ENERGY FLOW STREAMS IN THE MARINE STEAM PLANT DURING THE MAIN PROPULSION PROPELLER SPEED VARIATION

PhD Student Eng. Igor Poljak[1], PhD. Vedran Mrzljak[2], PhD. Josip Orovic[3],
Rožići 4/3, 51221 Kostrena[1], Faculty of Engineering, University of Rijeka, Vukovarska 58, 51000 Rijeka[2],
University of Zadar, Maritime Department, Mihovila Pavlinovića 1, 23000 Zadar[3], Croatia
E-mail: igor.poljak2@gmail.com, vedran.mrzljak@riteh.hr, jorovic@unizd.hr

Abstract: *For the analyzed LNG carrier with Rankine regenerative feed water cycle, energy analysis is presented. The intention was to determine auxiliary flow streams from the useful ones. Auxiliary energy flow supports plant operation on the one side, but reduces overall efficiency on the other. Steam generators energy streams are divided into two major groups, for the main and auxiliary stream consumers. The steam system test was performed by varying main propulsion shaft revolutions. The required thermodynamic data are collected at various steam system locations. For considered plant energy flow streams components are explained and analyzed. In this paper the recommendations for possible energy savings for the mentioned propulsion plant are proposed.*

Keywords: *MARINE STEAM PLANT, MACHINERY, ENERGY FLOW, ENERGY SAVING*

1. Introduction

Due to interpretation variability of power and mass flow of the superheated Rankine cycle, it has risen necessity for clarifying energy motion inside the marine steam plant at LNG carrier.

Although stationary steam power plants were wellbeing elaborated by many authors, marine steam plants have not been researched in that way yet.

In the context of electricity production, auxiliary load is the load or device which consumes electricity while contributing to the process of electricity generation or plant operation. Hence, this does not add to the total plant yield, but reduces the gross yield by a considerable amount. Thus, auxiliary load is the in-facility electrical load which needs to be minimized [1], [2].

In marine power plant, the main auxiliary loads include: motors used to run various service pumps which support plant operation, fans for the boilers, turbine turning gear in port, electric pre-heaters, etc. In addition to that, instrumentation, controls, computers, valve actuators, air compressors and lighting within the power plant also add on to the auxiliary load.

Electrical power which is generated on board the vessel for supporting plant operation is gained from turbo generator units. Beside to auxiliary load, LNG carrier consumes steam, which is used for lube oil heaters, fuel oil heaters, waste oil tank heaters, accommodation services heaters, etc. This amount of steam which is taken from the boiler contributes to efficiency degradation of the total plant cycle.

Considered marine steam plant overview is given in Fig.1. Explanation of all symbols from Fig.1 is presented in Table 1.

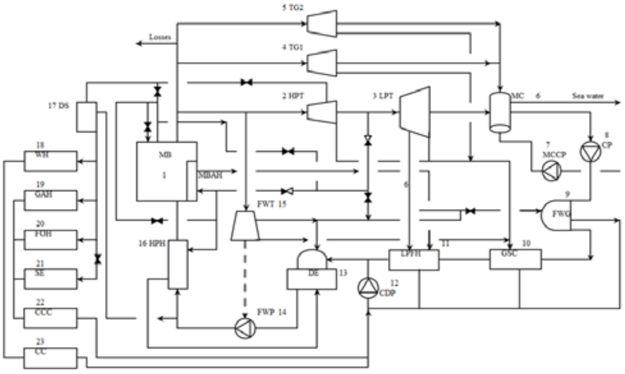

Fig.1. *Marine steam plant overview*

Table 1. *Marine steam plant chain indexes*

1 – Main boiler	13 – Deaerator
2 – High pressure turbine	14 – Feed water pump
3 – Low pressure turbine	15 – Feed water pump turbine
4 – Turbo generator No1	16 – High pressure feed water heater
5 – Turbo generator No2	17 – De super heater
6 – Main condenser	18 – Water heater
7 – Main condenser cooling sea water pump	19 – LNG heater
8 – Condensate pump	20 – Fuel oil heater
9 – Fresh water generator	21 – Contaminated service heaters
10 – Gland steam cooler	22 – Contaminated service cooler
11 – Low pressure feed water heater	23 – Condensate cooler
12 – Auxiliary condensate pump	

2. Numerical model

Elaborated power plant uses regenerative feed water cycle in order to increase cycle efficiency. The feed water group will not be considered in this study. Plant flows are divided into two main stream groups from the main boilers (plant consists of two identical steam boilers): superheated and the de superheated streams. Superheated stream may be divided into four sub streams: steam flow to the main turbine, steam flow to turbo generators No1 and No2 and steam flow to feed pump steam turbine. There is one additional superheated sub stream which relates to the losses and is noted as an additional superheated sub stream. The stream flows from the main boilers carry energy and mass notations. De superheated steam stream flow to the service consumers is noted in the opposite direction, as presented in Fig.2.

