimum fuel flexibility and are an ideal source of power, whether operating on gas, liquid fuel or liquid bio fuel. Liquid fuels are HFO, diesel, some types of crude biofuel and crude oil. Gaseous fuels are natural gas and ethane. Liquid gas fuels are LPG, DME, methanol and ethanol.

**Engine heat rate**

The data specified in the "MAN B&W Stationary Engine Programme" refers to mechanical output under ISO 3046/1-2002 ambient conditions, which are:
- Compressor inlet temperature 25°C
- Compressor inlet pressure 1000 mbar
- Charge-air inlet coolant temperature 25°C

For other ambient conditions please contact MAN Energy Solutions in Copenhagen.

**Fuel consumption**

The engine heat rate informed by MAN Energy Solutions is subject to a tolerance of ±5% at MCR under ISO 3046/1-2002 ambient conditions. For other ambient conditions, and for engines with emission control, TCS and/or BCST, please contact MAN Energy Solutions in Copenhagen for a calculation of the expected fuel consumption.

Technical data, such as power, speed and gross efficiency of the ME-S, ME-GI-S and ME-LGI-S type engines are the same as for the corresponding MC-S engines. MAN Energy Solutions in Copenhagen can provide the technical engine data for your specific project, including project-specific emission requirements.

**Operating mode**

Stationary engines operate at load patterns and ambient conditions which differ from those of their marine counterparts. This is illustrated in Figs. 2 and 3, showing the typical operating conditions for both applications.

Fig. 2 shows that for stationary engines the average load is 95-100% during 8,000 hours or more per year in operation, whereas for marine engines the average load is around 60-80% and, furthermore, often only for 6,000 hours per year in operation. This means that stationary engines typically have a load factor which is more than 25% higher than that of marine engines. In 2016, the load on a general marine engine installation is currently closer to 60%.

### Efficiency of MAN B&W two-stroke engines

**Stationary application**

**Fig. 1:** Overview of our stationary engine programme

**Fig. 2:** Typical load profiles during a year in operation
The actual fuel consumption can be estimated using the site specific actual heat rate and LCV.

**Difference between HCV and LCV**

The heat of combustion for fuels can be defined either by higher calorific value or lower calorific value.

- **Higher calorific value**
  
  The quantity known as higher calorific value (HCV) (or “gross energy” or “upper heating value” or “higher heating value” (HHV)) is determined by bringing all products of combustion back to the original pre-combustion temperature and, in particular, by condensing any water vapour produced. Such measurements often use a standard temperature of 25°C.

  This is the same as the thermodynamic heat of combustion since the enthalpy change for the reaction assumes a stoichiometric mixture of fuel and oxidiser (for example two moles of hydrogen and one mole of oxygen) is initiated by an ignition device and the reaction is allowed to complete. When hydrogen and oxygen react during combustion water vapour is produced. The starting vessel and its contents are then cooled to the original temperature and the higher calorific value is determined as being the heat released between the identical initial and final temperatures.

  When the LCV is determined, cooling is stopped at 150°C and the heat of condensation is not a recoverable part of the combustion products, because the water components are in liquid state at 150°C. The HCV assumes that all the heat of combustion back to the original pre-combustion temperature and, in particular, by condensing any water vapour produced. Such measurements often use a standard temperature of 25°C.

- **Lower calorific value**
  
  The quantity known as lower calorific value (LCV) (or “net calorific value” (NCV) or “lower heating value” (LHV)) is determined by subtracting the heat of condensation of the water in the fuel and the reaction products is impractical, or heat at a temperature below 150°C cannot be put to use.

**Measuring heating values**

Higher calorific value is experimentally determined in a bomb calorimeter. Combustion in a container of a stoichiometric mixture of fuel and oxidiser (for example two moles of hydrogen and one mole of oxygen) is initiated by an ignition device and the reaction is allowed to complete. When hydrogen and oxygen react during combustion water vapour is produced. The starting vessel and its contents are then cooled to the original temperature and the higher calorific value is determined as being the heat released between the identical initial and final temperatures.

As indicated in Fig. 3, stationary engines are exposed to greatly varying ambient conditions prevailing at site, for example higher and lower air- and cooling-water temperatures. Furthermore, stationary engines are frequently exposed to fuel oils of non-marine quality. The fuel is often delivered by one permanent supplier, meaning that the quality from this supplier, good or bad, will prevail. Therefore, lube oils, especially cylinder lube oils, have to be individually selected and, at times, even individually specified and optimised in order to match the fuel oil available.

**Heat rate versus specific fuel consumption**

In some industries fuel consumption is typically stated in terms of g/kWh, based upon a standard fuel with a lower calorific value (LCV) of 42.7 MJ/kg for stationary application. For stationary application the equivalent term “heat rate” is used, which is normally expressed in kJ/kW.

