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CHANGE OF EXERGY MOTION IN THE MARINE STEAM PLANT WITH MAIN SHAFT SPEED VARIATION

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Abstract: *Exergy flow motion insight and analysis of plant requirements for a typical conventional LNG carrier with Rankine regenerative feed water heating steam cycle is given in this paper to clarify and distinguish auxiliary flow streams from the useful ones. Auxiliary flow supports the plant operation, but reduces exergy efficiency by certain amounts. Main boilers exergy flow streams are divided into two major groups: superheated and de-superheated flow stream consumers. A plant run test was carried out by varying main shaft revolutions to collect required thermodynamic data at various plant locations. In the presented marine steam plant is explained exergy flow streams for considering components and flow streams ratios of particular plant components. It is detected and explained the points of excessive auxiliary stream flows consumption and recommendations for possible reduction in saving auxiliary power or steam consumption are given.*

Keywords: *MARINE STEAM PLANT, AUXILIARY MACHINERY, EXERGY STREAM FLOWS, AUXILIARY LOAD REDUCTION*

1. Introduction

Auxiliary power consumption is the power required for support plant operation and control. Stationary steam power plant auxiliary consumption was given by numerous authors, which varies with plant size. Although stationary steam power plants were wellbeing elaborated by many authors, marine steam plants have not been researched in that respect yet.

Thermal power plant auxiliary power consumption mainly varies about 5–8%, while in combined cycle power plant (CCPP) the auxiliary power consumption fall in the range of 2–5% of actual generating capacity [1]. According to ABB Ltd. Switzerland [2], auxiliary consumption of total electricity gained in thermal power plant is 6–15% of the total electricity generation, while it amounts 4–6% in nuclear power plants. EPRI [3], conducted an evidence-based analysis of internal plant usable power in the US for the fossil and nuclear generation fleet, with the conclusion that internal power need is roughly 5–10% of total power generation and that usage can vary by fuel type. Power need is also thought to vary somewhat across such parameters as age of unit, size of unit, heat rate, capacity factor and number of starts. Other variants can also include ambient temperature and cooling water temperature. Adate and Awale [4], specifies auxiliary power consumption of Indian thermal power plants, rated from less than 100 MW up to more than 500 MW as 10.31 to 6.13%.

Overview of the marine steam power plant [5] with regenerative feed water cycle analyzed in this paper is presented in Fig.1.

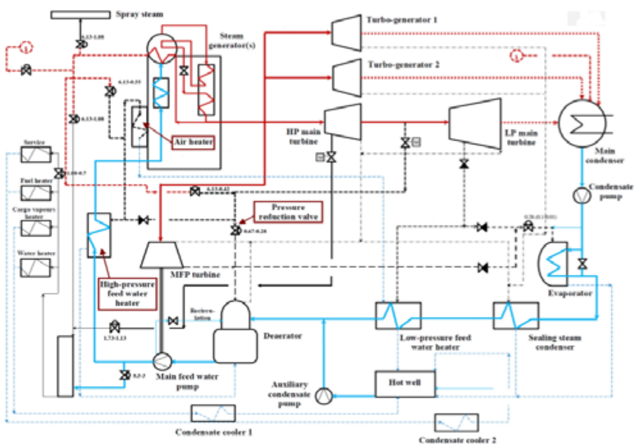

Fig.1. *LNG carrier steam propulsion plant overview*

2. Methodology

Although the ship's power plant is somewhat different in design from stationary power plants it may be compared with stationary cycles for the references in this study. Marine steam power plant uses regenerative feed water cycle in order to increase cycle efficiency. For the sake of simplicity steam exergy flows may be divided into the six main groups, where the superheated exergy stream is divided into four sub streams: stream flow to the main turbine, stream flow to turbo generators No1 and No2 and stream flow to the feed pump steam turbine. Additional superheated exergy sub stream which is related to the losses is considered after main boilers outlet on the superheated steam line and is noted as an additional superheated sub stream. De superheated steam stream flow to the service is noted in opposite dashed direction from the main boilers as presented in Fig.2.