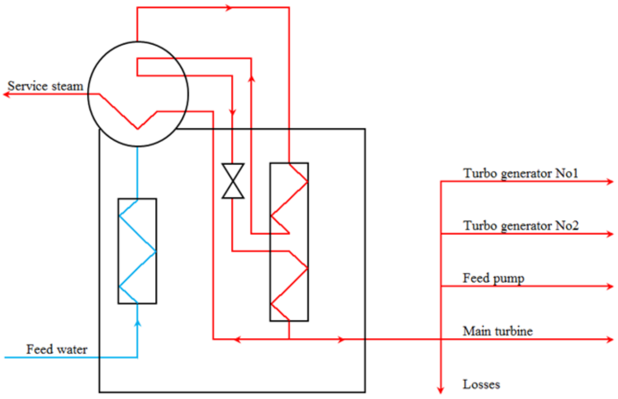

Fig.2. *Stream flows to and after main boilers*

3. Thermodynamic analysis

Pressure, temperature and power are measured with standard plant measuring equipment, which is displayed in Table 2.

***Table 2.** Marine steam plant 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 [3]
- Turbo generator and feed pump steam turbine inlet steam temperature - Main propulsion turbine inlet steam temperature	Temperature sensor MBT5113 [4]
- Main boiler de superheating steam outlet temperature	Thermocouple mV/I conversion module J-STP 90/95 [5]
- Main propulsion turbine shaft power	Kyma shaft power meter, Model KPM-PFS [6]
- Turbo generators power	Generator protection and power management unit HIMAP-BC [7]

Thermodynamic results were obtained from the measured data at various locations in the engine room. Individual stream flows to dedicated direction is calculated according to [8], [9].

In the steady state process the mass balance of control volume is calculated according to:

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

The energy balance of the control volume is presented as:

$$\sum_{IN} \dot{E}_i + \dot{Q} = \sum_{OUT} \dot{E}_o + \dot{W} \tag{2}$$

Table 3. specifies energy and mass stream flow calculation procedure for the steam plant components observed in this analysis.

***Table 3.** Mass and energy stream flow calculation routines*

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

Specific enthalpy of every steam flow was calculated by using measured pressures and temperatures.

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

$$\begin{aligned} \sum ALL = {} & \dot{m}_{MT} \cdot h_{i,MT} + 2 \cdot \dot{m}_{TG} \cdot h_{i,TG} + \dot{m}_{FP} \cdot h_{i,FP} + \\ & + \dot{m}_{SE} \cdot h_{i,SE} + m_{LO} \cdot h_{i,LO} \end{aligned} \tag{3}$$

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

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

- Main turbine:

$$\dot{E}_{MT} = \frac{\dot{m}_{MT} \cdot h_{i,MT}}{\sum ALL} \cdot 100[\%] \tag{4}$$

- Turbo generator No1 and No2:

$$\dot{E}_{TG1} = \frac{\dot{m}_{TG1} \cdot h_{i,TG1}}{\sum ALL} \cdot 100[\%] \tag{5}$$

$$\dot{E}_{TG2} = \frac{\dot{m}_{TG2} \cdot h_{i,TG2}}{\sum ALL} \cdot 100[\%] \tag{6}$$

- Feed pump steam turbine:

$$\dot{E}_{FP} = \frac{\dot{m}_{FP} \cdot h_{i,FP}}{\sum ALL} \cdot 100[\%] \tag{7}$$

- Service:

$$\dot{E}_{SE} = \frac{\dot{m}_{SE} \cdot h_{i,SE}}{\sum ALL} \cdot 100[\%] \tag{8}$$

- Losses:

$$\dot{E}_{LO} = \frac{\dot{m}_{LO} \cdot h_{i,LO}}{\sum ALL} \cdot 100[\%] \tag{9}$$

4. Analysis and discussion

The engine run test was made after cargo loading operation. Steam energy stream flows during variation of revolutions at the main propulsion shaft are presented in the Table 4.

