ANALYSIS OF AUXILIARY EXERGY FLOW STREAM DURING THE CHANGE IN MARINE STEAM PROPULSION SYSTEM LOAD

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Summary

The paper presents analysis of steam auxiliary exergy flow stream during the change in marine steam propulsion system load. The change in auxiliary steam exergy flow from marine steam generators during the increase in steam system load is compared with the change in main steam exergy flow. Exergy flow stream to each auxiliary device in steam system is analysed and operation dynamics of auxiliary devices are explained. The presented analysis provides an insight into operation of each observed marine steam system auxiliary device from the lowest to the highest steam system load.

Keywords: Marine steam propulsion, Load change, Exergy flow, Auxiliary steam systems

1. INTRODUCTION

Steam power systems today are the mostly land-based and its main function is electricity production, [1] and [2]. Marine power systems are mainly based on internal combustion engines with a lot of different variations in power and operational principle, [3] and [4]. Marine steam propulsion systems are relatively rare, but due to a lot of advantages they are dominant on LNG carriers [5] and [6]. As a land-based steam power system, each marine steam propulsion system consists of many components, necessary for safe and reliable operation [7] and [8].

The marine steam propulsion system consists of two steam flow streams from steam generators - main and auxiliary [9]. The main flow stream is used for steam turbines operation [10] and [11], while auxiliary steam flow stream is used for proper operation of auxiliary marine equipment [12] and [13]. The auxiliary steam flow stream has a lower pressure and temperature in comparison with a main one [14]. For both flow streams, it is interesting to analyse its operation dynamics during the change in marine steam system load.

In this paper an analysis of steam auxiliary exergy flow stream during the change in marine steam propulsion system load is presented. Steam auxiliary exergy flow stream and its dynamic is compared with the main exergy flow stream. Exergy flow stream to each auxiliary device in steam system was calculated and analysed. Operation dynamics of auxiliary devices and share of the current auxiliary exergy flow, from steam generators to each auxiliary device, are explained. This analysis provides an insight into operation of marine steam system auxiliary devices from the lowest to the highest steam system load.

2. MAIN AND AUXILIARY EXERGY FLOW STREAMS IN MARINE STEAM PROPULSION SYSTEM

Steam propulsion system in which main and auxiliary exergy flow streams were analysed is mounted on the conventional LNG carrier. Main characteristics and specifications of the LNG carrier are presented in Table 1.

Table 1 LNG carrier main characteristics and specifications

Dead weight tonnage	84812 DWT
Overall length	288 m
Max breadth	44 m
Design draft	9.3 m
Steam generators	2 x Mitsubishi MB-4E-KS
Propulsion turbine	Mitsubishi MS40-2 (max. power 29420 kW)

Steam flow streams which leave steam generators in marine propulsion system are main and auxiliary flow streams. Main steam flow stream represents a steam with maximum pressure and temperature. The auxiliary steam flow stream is produced from main flow stream in a way that part of produced main steam is sent back to the steam generators. That steam passes through steam drums and transfers heat to feed water. Due to heat transfer, steam temperature and pressure decreases. The auxiliary steam flow stream is used for the operation of auxiliary steam system devices. Those devices require steam with lower temperature and pressure when compared to main steam stream.

In marine steam propulsion system, auxiliary steam flow is used in the atomizing steam system, dump system, deaerator, desuperheater and air heater, Fig. 1. Operation principle of each auxiliary device is:

- Atomizing steam system: at atomizing steam system represents a small amount of auxiliary steam from steam generators that is used for fuel oil atomizing and for cooling of burners when they are not in use.
- Dump line: At low steam system loads, steam generators produce more steam than an entire system requires. Steam excess is led directly to the main steam condenser through the steam system dump line.
- Deaerator: Deaerator is a component which uses auxiliary steam from steam generators for feed water heating and for gas removal from feed water in order to avoid cavitation.
- Desuperheater: Desuperheater is an open heater (with direct mixing of auxiliary steam and water). Desuperheater in the marine steam system is used to prepare auxiliary steam for additional heating purposes.
- Air heater: Before entrance in each steam generator combustion chamber, air is heated in air heater by auxiliary steam. Heating medium is auxiliary steam only, because flue gas temperature is not sufficient for air heating purposes.