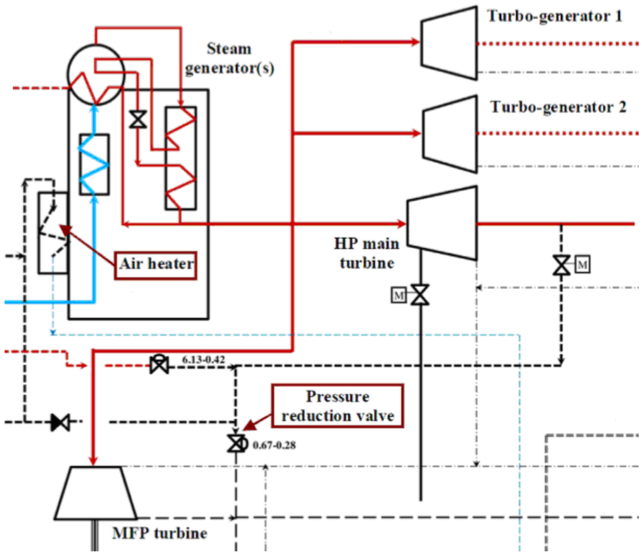

Fig.2. *Exergy steam stream flows after main boilers*

3. Thermodynamic analysis

Required pressures, temperatures and power for various places in the engine room were collected with standard engine measuring equipment, Table 1.

This measured data were the basis for calculating specific exergies of all steam streams. Based on specific exergies and mass stream flows were finally calculated and analyzed exergy steam flow rates. Dedicated exergy steam flows were calculated according to [6] and [7].

In the steady state process the mass balance of a control volume is:

$$\sum_{IN} \dot{m}_i = \sum_{OUT} \dot{m}_o \tag{1}$$

Table 1. *Engine room measuring equipment*

- Turbo generator and feed pump steam turbine inlet steam pressure - Main propulsion turbine inlet steam pressure - Main boiler de superheating outlet steam pressure	Pressure transmitter Yamatake 960A [8]
- Turbo generator and feed pump steam turbine inlet steam temperature - Main propulsion turbine inlet steam temperature	Temperature sensor MBT5113 [9]
- Main boiler de superheating steam outlet temperature	Thermocouple mV/I conversion module J-STP 90/95 [10]
- Main propulsion turbine shaft power	Kyma shaft power meter, Model KPM-PFS [11]
- Turbo generators power	Generator protection and power management unit HIMAP-BC [12]

The exergy balance of the control volume system is written as:

$$\sum_{IN} \dot{E}_{Xi} + \sum_{k} (1 - \frac{T_0}{T_k}) \cdot \dot{Q}_k = \sum_{OUT} \dot{E}_{Xo} + \dot{W} + \dot{E}_{Xd} \tag{2}$$

The exergy stream flow rate can be calculated as:

$$\dot{E}_X = \dot{m} \cdot e_X \tag{3}$$

The specific exergy is presented as:

$$e_X = (h - h_0) - T_0 \cdot (s - s_0) \tag{4}$$

Standard ambient state of marine steam plant is defined with ambient pressure and temperature:

$$p_0 = 0.1 \text{ MPa} \tag{5}$$

$$T_0 = 298 \text{ K} \tag{6}$$

Specific enthalpies and entropies of every steam flow were calculated by using measured pressures and temperatures.

Cumulative exergy flow from main boilers to all observed steam plant components can be defined with:

$$\sum ALL = \dot{m}_{MT} \cdot \varepsilon_{Xi,MT} + 2 \cdot \dot{m}_{TG} \cdot \varepsilon_{Xi,TG} + \dot{m}_{FP} \cdot \varepsilon_{Xi,FP} + \dot{m}_{SE} \cdot \varepsilon_{Xi,SE} + m_{LO} \cdot \varepsilon_{Xi,LO} \tag{7}$$

It is important to emphasize that both turbo generators have identical mass flows and identical inlet pressures and temperatures (consequently identical inlet specific entropies).