***Table 4.** Energy flow streams under speed variation of the main propulsion shaft*

Main shaft RPM (min^{-1})	**Main turbine (kW)**	**Turbo generator No1 (kW)**	**Turbo generator No2 (kW)**	**Feed pump (kW)**	**Service (kW)**	**Losses (kW)**
25.58	3606	4389	4389	3035	24305	223
34.33	9060	4424	4424	3079	22431	240
41.78	15645	4302	4302	3039	14242	225
53.50	33082	4470	4470	3205	9707	289
56.65	27124	3779	3779	3143	12230	266
61.45	35697	3877	3877	2994	10782	300
62.52	35474	3782	3782	2989	10881	298
63.55	38090	3928	3928	3032	11218	316
65.10	41022	3626	3626	3063	11524	330
66.08	42496	3663	3663	3092	11909	342
67.68	45808	3562	3562	3146	12440	360
68.66	47362	3607	3607	3149	10914	359
69.49	48755	3595	3595	3177	11258	368
70.37	50270	3599	3599	3198	11278	377
71.03	50832	3619	3619	3206	11187	379
73.09	56002	3669	3669	3283	11760	408
74.59	62370	3767	3767	3314	8495	422
76.56	67454	3883	3883	3388	8660	449
78.41	73766	3926	3926	3472	8580	482
79.46	79287	4199	4199	3457	2620	476
80.44	82766	4465	4465	3509	2704	495
81.49	85339	4156	4156	3488	382	491
82.88	90640	4193	4193	3557	369	518
83.00	91766	4250	4250	3574	371	525

The energy stream flow ratio of the specified stream flows, to observed machineries or systems, according to the previously explained calculation procedure is presented in the Table 5.

Table 5. *Energy ratios for flow streams under speed variation of the main propulsion shaft*

Main shaft RPM (min^{-1})	Main turbine (%)	Turbo generator No1 (%)	Turbo generator No2 (%)	Feed pump (%)	Service (%)	Losses (%)
25.58	9.02	10.99	10.99	7.60	60.84	0.56
34.33	20.75	10.13	10.13	7.05	51.38	0.55
41.78	37.47	10.30	10.30	7.28	34.11	0.54
53.50	59.91	8.09	8.09	5.80	17.58	0.52
56.65	53.90	7.51	7.51	6.25	24.30	0.53
61.45	62.05	6.74	6.74	5.20	18.74	0.52
62.52	62.01	6.61	6.61	5.22	19.02	0.52
63.55	62.95	6.49	6.49	5.01	18.54	0.52
65.10	64.92	5.74	5.74	4.85	18.24	0.52
66.08	65.21	5.62	5.62	4.74	18.28	0.52
67.68	66.51	5.17	5.17	4.57	18.06	0.52
68.66	68.64	5.23	5.23	4.56	15.82	0.52
69.49	68.91	5.08	5.08	4.49	15.91	0.52
70.37	69.51	4.98	4.98	4.42	15.59	0.52
71.03	69.78	4.97	4.97	4.40	15.36	0.52
73.09	71.08	4.66	4.66	4.17	14.92	0.52
74.59	75.94	4.59	4.59	4.03	10.34	0.51
76.56	76.90	4.43	4.43	3.86	9.87	0.51
78.41	78.35	4.17	4.17	3.69	9.11	0.51
79.46	84.13	4.46	4.46	3.67	2.78	0.50
80.44	84.11	4.54	4.54	3.57	2.75	0.50
81.49	87.07	4.24	4.24	3.56	0.39	0.50
82.88	87.60	4.05	4.05	3.44	0.36	0.50
83.00	87.62	4.06	4.06	3.41	0.35	0.50

Presentation of main and auxiliary steam energy flows with variations of main propulsion shaft speed is given in Fig.3. Only flow which is related to the ship propulsion is main (useful) flow. For the observed ship steam plant, main energy flow is only one - energy flow to the main turbine. Other observed energy flows are considered as auxiliary flows.