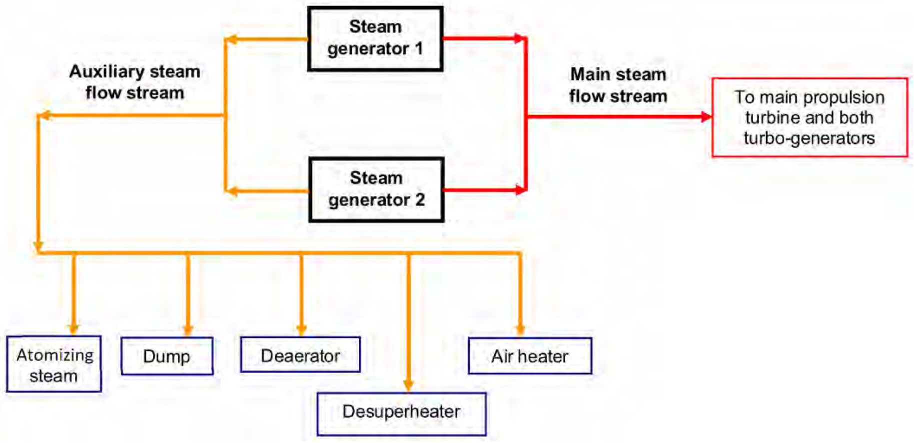

Figure 1 Scheme of marine steam generators with main and auxiliary steam flow streams

3. EXERGY FLOW STREAMS NUMERICAL ANALYSIS

3.1. Governing equations of exergy analysis

Mass flow rate balance equation for any flow stream is expressed as [15]:

$$\sum \dot{m}_{\mathrm{IN}} = \sum \dot{m}_{\mathrm{OUT}} \tag{1}$$

The second law of thermodynamics defines exergy analysis [16]. The main exergy balance equation is [17]:

$$\dot{X}_{\mathrm{heat}} - P = \sum \dot{m}_{\mathrm{OUT}} \cdot \varepsilon_{\mathrm{OUT}} - \sum \dot{m}_{\mathrm{IN}} \cdot \varepsilon_{\mathrm{IN}} + \dot{E}_{\mathrm{ex,D}} \tag{2}$$

where the net exergy transfer by heat ( ) at the temperature T is [18]:

$$\dot{X}_{\mathrm{heat}} = \sum (1 - \frac{T_0}{T}) \cdot \dot{Q} \tag{3}$$

According to [19], specific exergy is defined as:

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

The exergy power of a flow, according to [20] is:

$$\dot{E}_{\mathrm{ex}} = \dot{m} \cdot \varepsilon = \dot{m} \cdot \left[(h - h_0) - T_0 \cdot (s - s_0) \right] . \tag{5}$$

3.2. Calculation of main and auxiliary exergy flow streams

Exergy power of main and auxiliary steam flow stream was calculated by using measured steam pressures, temperatures and mass flow rates, according to equation (5). Steam specific enthalpies and specific entropies were calculated from measured steam pressures and temperatures by using NIST REFPROP software [21].

Throughout this paper, exergy power values are presented for both steam generators (cumulative exergy power). A steam flow stream which enters to any system device was produced by both steam generators. Therefore, only the cumulative flow streams can be relevant in the steam system exergy analysis.

Auxiliary steam specific enthalpy and specific entropy are not the same as at the steam generator’s outlet, when compared to flow streams to each auxiliary device, due to losses through the pipeline. Decrease in auxiliary steam pressure and temperature in the pipeline (and consequentially decrease in specific enthalpy and specific entropy) is small and in this paper is neglected. Auxiliary steam flow streams to each auxiliary device were calculated with the same specific enthalpy and specific entropy as at the steam generator's outlet, but with corresponding steam mass flow rates.

Cumulative steam mass flow rate, which exits from both steam generators, is defined as:

$$\dot{m}_{\mathrm{CU}} = \dot{m}_{\mathrm{MA}} + \dot{m}_{\mathrm{AUX}} \tag{6}$$

Cumulative steam exergy power from steam generators is:

$$\dot{E}_{\mathrm{ex,CU}} = \dot{E}_{\mathrm{ex,MA}} + \dot{E}_{\mathrm{ex,AUX}} \tag{7}$$

where cumulative main and auxiliary steam exergy power are defined as:

$$\dot{E}_{\mathrm{ex,MA}} = \dot{m}_{\mathrm{MA}} \cdot \varepsilon_{\mathrm{MA}} \tag{8}$$

$$\dot{E}_{\mathrm{ex,AUX}} = \dot{m}_{\mathrm{AUX}} \cdot \varepsilon_{\mathrm{AUX}} \tag{9}$$

The share of cumulative main steam exergy power in cumulative exergy power from steam generators is:

$$SH_{\mathrm{MA}} = \frac{\dot{E}_{\mathrm{ex,MA}}}{\dot{E}_{\mathrm{ex,CU}}} \cdot 100 \tag{10}$$

The share of cumulative auxiliary steam exergy power in cumulative exergy power from steam generators is:

$$SH_{\mathrm{AUX}} = \frac{\dot{E}_{\mathrm{ex,AUX}}}{\dot{E}_{\mathrm{ex,CU}}} \cdot 100 \tag{11}$$

Cumulative auxiliary steam flow stream is divided on flow streams to each auxiliary device (auxiliary devices are atomizing steam system, dump, deaerator, desuperheater and air heater), Fig. 1.