Table 2. *Exergy stream flow calculation routines*

Mass flow	Exergy flow
$\dot{m}_{TG1} = \dot{m}_{TURBO\ GEN.\ NO1}$	$\dot{E}_{X,TG1} = (\dot{m}_{TG1} \cdot e_{Xi,TG1})_{TURBO\ GEN.\ NO1}$
$\dot{m}_{TG2} = \dot{m}_{TURBO\ GEN.\ NO2}$	$\dot{E}_{X,TG2} = (\dot{m}_{TG2} \cdot e_{Xi,TG2})_{TURBO\ GEN.\ NO2}$
$\dot{m}_{FP} = \dot{m}_{FEED\ PUMP}$	$\dot{E}_{X,FP} = (\dot{m}_{FP} \cdot e_{Xi,FP})_{FEED\ PUMP}$
$\dot{m}_{MT} = \dot{m}_{MAIN\ TURBINE}$	$\dot{E}_{X,MT} = (\dot{m}_{MT} \cdot e_{Xi,MT})_{MAIN\ TURBINE}$
$\dot{m}_{SE} = \dot{m}_{SERVICE\ STEAM}$	$\dot{E}_{X,SE} = (\dot{m}_{SE} \cdot e_{Xi,SE})_{SERVICE\ STEAM}$
$\dot{m}_{LO} = \dot{m}_{LOSSES}$	$\dot{E}_{X,LO} = (\dot{m}_{LO} \cdot e_{Xi,LO})_{LOSSES}$

Ratio of cumulative exergy flow stream distributed to the observed components is defined by the equations:

- Main turbine:

$$\dot{E}_{X,MT} = \frac{\dot{m}_{MT} \cdot e_{Xi,MT}}{\sum ALL} \cdot 100 \ [\%] \tag{8}$$

- Turbo generators No1 and No2:

$$\dot{E}_{X,TG1} = \frac{\dot{m}_{TG1} \cdot e_{Xi,TG1}}{\sum ALL} \cdot 100 \ [\%] \tag{9}$$

$$\dot{E}_{X,TG2} = \frac{\dot{m}_{TG2} \cdot e_{Xi,TG2}}{\sum ALL} \cdot 100 \ [\%] \tag{10}$$

- Feed pump steam turbine:

$$\dot{E}_{X,FP} = \frac{\dot{m}_{FP} \cdot e_{Xi,FP}}{\sum ALL} \cdot 100 \ [\%] \tag{11}$$

- Service steam:

$$\dot{E}_{X,SE} = \frac{\dot{m}_{SE} \cdot e_{Xi,SE}}{\sum ALL} \cdot 100 \ [\%] \tag{12}$$

- Losses:

$$\dot{E}_{X,LO} = \frac{\dot{m}_{LO} \cdot e_{Xi,LO}}{\sum ALL} \cdot 100 \ [\%] \tag{13}$$

4. Analysis and discussion

Exergy stream flow power to dedicated directions with variation of revolutions at the ship main propulsion shaft is presented in Fig.3. On the lower propulsion shaft speeds, exergy power related to the main propulsion turbine (1445 kW at 25.58 min^{-1}) is almost negligible. With propulsion shaft speed increase, exergy power related to the main propulsion turbine (36824 kW at 83 min^{-1}) becomes an essential element in comparison with all the other exergy flow powers.

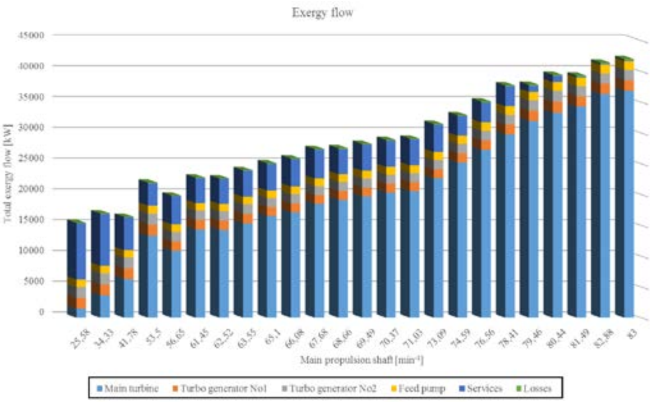

Fig.3. *Exergy flow rates under main propulsion shaft speed variation*

Exergy flow rates overview during variations of the main propulsion shaft speed to named groups and sub groups is given in Fig.4, where may be seen that on the lower propulsion shaft revolutions dominating auxiliary exergy stream flow request goes to the services, whereas the main turbine is taking the main part of the exergy flow stream at the higher propulsion shaft speeds.

