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Operational characteristics of selected marine turbogenerators powered by steam from auxiliary oil-fired boilers

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Abstract

This paper describes such quantitative characteristics and operational parameters for marine turbogenerator as: efficiency, and steam consumption per unit or hour for various loads. Characteristic numbers and operational parameters were estimated from the results of operational tests of a turbogenerator aboard a petroleum tanker.

Introduction

Reduced fuel consumption by engines is motivated not only by economic concerns, but also by more restrictive regulations regarding allowable emissions of hazardous exhaust gases.

At the engine room level, fuel consumption depends mainly on the appropriateness and efficiency of the machinery installed, as well as the skill of its operation and the power control methods employed.

Efficiency assumptions may be empirically assessed by comparing predictions to the actual performance of a vessel during sea tests.

The efficiency of marine turbogenerators depends mainly on power load and the method of controlling the power load. Both the literature (Krzyślak, 2002; Kosowski, 2005) and author's own research (Behrendt, 2007), show that the efficiency of steam turbogenerators drops by as much as 50% when the machines are operated in the range of 25% to 30% of nominal power.

The two power governing methods typically applied to low-power steam powered units (such as turbogenerators) are so-called "quality governing methods" and "quantity-quality governing methods."

The quality governing method is the simplest way to regulate power. This method entails throt-

tling the governor valve for the entire stream of steam provided to the turbine. The simplicity and effectiveness of this approach must be weighed against significant disadvantages. Steam throttling in the governor valve not only results in a decreased mass flow rate, but also in a reduction of steam pressure.

The pressure reduction of the entire volume of the steam provided to the turbine has economic implications associated with increased fuel consumption. This is so because the difference between the heat required to generate steam in the boiler with nominal parameters and the smaller amount of heat that would be necessary to generate steam with parameters sufficient for the engine downstream the governor valve.

Moreover, the pressure drop due associated with the power quality governing method reduces the available theoretical and actual decrease in enthalpy in the turbine, even though it maintains constant pressure in the condenser. Accordingly, to maintain required turbine power, the steam demand must increase.

The said disadvantages occur to a lesser extent when the quantity-quality governing method has been applied where sections at the turbine supply are used. Each section is equipped with a governor

valve. In addition to increasing demand on turbine power, the opening degree of the governor valve increases causing that the mass flow rate is higher as well as the pressure of the steam provided to the section. This procedure is the quality governing method. The quantity governing method is applied only when the section governor valve is entirely open, and the steam is not throttled. Further increase of turbine power requires the valves to be opened and the steam to be directed and supplied to the following sections. The quantity governing method in the pure form occurs when the governor valves are completely open for particular sections. Under these conditions, power control may be carried out by a change of the rate of flow of steam mass through the turbine. In practice, this requires step power control.

It is not appropriate to apply the quantity governing method to the rate of steam flow thorough number of sections to obtain a specific turbine power. For example, for four sections, the quantity governing method may be applied for 25%, 50%, 75% and 100% of the nominal power of the turbine. At the intermediate values, the quality – quantity power governing method will be used. It should be noted that for a hypothetical turbine power load of 80%, the steam will be directed and supplied to four sections. However, when the steam flows through the first three sections, it will not be throttled (quantity governing method), and only some of the steam required for 75% and 80% power will be throttled in the governor valve of the fourth section (quantity governing method).

The quality-quantity governing method was employed in the turbogenerator in the vessel subsequently subjected to sea tests.

The research was conducted on a ship during a mooring trial. The aim of the trial was to prove that the turbogenerator reached such design parameters as nominal power and steam consumption. In addition, the measurement data permitted the determination of such additional operational parameters as, among other things, turbogenerator efficiency and unit steam consumption under various power load modes.

Tests – description and results

The turbogenerator tested consisted of a steam turbine, a reduction gear, a condenser, and a power generator installed on a common foundation. It provided the engine room of the petroleum tanker tested with a load capacity of 308,000 DWT (ME&S, 2011a). When the vessel was not under way, the turbogenerator was supplied with saturated steam generated by an auxiliary oil-fired boiler;

when under way, the turbogenerator received saturated and superheated steam provided by a two-pressure waste-heat generator.