Mass flow rate balance for cumulative auxiliary steam flow stream is:

$$\dot{m}_{\mathrm{AUX}} = \dot{m}_{\mathrm{AS}} + \dot{m}_{\mathrm{DU}} + \dot{m}_{\mathrm{DEA}} + \dot{m}_{\mathrm{DES}} + \dot{m}_{\mathrm{AH}} \tag{12}$$

The change in auxiliary steam pressure and temperature through the pipeline is neglected, so cumulative auxiliary steam exergy power divided to each auxiliary device is:

$$\dot{E}_{\mathrm{ex,AUX}} = \dot{m}_{\mathrm{AUX}} \cdot \varepsilon_{\mathrm{AUX}} = \left(\dot{m}_{\mathrm{AS}} + \dot{m}_{\mathrm{DU}} + \dot{m}_{\mathrm{DEA}} + \dot{m}_{\mathrm{DES}} + \dot{m}_{\mathrm{AH}}\right) \cdot \varepsilon_{\mathrm{AUX}} \tag{13}$$

Steam exergy power to each auxiliary device is then:

$$\dot{E}_{\mathrm{ex,AD}} = \dot{m}_{\mathrm{AD}} \cdot \varepsilon_{\mathrm{AUX}} \tag{14}$$

The share of each auxiliary device exergy power in the entire (cumulative) auxiliary exergy power is:

$$SH_{\mathrm{AD}} = \frac{\dot{E}_{\mathrm{ex,AD}}}{\dot{E}_{\mathrm{ex,AUX}}} \cdot 100 \ . \tag{15}$$

Exergy analysis depends greatly on the ambient state (pressure and temperature of the ambient) in which system operates. The ambient state in the LNG carrier engine room during the measurements was:

- pressure: p_0 = 0.1 MPa = 1 bar,
- temperature: T_0 = 25 °C = 298.15 K.

4. REQUIRED MEASUREMENT RESULTS OF MAIN AND AUXILIARY STEAM FLOW STREAMS

Steam temperature, pressure and mass flow rate at each steam system load were measured with equipment already mounted on the steam system pipeline. The same equipment is used for control and regulation of the entire steam system during LNG carrier exploitation. Steam operating parameters are presented in relation to propulsion propeller speed. Increase in propulsion propeller speed is directly proportional to increase in steam system load and vice versa.

Table 2 present measurement results of main and auxiliary steam flow streams. Cumulative auxiliary steam flow stream is divided on flow streams to each auxiliary device. Losses of steam pressure and temperature in auxiliary steam pipeline are small and in this paper are neglected. Therefore, for exergy power calculation it was necessary to measure only steam mass flow rate to each device.

Table 2 Measurement results for main and auxiliary steam flow streams

Propulsion propeller speed (rpm)	Main steam flow stream			Auxiliary steam flow stream-cumulative			Atomizing steam mass flow rate (kg/h)	Dump steam mass flow rate (kg/h)	Deaerator steam mass flow rate (kg/h)	Desuperheater steam mass flow rate (kg/h)	Air heater steam mass flow rate (kg/h)
	Steam temperature (°C)	Steam pressure (MPa)	Steam mass flow rate (kg/h)	Steam temperature (°C)	Steam pressure (MPa)	Steam mass flow rate (kg/h)					
25.00	501	6.20	16744	313	6.01	29876	428	15764	5881	3022	4781
34.33	500	6.20	22696	309	6.08	27710	441	13178	6467	2797	4827
41.78	500	6.19	29394	304	6.11	17708	416	3696	6049	2687	4860
53.50	509	6.10	47985	297	6.07	12170	442	0	3639	2792	5297
56.65	498	5.98	40363	297	5.94	17038	475	0	8392	2796	5375
61.45	500	5.98	49438	297	5.94	14486	472	0	5367	2685	5962
62.52	499	5.99	48977	299	5.95	14528	470	0	5282	2903	5873
63.55	500	5.99	52080	298	5.95	14915	478	0	5657	2677	6103
65.10	504	6.10	54438	299	6.10	15633	470	0	6318	2587	6258
66.08	515	6.08	56078	300	6.04	16133	489	0	6541	2690	6413
67.68	515	6.08	59201	301	6.04	16756	494	0	6983	2797	6482
68.66	516	6.09	61300	302	6.05	13618	488	0	3840	2685	6605
69.49	515	6.09	62723	302	6.05	14039	483	0	4077	2792	6687
70.37	516	6.09	64366	302	6.05	14150	472	0	4078	2688	6912
71.03	516	6.10	65019	302	6.06	13954	464	0	3994	2687	6809
73.09	515	6.10	70515	301	6.07	14690	494	0	4484	2584	7128
74.59	515	6.07	77211	299	6.04	10641	491	0	0	2688	7462
76.56	515	6.07	82881	299	6.04	10848	468	0	0	2793	7587
78.41	515	6.09	89907	299	6.06	10744	472	0	0	2687	7585
79.46	498	5.94	95990	298	5.92	3273	479	0	0	2794	0
80.44	502	6.00	100540	297	5.94	3384	478	0	0	2906	0
81.49	500	5.99	102883	290	5.99	483	483	0	0	0	0
82.88	501	5.99	108601	280	5.99	474	474	0	0	0	0
83.00	501	5.99	109961	280	5.99	477	477	0	0	0	0