Exergy flow request from the turbo generator decreases after maneuvering zone, as bow thruster is switched off. Additionally, after maneuvering zone tugs were let go along with mooring and windlass winches which are switched off as well. A further decrease in the power request on the turbo generator units is explained by switching off the main condenser circulation pump power when the main condenser cooling system changes to scoop mode. In scoop mode the main condenser is cooled with ship's speed what has to be over 13 nautical miles in order to satisfy velocity request of sea water through main condenser.

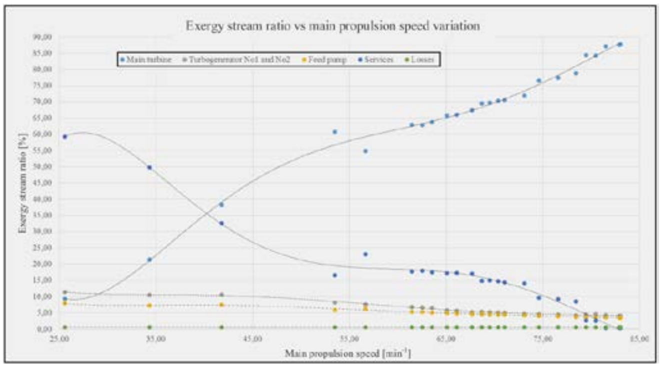

Fig.4. *Exergy ratios of flow streams under speed variation at main propulsion shaft*

Accordingly, at upper working ranges, close to the maximum continuous running zone of the last test point at 83 min^{-1}, the marine steam plant consumes 12.34% of the exergy flow ratio for auxiliary requirements. Feed pump steam turbine consumes 3.41% of exergy flow, while turbo generators consumes 2 x 4.05% of exergy flow, services and losses are taking less than one percent of exergy flow stream consumption in the plant, what is presented in Fig.5.

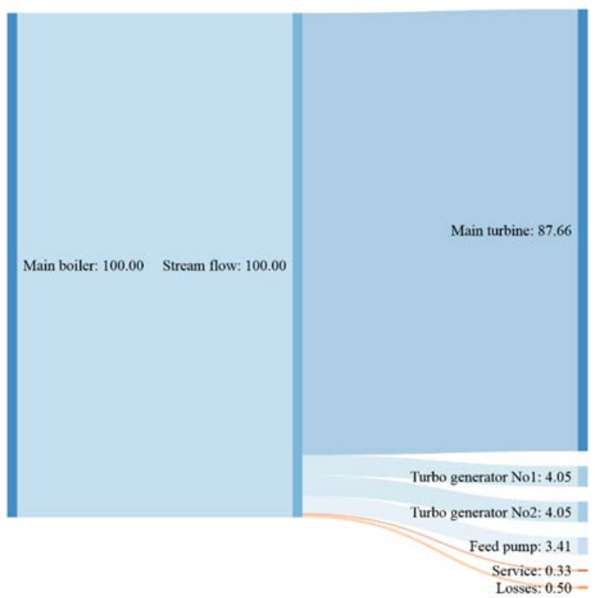

Fig.5. *The exergy ratio in (%) at 83 min^{-1} of the main propulsion shaft*

5. Conclusion

The analysis of auxiliary exergy power consumption of marine steam plant for conventional LNG carrier with Rankine regeneration feed water heating cycle is presented. It is found that due to safety and construction limitations, most auxiliary power are is consumed at the lower operating zones of the main propulsion shaft, mainly due to manoeuvring with the vessel, where is additional electric power consumed for bow thruster propulsion and due to lower operation requirements of the main feed pump steam turbine, Fig.3. Deck auxiliary, mooring and windlass equipment is running by that time, until the captain estimates that vessel is safe for sea navigation.

Problematic consumption of the huge exergy flow portion to the service requirements at the lower propulsion shaft operating zones is due to steam dumping process, which is seen in the Fig.6. A reason behind of such a process is to avoid venting of LNG vapors to the atmosphere as methane is a far more potent greenhouse gas than is CO_2 [13], [14]. The global warming potential of methane compared to CO_2 is 105 and 33 on a mass-to-mass basis for 20 and 100 years, respectively, with an uncertainty of plus or minus 23%. Accordingly, steam dumping is useful concept from the viewpoint of greenhouse emission.