The heat rate indicates the amount of energy required to generate one unit of shaft power. By using this term the heat rate value remains the same independent of the LCV of the fuel.

Engine programme data can be converted by application of the ISO LCV of the fuel, for example 42.7 MJ/kg, applying the following relation:

\[ FC \text{ [g/kWh]} = \frac{\text{Heat Rate [kJ/kWh]}}{42700} \]

**Stationary engines**

<table>
<thead>
<tr>
<th>Ambient conditions</th>
<th>Unit</th>
<th>High yearly site-climatic conditions</th>
<th>Low yearly site-climatic conditions</th>
<th>Design</th>
<th>Tropical</th>
<th>Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling water temp.</td>
<td>°C</td>
<td>51</td>
<td>Yearly climatic conditions on site; design average chosen by MAN Energy Solutions</td>
<td>6</td>
<td>32</td>
<td>25</td>
</tr>
<tr>
<td>Air inlet temp.</td>
<td>°C</td>
<td>50</td>
<td>Yearly climatic conditions on site; design average chosen by MAN Energy Solutions</td>
<td>20</td>
<td>45</td>
<td>25</td>
</tr>
<tr>
<td>Compressor inlet pressure</td>
<td>mbar</td>
<td>1,013</td>
<td>Depends on height above sea level</td>
<td>930</td>
<td>1,000</td>
<td>1,000</td>
</tr>
</tbody>
</table>

**Engine and generator heat rates and efficiency**

In the following sections the term heat rate (HR) is utilised in different scenarios.

**Fuel engine**

Fig. 4 shows the fuel data terms of mass flow (G), the lower calorific value as (LCV), the output from the engine (mechanical power) as (Pm), the electrical power from the generator as (Pe), and the generator efficiency as nG. Based on these definitions, the following relationships may be established, as shown in equations (1) to (5), see Fig. 4.a

\[ \text{Fuel equations} \]

\[ G \text{ [kg/h]} = \frac{\text{HR, mech}}{\text{LCV}} \]  
\[ \text{Pe [kWe]} = \frac{\text{HR, mech} \times \text{LCV}}{3600} \]  
\[ \text{nG} = \frac{\text{HR, mech}}{\text{HR, mec, gas}} \times 100 \% \]

**Dual fuel engines**

Based on the data in Fig. 5 the following relationships may be established, as shown in equations (6) to (11), see Fig. 5.a

\[ \text{Dual fuel, equations} \]

\[ \text{Pe [kWe]} = \frac{\text{HR, mech, gas} \times \text{LCV}}{3600} \]  
\[ \text{HR, mec, gas} = \frac{\text{Pe}}{\text{LCV}} \]  
\[ \text{nG} = \frac{\text{HR, mech, gas} \times \text{HR, mec, gas, eff}}{\text{HR, mec, gas}} \times 100 \% \]  

The quantity of pilot fuel is typically 0.5% of MCR engine heat rate and is almost constant at all loads, i.e. the percentage of pilot fuel of the total heat rate is higher at lower loads.
Engines with TCS and BCST

The turbo compound system (TCS) is an installation comprising a power turbine coupled to a generator utilising exhaust-gas heat for the additional production of electrical energy. A bottoming cycle steam turbine (BCST) is an installation utilising exhaust-gas heat for the additional production of electrical energy. Based on the data in Fig. 6, relationships may be established as shown in equations (12) and (13), see Fig. 6.a. The above methods can be readily adapted for dual-fuel engines.

Power consumption in auxiliary systems

In addition to the foregoing explanation regarding the engine, generator and possible waste heat recovery in terms of BCST and TCS, the electrical power consumption of auxiliary systems must be considered. A single-line electrical system is shown diagrammatically in Fig. 7 for a power plant equipped with a 10G90ME-S engine.

The transformer to the right in the single-line diagram shown in Fig. 7 is connected to the auxiliary busbar supplying power for local use, such as pumps, fans, auxiliary blowers, heaters, etc. An auxiliary generating set is indicated in case the plant must be prepared for a black start. The nominal voltage of a busbar is 60 kV, and for this reason the operational voltage is estimated to 105%, i.e. 63 kV.
The voltage level, however, varies from country to country. Fig. 8 provides explanations of symbols.

Based on Fig. 7, the following relationships may be established, as shown in equations (14) and (15).

**Thermal efficiency**

In thermodynamics, thermal efficiency ($\eta_{th}$) is a dimensionless performance measure of a device which uses thermal energy, such as a reciprocating internal combustion engine, a gas turbine, a steam turbine, a steam engine, a boiler or a furnace, for example. In other words, thermal efficiency indicates how well a process of energy conversion or transfer is accomplished.