5. MAIN AND AUXILIARY STEAM FLOW STREAMS EXERGY ANALYSIS RESULTS WITH THE DISCUSSION

The mass flow rate difference between main and auxiliary steam flow streams can be seen in Fig. 2. At the lowest observed propulsion propeller speeds this difference is negative (25.00 rpm and 34.33 rpm) because at the propulsion system start-up, mass flow rate of the auxiliary steam flow stream is higher. Increase in propulsion system load resulted with an increase in mass flow rate of main steam stream (from 41.78 rpm to the highest system load). At the highest observed steam system load, the mass flow rate difference between main and auxiliary steam flow stream is the highest and amounts 109484 kg/h, Table 2.

It should be noted that the increase in propulsion system load resulted in a proportional increase of main steam mass flow rate (with the exception of just a few operating points at middle load), which means that steam system turbines use more and more steam. At high steam system loads, the majority of analysed auxiliary devices in this study get steam for its operation from the main turbine subtractions. Following the operation principle of this steam propulsion system, it can be concluded that increase in main and the decrease in auxiliary steam mass flow rate during the load increase is expected.

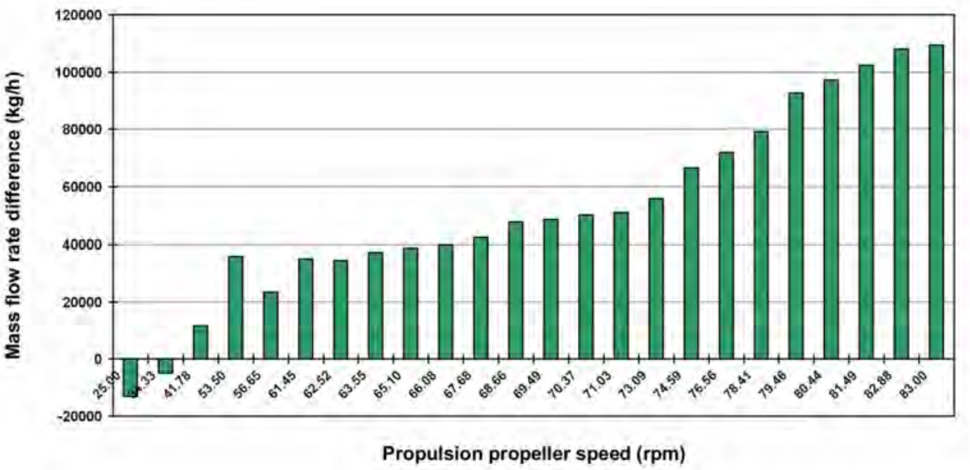

Figure 2 Mass flow rate difference between main and auxiliary steam flow stream

Main and auxiliary exergy power of steam flow streams was calculated according to equations (8) and (9). Increase in steam system load resulted with increase in main flow stream exergy power, while at the same time auxiliary flow stream exergy power decreases, Fig. 3.

Only at the lowest observed load at 25.00 rpm, exergy power of the auxiliary flow stream is higher than exergy power of the main flow stream. From the lowest to the highest steam system load, exergy power of main steam flow stream increases from 6418.53 kW up to 42057.03 kW, while exergy power of the auxiliary flow stream decreases from 9147.04 kW up to 137.26 kW. At high steam system load exergy power of the auxiliary steam flow stream is so small in comparison with the exergy power of the main steam flow stream that it can be declared as negligible.