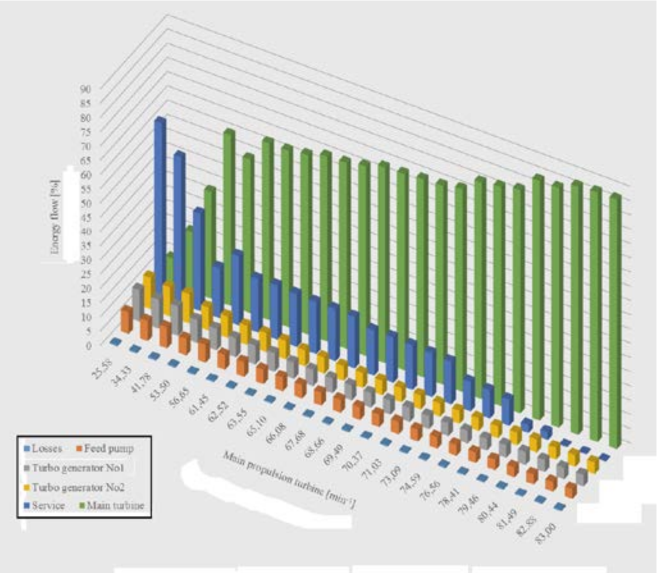

Fig.3. *Energy ratio at various main propulsion shaft speeds*

At the beginning of manoeuvring mode, 25 to 41 min^{-1}, dominating energy stream flows goes to the services, Table 5 and Fig.3. This effect can be clearly explained. After loading operation, cargo tank pressure is maintained with extra combusting inside the main boilers. Steam excess which cannot be used for the auxiliary turbines or the main turbine drive is then dumped into the main condenser. Steam is fed into main boilers internal de super heater, which is located in the steam drum and there is cooled from ~ 500 °C to 300 °C from where it goes to service line, back to the main condenser via dump system. The only benefit of such action is to avoid air pollution with releasing methane to the atmosphere, since methane belongs into group of greenhouse gasses. Sankey diagram which presents this operational period, during main propulsion shaft speed of 25 min^{-1} is presented in Fig.4.

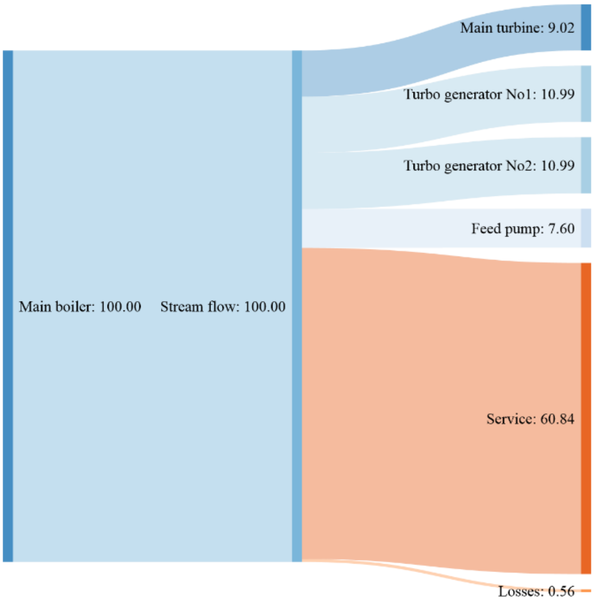

Fig.4. *Energy ratio in (%) at the main propulsion shaft speed of 25* min^{-1}

Higher relative energy stream flow consumption of the feed pump steam turbine, Fig.4, occurs due to fact that feed pump is recycling certain amount of the water at low plant loads in order to protect itself from the cavitation which will be caused by water overheating through the pump stages at reduced flow. Turbo generator higher energy consumption in the lower propulsion shaft operating zone is caused by the bow thruster run and related electrical consumption.

Conducted analysis shows that 12.38% of the cumulative energy ratio goes for auxiliary requirements at main propulsion shaft speed of 83 min^{-1}, Fig.5. The steam propulsion system load is directly proportional to main shaft speed, so at the highest observed steam system load the majority of energy flow from steam generators goes to the main turbine.

It may be seen that feed pump steam turbine power consumption at 83 min^{-1} is 3.41%, what is lower in comparison with the similar auxiliary steam turbines in stationary steam plants for the rated loads. The main difference is lower pumping pressure as marine boiler MB-4-KS is designed to operate at steam pressure of 6 MPa, in that respect pumping power is lower than, for example, of a boiler which is operating at 16 MPa.

Considering the overall developed power, steam turbine for a feed pump drive in this mode (83 min^{-1}) is fed with a greater energy flow than required. The reason for that can be found in deaerator operation. From the observed steam system, steam after the feed pump turbine is drained to the deaerator. At the highest steam system operating load, calculated energy flow ratio to the feed pump steam turbine is not in function to produce high power of the turbine than that to ensure smooth deaerator operation.