The general characteristics of the steam turbine (Shinko, 2010; ME&S, 2011c) are as follows:

Manufacturer	Shinko Ltd
Model	RG 64-M
Type	6-stage impulse mixed pressure
Speed – turbine rotor	10000 rpm/166.66 s ⁻¹
Speed – gear outlet	1800 rpm/30 s ⁻¹
Nominal power	1000 kW
Operational power – steam supply from:	
oil-fired boiler	1000 kW
waste-heat boiler	750 kW

Table 1. The parameters and the mass steam flow rate at the turbine inlet at nominal load

	Steam type	Pressure [MPa]	Steam temperature [°C]	Steam mass flow rate [kg/h]/[kg/s]
Steam supply from the oil-fired boiler	Saturated	1.42	196	11,000/3.06
Steam supply from the waste-heat boiler	Saturated	0.22	128	340/0.094
	Superheated	0.58	230	5720/1.59

The general characteristics of the steam boilers (MHI, 2010; Osaka, 2010) are as follows:

Oil-fired boiler

Manufacturer	Mitsubishi Heavy Industries Ltd
Model	MAC-80B
Type	water tube
Designed pressure	1.96 MPa
Steam type	saturated
Steam temperature	214°C
Nominal capacity	80 t/h/22.22 kg/s

Waste-heat boiler

Manufacturer	Osaka Boiler Co. Ltd
Model	SGG
Type	two pressure, water fine tube

Table 2. The parameters and the mass flow rate of the steam at the waste-heat boiler outlet

Steam	Pressure [MPa]	Steam temperature [°C]	Steam mass flow rate [kg/h]/[kg/s]
Superheated	0.63	234	5720/1.59
Saturated	0.30	143	340/0.094

The general characteristics of the power generator are as follows (ME&S, 2011c):

Manufacturer	NISHISHIBA ELECTRIC Co.
Nominal power	1000 kW
Voltage	450 V
Current frequency	60 Hz
Speed	1800 rpm/30 s ⁻¹

A diagram of the turbogenerator showing the location of the measurement equipment is shown in Figure 1.

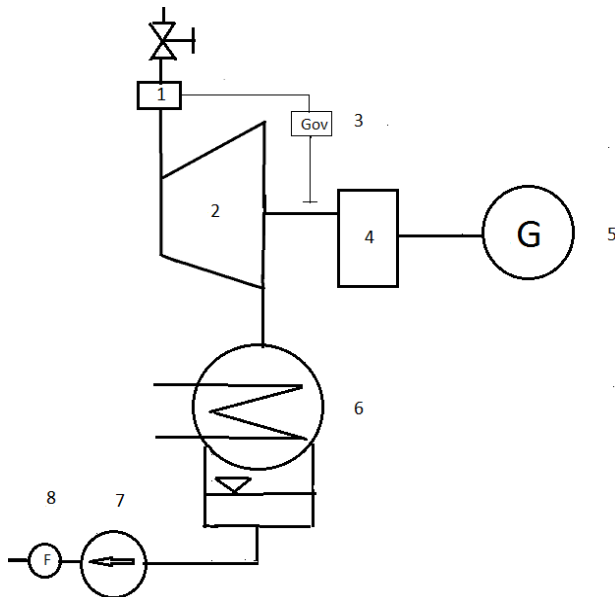


Figure 1. Turbogenerator diagram: 1 – governor valves block, 2 – steam turbine, 3 – speed governor, 4 – reduction gear, 5 – power generator, 6 – condenser, 7 – condenser pump, 8 – flow meter

Steam from the boiler is routed to the expansion instruments of the first degree of the turbine through the governor valves of the first degree of the turbine through the governor valves block (1). This operation allows required turbine power to be obtained. The governor valve block (1) is a type of bar lift with three regulation (section) valves. It is controlled by a speed governor (3) through the connecting rod and lever. The valve stem is connected to the governor lever at the top end, and is also connected to the lifting beam on the other side. The valve lift is regulated by a hydraulic servomotor piston through the connecting rod and the governor lever. The valve stem and the lifting beam control steam flow to keep a constant turbine speed.

The maximum opening of each of the three section valves is such that the quantity governing method is used for turbine power output values of 50%, 75% and 100% of the nominal power, respectively. The quantity – quality governing method is

employed for all other values of turbine power output.

Because tests occurred only during mooring trials, the turbine could only be supplied with steam from the auxiliary oil-fired boiler.

The turbogenerator was loaded with power by switching on electric power receivers located in the engine room, and the power values were monitored with measurement equipment in the main switchboard.

The pressure value of the steam supplying the turbogenerator was been monitored by a manometer on the inlet to the governor valves block.