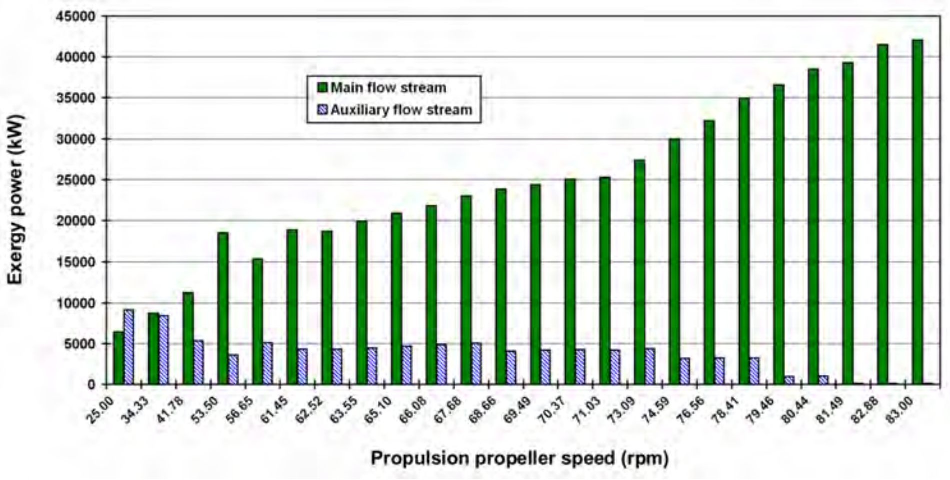

Figure 3 Change in exergy power of main and auxiliary steam flow stream

Analysis of auxiliary steam exergy power which was transferred from steam generators to each auxiliary device must be presented in two parts, for lower and for higher propulsion propeller speeds, Fig. 4 and Fig. 5.

At the lowest propulsion propeller speeds (25.00 rpm and 34.33 rpm) the highest auxiliary steam exergy power is sent to the main condenser through dump line (4826.41 kW and 4010.50 kW), Fig. 4. That amount of auxiliary steam exergy power is lost because at the lowest loads it is not required in the steam system. It can also be seen from Fig. 4 that increase in system load resulted with a decrease in dump exergy power and already on 41.78 rpm dump exergy power is not the dominant one. After 41.78 rpm, dump line is closed because from that moment on, all produced steam exergy power is used in the steam system.

After dump line at low propulsion propeller speeds, the most dominant amount of auxiliary steam exergy power is sent to deaerator and air heater. Atomizing steam system at low steam system loads takes a significantly smaller amount of auxiliary steam exergy power in comparison to other auxiliary components.

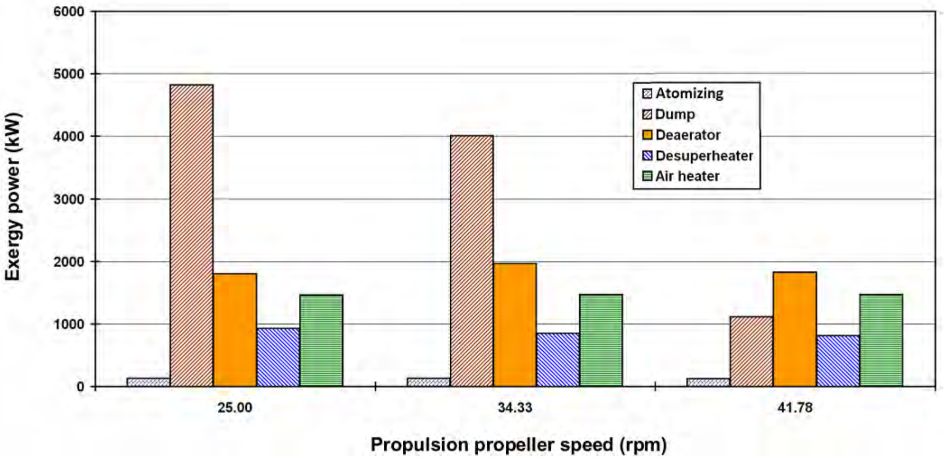

Figure 4 Steam exergy power to each auxiliary device - low propulsion propeller speeds

At middle and high propulsion system loads (from 53.50 rpm up to 83.00 rpm) dump line is closed and the auxiliary steam exergy power is sent to other auxiliary devices, Fig. 5. The greatest consumers of auxiliary steam exergy power are deaerator and air heater, after which follows desuperheater. The atomizing steam system uses almost constant auxiliary steam exergy power in the entire area of middle and high steam system loads. At the highest observed propulsion system loads atomizing steam system is the only auxiliary device which consumes auxiliary steam exergy power.