In general, energy conversion efficiency is the ratio between the useful output of a device and the input, in energy terms, see equation (16). The net efficiency of a power plant may be expressed as shown in equation (17).

Power at power lines may be measured in kW. Input energy is the product of the lower specific heating energy [kJ/kg] of the fuel and the flow [kg/s] into the engine(s).

Let us assume that the output of a power plant is 195 MWe based upon MAN B&W engines may consist of multiple two-stroke engines, as shown diagrammatically in Fig. 9 for a 191.5 MWe installation with 10G90-ME-S.

If the total power is to be exported by means of one transmission line, one solution may be to transform the voltage upwards and hence reduce the current and, consequently, the transmission-line resistance losses. The power loss in the transmission line is directly proportional to the resistance in the line and the square of the current.

Selection of the voltage for the main busbar depends upon the transformers available and the current for which the main busbar is designed. Generally, direct-coupled synchronous generators are designed for voltages of 10 to 15 kV, depending upon power size. Power at power lines may be measured in MW. Input energy is the product of the lower specific heating energy [kJ/kg] of the fuel and the flow [kg/s] into the engine(s).

When comparing efficiency by means of different energy conversion systems, it is important to ensure that the same type of calorific value is used. By doing so, calculations will have a comparable baseline.

A power plant based upon MAN B&W engines may consist of multiple two-stroke engines, as shown diagrammatically in Fig. 9 for a 191.5 MWe installation with 10G90-ME-S.

If the total power is to be exported by means of one transmission line, one solution may be to transform the voltage upwards and hence reduce the current and, consequently, the transmission-line resistance losses. The power loss in the transmission line is directly proportional to the resistance in the line and the square of the current.

Selection of the voltage for the main busbar depends upon the transformers available and the current for which the main busbar is designed. Generally, direct-coupled synchronous generators are designed for voltages of 10 to 15 kV, depending upon power size. Power at power lines may be measured in MW. Input energy is the product of the lower specific heating energy [kJ/kg] of the fuel and the flow [kg/s] into the engine(s).
Due to the very high voltage at the main busbar, the auxiliary busbar has to be connected by means of two transformers because a 120/0.4 kV transformer would be of a special design.

**Engine control**

A marine engine coupled directly to a propeller is controlled by a governor which controls engine speed by means need for energy, being a function of the engine speed.

For a stationary engine coupled directly to a synchronous generator, the governor is extended with speed droop and pure kW control modes, to be utilised when the generator is connected to a grid.

The grid determines the frequency and the engine is forced to run at the speed required by the grid frequency. The governor performs speed control until the generator is connected to the grid, and once the generator is connected to the grid the governor performs load control. The governor mode selection and set points for the speed or load are determined by a power-plant control system.

**Installation planning**

Marine engines operate in an environment at sea level and at modest temperatures. The average load factor is lower when compared to its stationary counterpart.

Each stationary engine is optimised for the site-specific environment. The application of TCS or HRSG units in connection with a steam turbine enhances the electrical output.

The electrical efficiency of multiple transformers and auxiliary equipment has an impact on the net total efficiency of the power plant, hence CAPEX and OPEX should be evaluated in relation to overall plant efficiency. Generally speaking, transformer efficiency is a function of initial cost.

High efficiency of the prime mover impacts directly on the overall efficiency of the whole plant. It is recommended that the efficiency of the prime mover should be studied when selecting/designing the power plant, together with examining any demanding ambient conditions.

---

**References**


2. Efficiency of MAN B&W two-stroke engines, 5510-0200-00ppr Jan 2017

**Abbreviations**

LCV – Lower Calorific Value [kJ/kg]
HCV – Higher Calorific Value [kJ/kg]
LPG – Liquefied Petroleum Gas
DME – DiMethyl Ether
HFO – Heavy Fuel Oil
TCS – Turbo Compound System
BCST – Bottoming Cycle Steam Turbine
HRSG – Heat Recovery Steam Generator
MAN B&W – Engine brand name
MCR – Maximum Continuous Rating
HR – Heat Rate [kJ/kWh]
Pm – Power mechanical [kW]
Pe – Power electrical [kW]
ṁ – Mass flow [kg/h]
ηG – Generator efficiency [%]
ṁG – Mass flow of gas [kg/h]
ṁP – Mass flow of pilot oil [kg/h]
PBCST – Power electrical from BCST [kW]
PBCST – Power electrical from TCS [kW]
PEng – Power electrical from the engine delivered by the generator [kW]
ηth, LCV – Thermal efficiency based on LCV [%]
ηth, HCV – Thermal efficiency based on HCV [%]
ISO – International Organization for Standardization
ASTM – American Society for Testing and Materials
FC – Fuel Consumption [g/kWh]