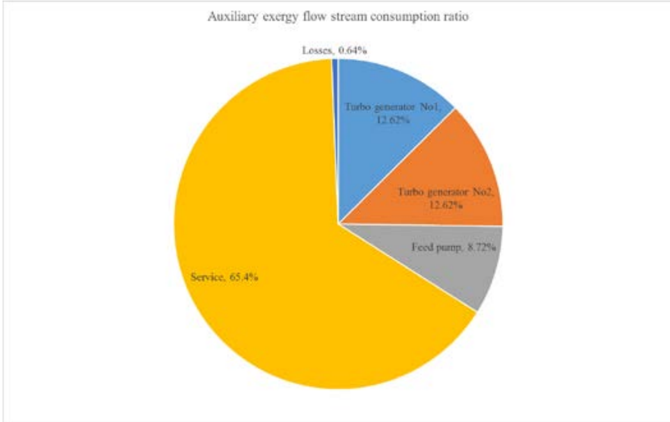

Fig.6. *Exergy ratio of auxiliary requirements for marine plant at propulsion shaft speed of 25.52 min^{-1}*

At higher continuous propulsion shaft revolutions, Fig.7, portion of service steam consumption is minor, due to extractions from the main turbine, which are used for regenerative feed water heating and for various system heating's. Turbo generator power in this operating zone is lower compared to manoeuvring zone, but its ratio in auxiliary consumption now dominates, what was to be expected. Unfortunately, around 28% of all exergy stream auxiliary flow in this operating zone goes to the feed pump steam turbine.

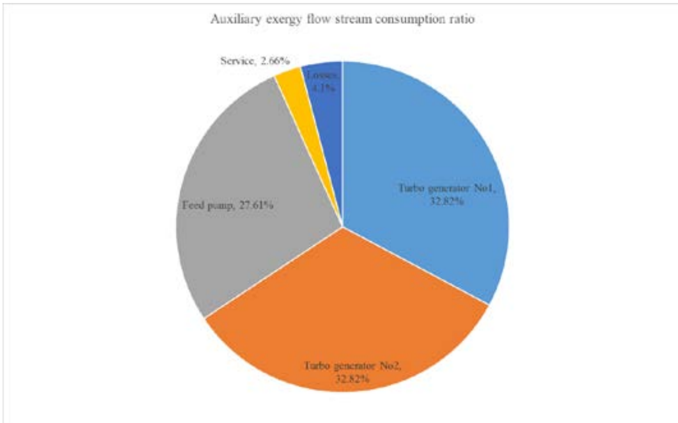

Fig.7. *Exergy ratio of auxiliary requirements for marine plant at propulsion shaft speed of 83 min^{-1}*

The auxiliary power consumption analysis clearly shows that the deeper and more accurate insight into auxiliary power consumption is given by the exergy flow analysis, where the quality of the flow streams is estimated and the exergy losses may be properly defined.

Comparing to stationary thermal plant, marine steam plant auxiliary consumption for conventional LNG carrier is in the range of 12% what is similar to the shore thermal plants according to ABB Ltd. Switzerland studies.

The analysis provided in this paper determines exact exergy stream flow consumption for the feed pump steam turbine, which is in the range from 7.91 to 3.41% as the power at main propulsion turbine increases.

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Nomenclature

Symbols		**Subscripts**	
$\dot{m}$	mass flow rate (kg/s)	*d*	destruction
$\dot{E}_X$	exergy flow rate (kW)	*MT*	main turbine
h	specific enthalpy (kJ/kg)	*TG*	turbo generator
e_X	specific exergy (kJ/kg)	*FP*	feed pump
$\dot{Q}$	heat power (kW)	*SE*	service
$\dot{W}$	mechanical power (kW)	*LO*	losses
s	specific entropy (kJ/kg·K)	*i*	inlet
T	temperature (K)	*o*	outlet
		k	boundary temperature
		0	ambient condition

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