Auxiliary steam from steam generators is sent to auxiliary devices until the moment when each auxiliary device (with an exception of the atomizing steam system) gets steam for its operation from the main steam turbine subtractions. The first device which gets steam for its operation from a main steam turbine is deaerator after 73.09 rpm. After deaerator, main steam turbine subtraction brings steam to the air heater after 78.41 rpm. The auxiliary device which gets steam from the main turbine the latest is desuperheater and this occurrence happens after 80.44 rpm. Only the atomizing steam system gets auxiliary steam for its operation from the steam generators the entire time, irrespective of steam system load.

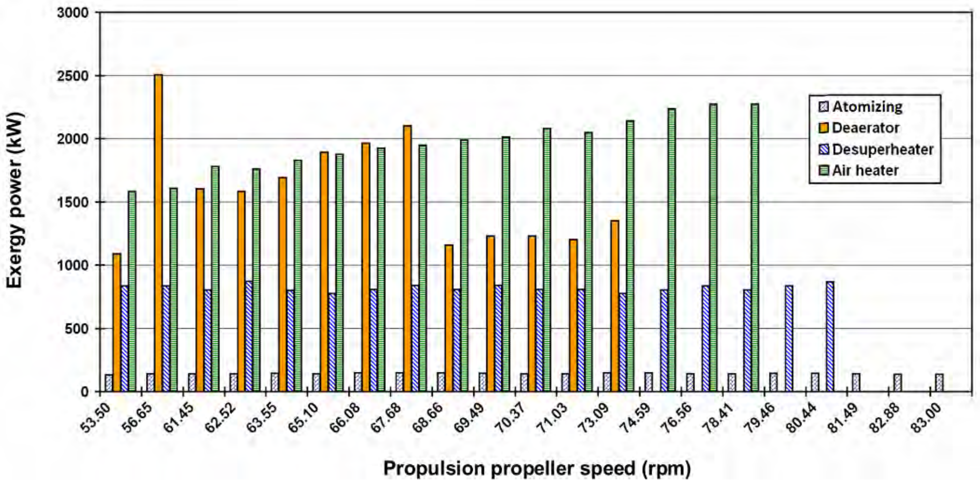

Figure 5 Steam exergy power to each auxiliary device - middle and high propulsion propeller speeds

At three different steam system loads (at three different propulsion propeller speeds) the share of each auxiliary device in current cumulative auxiliary steam exergy power is presented in Fig. 6, Fig. 7 and Fig. 8.

At the lowest observed steam system load (25.00 rpm) dump system takes the most significant share of current cumulative auxiliary steam exergy power with 53%, Fig. 6. At this propulsion system load, the deaerator takes 20% and air heater takes 16% of cumulative auxiliary steam exergy power. The atomizing steam system has the lowest share in cumulative auxiliary steam exergy power (only 1%) at the lowest observed propulsion propeller speed as measurements were taken on dual burning mode, with minimum fuel and maximum gas mode, what results in only small mass variation of that system during all measured modes.

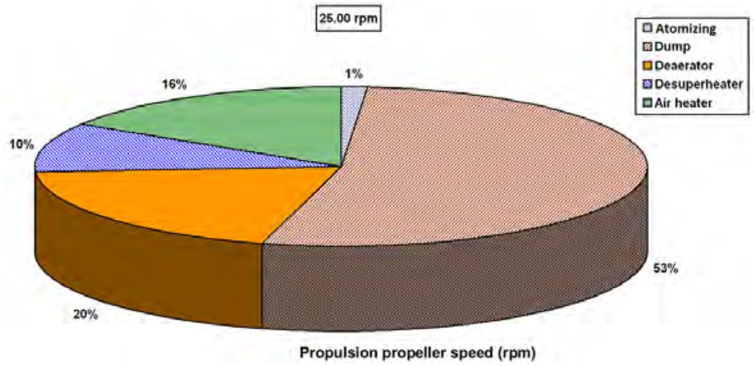

Figure 6 Share in the cumulative auxiliary exergy power of each auxiliary device - propulsion propeller speed of 25.00 rpm

At middle steam system load of 65.10 rpm, Fig. 7, dump line is closed and all steam exergy power produced in the steam generators (main and auxiliary) is used in the steam system. At observed system load, deaerator and air heater take the highest share in current cumulative auxiliary steam exergy power (40% each). In desuperheater goes 17% of cumulative auxiliary steam exergy power, while the atomizing steam system takes a share of 3%. When compared with the lower steam system load, it can be concluded that share in current cumulative auxiliary steam exergy power of each auxiliary device increases with an increase in steam system load.