Steam mass flow rate into turbogenerator was estimated by the volume of condensate discharged from the condenser (6). Therefore, on the pressure side of the condenser pump (7), flow meter (8) was installed. Such a measurement method complies with applicable norms and standards (DIN; PN, 1971). In converting observed volumetric flow rates of condensate into mass flow rates of steam, it is important to take account of the variation of water density.

Condensate temperature, as measured by a thermometer in the condenser, was 42°C. Water density at 42°C is 994.8 kg/m³ (Wukałowicz, 1975).

The selected values were measured over one-hour periods, which began about 30 minutes after the test work mode of the turbogenerator had been set (ME&S (2011a; 2011b).

The values of the parameters observed and estimated are summarized in Table 3.

The results of the measurements and the calculations included in Table 3 have been used to specify the operational parameters of the turbogenerator.

Selected operational parameters of the tested turbogenerator

The mathematical relations described below have been applied to determine such operational parameters of the turbogenerator as the theoretical power of the steam turbine, unit steam consumption in relation to the power of the power generator, and turbogenerator general efficiency. Index

Table 3. Measured and estimated values of parameters as observed during operational tests of turbogenerator

Measurement number	Relative power of turbogenerator P_w [%]	Power of turbogenerator P_g [kW]	Steam pressure at inlet to turbine p_p [MPa]	Pressure in condenser p_s [kPa]	Steam consumption D_p [kg/h]/[kg/s]
1	25	250	1.42	-92.7	6230/1.73
2	50	500	1.41	-92.6	7820/2.17
3	75	750	1.40	-90.0	9610/2.67
4	100	1000	1.42	-90.6	11300/3.06
5	110	1100	1.42	-91.8	11920/3.31

$i = 1, 2, \dots, 5$ in the formulae refer to the measurement numbers summarized in Table 3.

$$P_{ti} = D_{pi} \Delta h_{ti} = D_{pi} (i_{pi} - i_{si}) \text{ [kW]} \quad (1)$$

In order to calculate the theoretical power, P_{ti} , of the turbine, it is essential to determine enthalpy drop, Δh_{ti} , estimated as the difference between the enthalpy, i_{pi} , of the steam downstream the governor valve and the enthalpy, i_{si} , of the steam pressure in the condenser, as well as the assumed isentropic decrease of enthalpy.

Since during the quantity governing of the turbine power on the section governor valves the process of steam isenthalpic throttling occurs, in order to determine the theoretical power, the value of the enthalpy i_{pi} of the steam on the inlet to the turbine expansion instruments depend only on the pressure p_{pi} . The need to adopt such an assumption has also been supported by the fact that there has been no possibility to measure the steam pressure in the sections.

The values of the enthalpies, i_{pi} , and, i_{si} , of the steam were obtained from steam-water tables (Wukałowicz, 1975).

General turbogenerator efficiency is given by the following expression:

$$\eta_{oi} = \frac{P_{gi}}{P_{ti}} \text{ [-]} \quad (2)$$

Unit steam consumption in relations to the power, P_g , of the power generator

$$d_{pi} = \frac{D_{pi}}{P_{gi}} \text{ [kg/kWh]} \quad (3)$$

The calculation results, applying the Equations (1)–(3) and the data in Table 3, are presented in Table 4.

Using the data contained in Tables 3 and 4, the charts presented in Figures 2–4 have been prepared. As the independent variable, the power, P_g , of the power generator has been adopted, while the steam consumption, D_p , the unit steam consumption, d_p , the turbogenerator efficiency, η_o , have been adopted as the dependent variables.