When compared energy ratios at the main propulsion shaft speed of 25 min^{-1} and 83 min^{-1} it is obvious from Fig.4 and Fig.5 that energy flow ratio, which is leading to both turbo generators and feed pump steam turbine decreases as steam system load increases. On the other side, the energy flow ratio of the main turbine has the opposite pattern of behavior in comparison with the turbo generators and feed pump steam turbine. Energy flow ratio of the main turbine increases during increase in steam system load.

Finally, it is interesting to mention that steam system losses energy ratio decreases from the lowest to the highest observed main propulsion shaft speeds.

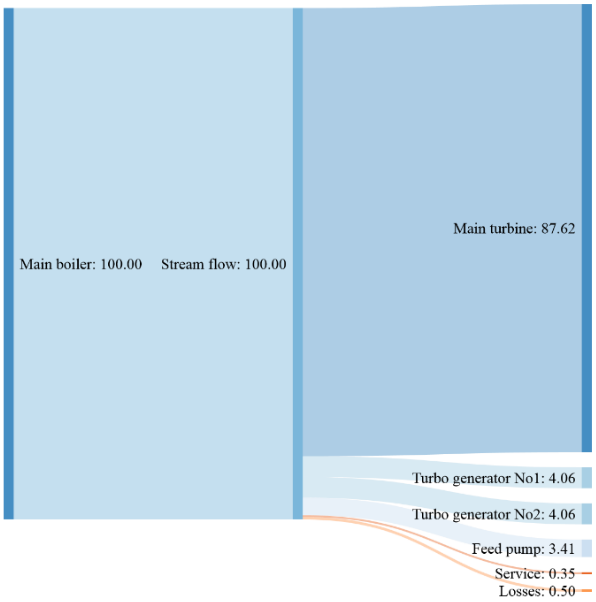

Fig.5. *Energy ratio in (%) at the main propulsion shaft speed of 83 min^{-1}*

When comparing auxiliary with the main turbine energy flows for the observed steam system, it is interesting to present ratio according to Table 4. Values from Table 4 for all auxiliary energy flows are summarized and divided by the energy flow to the main turbine, at each observed main propulsion shaft speed. Fig. 6 presents that this ratio constantly decreases from 1008% at the main shaft speed of 25 min^{-1} to the 14% at the main shaft speed of 83 min^{-1}.

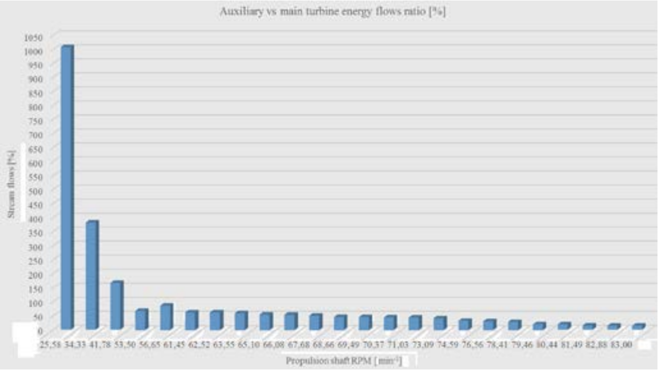

Fig.6. *Auxiliary requirement vs main turbine ratio for energy stream flows*

5. Conclusion

Described marine steam plant generates more auxiliary energy flows at lower main propulsion shaft speeds than on the higher, so the efficiency of the plant at lower operation speeds will be lower.

As for recommendation, reducing of auxiliary flow may be achieved with higher speed of the LNG carrier and one turbo generator operation after manoeuvring zone. Moreover, the steam driven feed pump turbine has to be changed with electrically driven pump, what will act beneficially to turbo generator specific steam consumption.

Additionally, the high rate feed pump should be changed to a lower rate feed pump in port and during manoeuvring zone as to avoid recycling of feed water, what will cause decreased auxiliary load consumption either steam or electrical power.

Further studies should include the profitability of installation of variable speed driven pump electro motors, which could further decrease auxiliary power consumption on given example.

Nomenclature

Symbols		**Subscripts**	
$\dot{m}$	mass flow rate (kg/s)	*MT*	main turbine
$\dot{E}$	energy flow rate (kW)	*TG*	turbo generator
h	specific enthalpy (kJ/kg)	*FP*	feed pump
$\dot{Q}$	heat power (kW)	*SE*	service
$\dot{W}$	mechanical power (kW)	*LO*	losses
		i	inlet
		o	outlet

6. Literature

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