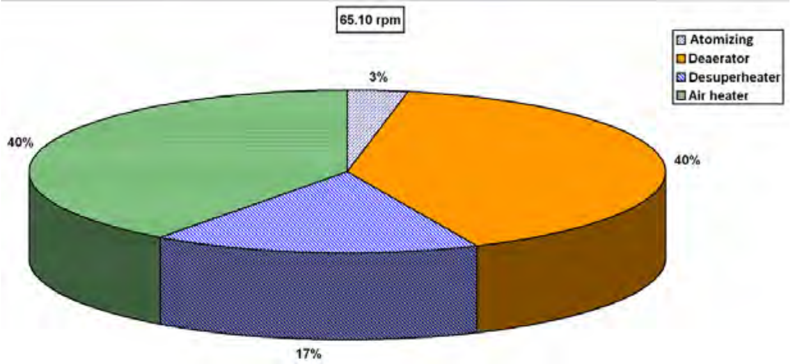

Figure 7 Share in the cumulative auxiliary exergy power of each auxiliary device - propulsion propeller speed of 65.10 rpm

At propulsion propeller speed of 78.41 rpm, auxiliary steam flow is sent to just three auxiliary devices (air heater, desuperheater and the atomizing steam system). Air heater takes the highest share in current cumulative auxiliary steam exergy power with 71%, Fig. 8. Desuperheater takes 25% and atomizing steam system takes 4% of current cumulative auxiliary steam exergy power.

At the highest observed propulsion propeller speeds (from 81.49 rpm to 83.00 rpm) cumulative auxiliary steam exergy power is sent only to atomizing steam system, so its share in that steam system operation area is 100%.

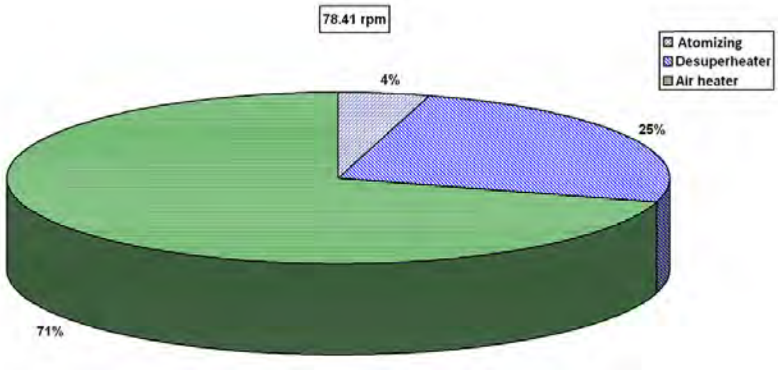

Figure 8 Share in the cumulative auxiliary exergy power of each auxiliary device - propulsion propeller speed of 78.41 rpm

6. CONCLUSION

This paper presents an analysis of steam auxiliary exergy flow stream during the change in marine steam propulsion system load.

At low propulsion propeller speeds the highest auxiliary steam exergy power is sent to the main condenser through dump line. That amount of auxiliary steam exergy power is lost because at the lowest loads it is not required in the steam system. After dump system, at low system loads the most dominant amount of auxiliary steam exergy power is sent to the deaerator and air heater while the atomizing steam system takes a significantly smaller amount of auxiliary steam exergy power in comparison to other components.

At middle and high propulsion system loads, dump line is closed and the greatest consumers of auxiliary steam exergy power are deaerator and air heater, after which follows desuperheater. The atomizing steam system uses low and almost constant auxiliary steam exergy power in the entire area of middle and high steam system loads due to dual burning mode, with minimum fuel and maximum gas mode. At the highest observed system loads atomizing steam system is the only auxiliary device which consumes auxiliary steam exergy power.

Auxiliary steam from steam generators is sent to auxiliary devices until the moment when each auxiliary device (with an exception of the atomizing steam system) gets a steam for its operation from the main steam turbine subtractions.

Share in current cumulative auxiliary steam exergy power of each auxiliary device increases with an increase in steam system load.