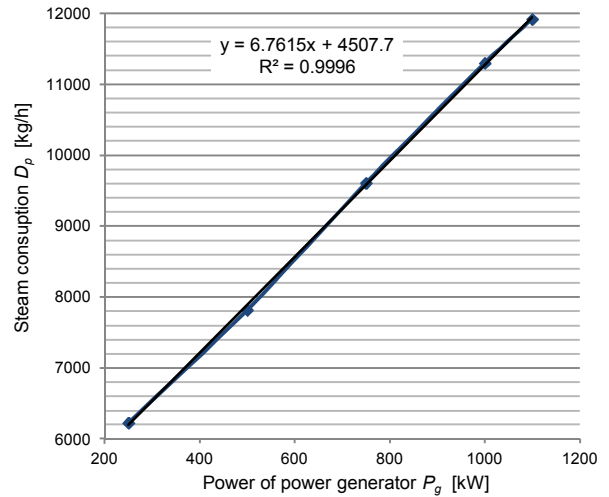


Figure 2. Steam consumption by the tested turbogenerator

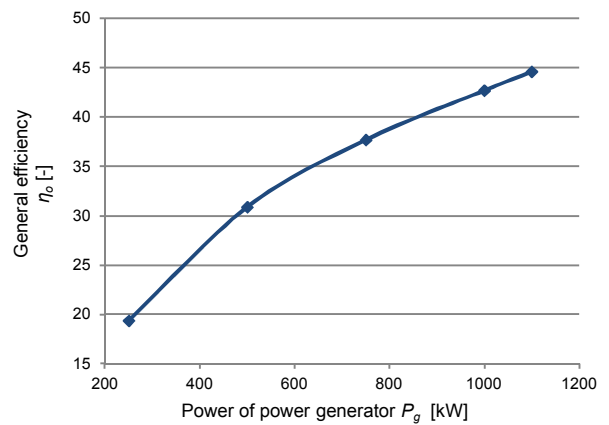


Figure 3. General efficiency of the tested turbogenerator

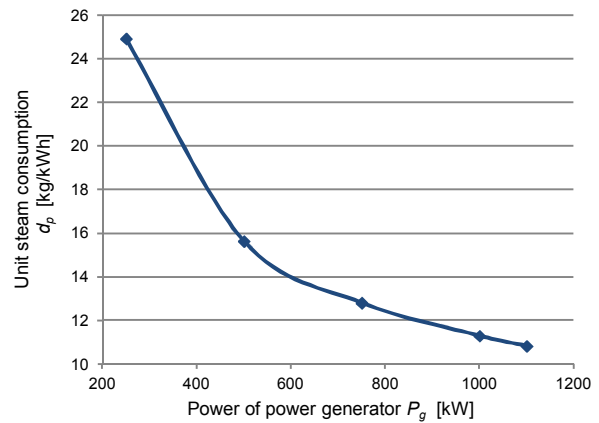


Figure 4. Unit steam consumption by the tested turbo-charger

Table 4. Results of calculating operational parameters for the tested turbogenerator

Measurement number	Relative power of turbogenerator P_w [%]	Power of turbogenerator P_g [kW]	Turbine theoretical power P_t [kW]	Turbogenerator general efficiency η_o [-]	Unit steam consumption d_p [kg/kWh]
1	25	250	1290	19.4	24.92
2	50	500	1618	30.9	15.64
3	75	750	1988	37.7	12.81
4	100	1000	2339	42.7	11.30
5	110	1100	2467	44.6	10.83

The curves in Figures 2–4 indicate that fluctuation of estimated operational parameters was affected mostly by the magnitude of turbine load under power.

At the power load in the range of 75–100% of the operational power, the maximum turbine efficiency, in the range of 37.7–42.7%, as well as the lowest unit steam consumption in the range of 12.81–11.30 kg/kWh, have been obtained. While the minimum turbogenerator efficiency equalled to 19.4% and the unit steam consumption amounted to 24.92 kg/kWh occurred at 25% of the turbogenerator power load.

The turbine steam consumption, depending on its power load, may be determined with the high accuracy from the relation (Figure 2):

$$D_p = 6.7615P_g + 4507.7 \quad [\text{kg/kWh}] \quad (4)$$

Conclusions

The operational parameters estimated for the tested turbogenerator imply the following conclusions:

- A turbogenerator operational power of 1000 kW was attained.
- Measured steam consumption under turbogenerator load with operational power was 11,300 kg/h, and was 3% higher than predicted in the technical documentation.
- Estimated turbogenerator efficiencies in the range of 19.4–42.7% should be considered high for such a machine (Krzyślak, 2002; Kosowski, 2005; Behrendt, 2007). One of the main reasons for this situation can be explained as follows: the quantity governing method was applied at tested loads of 50, 75 and 100% of turbine operational power, and the fact that the tested turbogenerator was new, with a small number of hours in operation.
- The fact that operational parameters were estimated over such a wide range of power loads should facilitate the development of operational tasks for the turbogenerator. In particular, the strong relationship between total and unit steam consumption and power load should be highlighted in operational recommendations.
- The minimum values of the unit and total steam consumption occur at turbogenerator power in the range of 70–100% of the operational power.

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