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Nomenclature

Abbreviations:

LNG	Liquefied Natural Gas

Latin Symbols:

$\dot{E}$	stream flow power, kJ/s
h	specific enthalpy, kJ/kg
$\dot{m}$	mass flow rate, kg/s or kg/h
p	pressure, MPa
P	power, kJ/s
$\dot{Q}$	heat transfer, kJ/s
s	specific entropy, kJ/kg•K
SH	share, %
T	temperature, °C or K
$\dot{X}_{\mathrm{heat}}$	heat exergy transfer, kJ/s

Greek symbols:

ε	specific exergy, kJ/kg

Subscripts:

0	ambient conditions
AD	Auxiliary device
AH	Air heater
AUX	Auxiliary
CU	Cumulative
D	destruction (losses)
DEA	Deaerator
DES	Desuperheater
DU	Dump
ex	exergy
IN	inlet (input)
MA	Main
OUT	outlet (output)
AS	Atomizing steam

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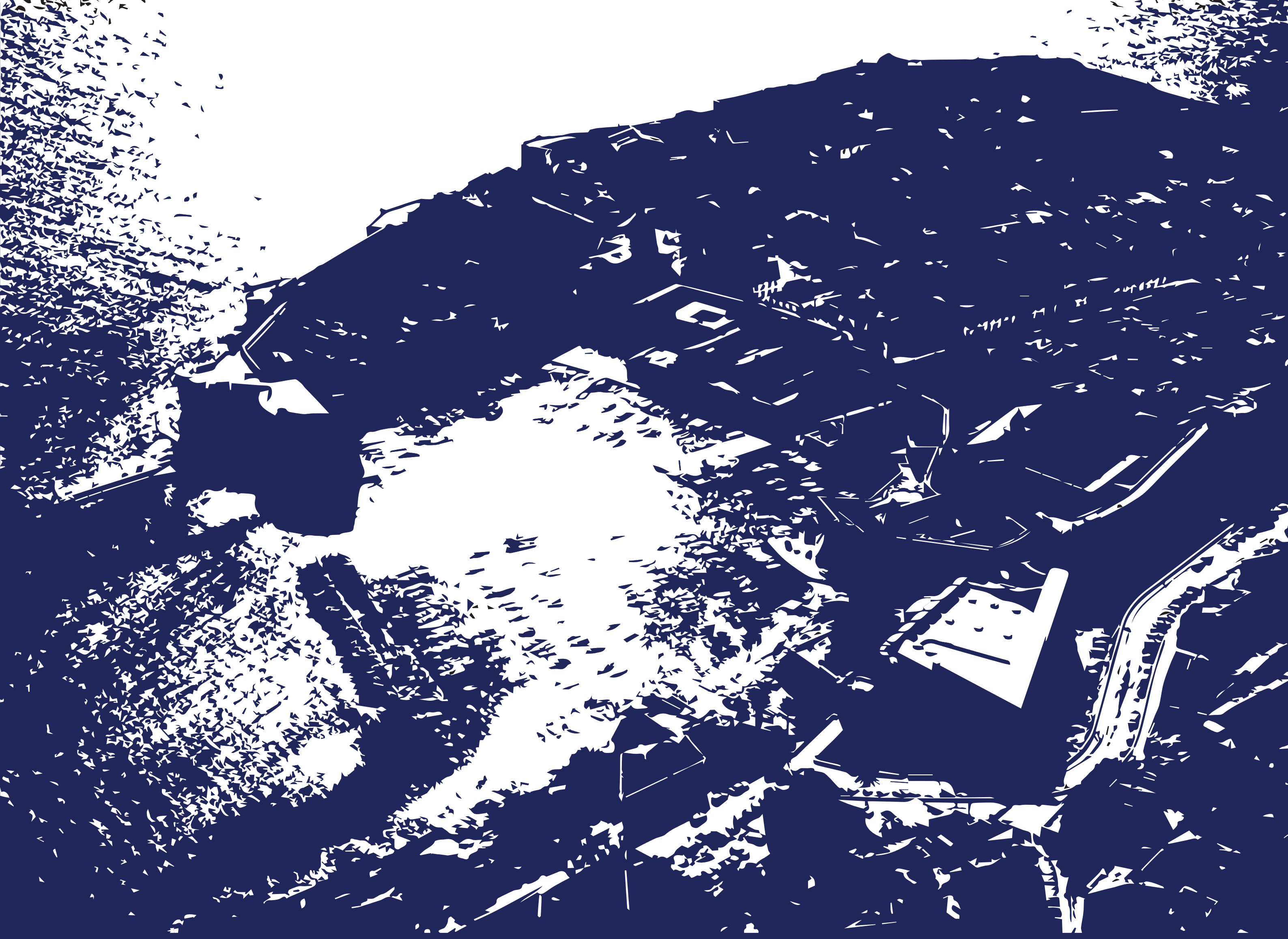

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