THE CHANGE IN ENERGY FLOW STREAMS FOR MAIN MARINE PROPULSION STEAM TURBINE AT DIFFERENT LOADS

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Abstract: *This paper present analysis of energy flow streams through the main steam turbine (the turbine is used for commercial LNG carrier propulsion) at three different loads. An increase in the propulsion plant (and proportionally increase in the main turbine) load resulted with an increase in energy flow streams and with an increase in the amount of water droplets inside steam at the main turbine outlet. Analyzed turbine has three steam extractions which opening as well as the amount of energy flow stream delivered through each extraction, significantly differs at various loads. The analysis shows that the highest energy flow stream consumers from the main turbine are deaerator and high pressure feed water heating system.*

KEYWORDS: MAIN MARINE STEAM TURBINE, ENERGY FLOW STREAMS, LOAD CHANGE, POWER DISTRIBUTION

1. Introduction

In a worldwide fleet, the dominant power producers for ship propulsion are nowadays internal combustion engines [1-3]. Steam and gas turbines are usually rarely used, but however, they have application in engine rooms of a certain ship types [4] and they are (or can be) a baseline for new complex marine propulsion plants [5, 6].

In propulsion of LNG carriers, steam propulsion plants still have a dominant role caused by its operation specificity and characteristics of transported cargo [7, 8], but also, the internal combustion engines impact in this ship type is each day more and more evident [9].

This paper presents analysis of energy flow streams through main marine propulsion steam turbine, which operates at the LNG carrier. Analysis was performed at three different turbine loads. It is analyzed and explained the dynamics in energy flow streams change during the change in turbine load, and the influences of such change on the entire marine propulsion plant operation are discussed. At the end is presented cumulative produced power distribution at each turbine cylinder (for each observed turbine load) and the guidelines for a future research are provided.

2. Description and operating characteristics of main marine propulsion steam turbine

Main marine propulsion steam turbine analyzed in this study is used for the conventional LNG carrier drive. The main specifications of the LNG carrier are presented in [10]. Turbine consists of two cylinders - HPC (High Pressure Cylinder) and LPC (Low Pressure Cylinder), Fig. 1. Both turbine cylinders are connected to a gearbox, through which is obtained propulsion propeller drive.

The marine steam propulsion plant has two identical steam generators (due to safety reasons). Cumulative produced steam mass flow rate is mainly delivered to all turbines which exist inside the power plant (main propulsion turbine, turbogenerators and steam turbine for the main feed water pump drive [11, 12]), while one smaller amount of steam (with reduced temperature) is delivered to other ship systems (auxiliary steam).

Steam delivered to the main propulsion turbine expanded firstly through HPC and after expansion in HPC, steam is delivered directly to LPC (analyzed steam turbine did not posses steam reheating like newer versions of such turbines [13]). After expansion in LPC, steam is delivered to the main marine steam condenser.

Entire main marine propulsion steam turbine has three steam extractions, as presented in Fig. 1. First extraction is from HPC (extracted steam is used for ship auxiliary systems heating), second extraction is located between HPC and LPC (extracted steam is used for steam delivery into the deaerator and high pressure feed water heating system); while third extraction is from LPC (extracted steam is used for heating low pressure condensate heating system components). It should be noted that steam extractions opening/closing as well as steam mass flow rate extracted from each extraction depend on current steam propulsion plant load (steam propulsion plant load is proportional to main propulsion turbine load). Also, in this analysis, steam mass flow rates lost through both gland seals of each main propulsion steam turbine cylinder are neglected [14] in order to present the change of dominant energy flow streams through turbine at different loads.

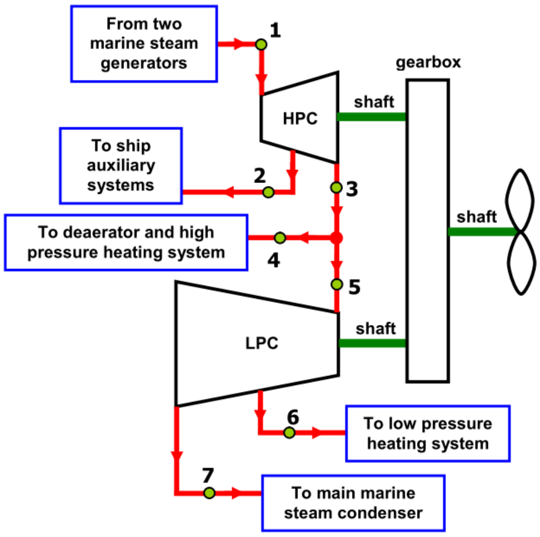

Fig. 1. *Main marine propulsion steam turbine with operating points required for the analysis*

3. Governing equations required for the analysis

All of the equations in this section are based on the observed main marine propulsion steam turbine and its operating points presented in Fig. 1.

Energy analysis of any plant, system or a component is based on the first law of thermodynamics [15, 16]. The main energy balance equation can be expressed as presented in [17]:

$$\left(\dot{Q} + P + \sum(\dot{m} \cdot h)\right)_{\text{input}} = \left(\dot{Q} + P + \sum(\dot{m} \cdot h)\right)_{\text{output}}, \quad (1)$$

where $\dot{Q}$ is heat transfer in kW, P is power in kW, $\dot{m}$ is operating medium mass flow rate in kg/s and h is operating medium specific enthalpy in kJ/kg.

For any fluid stream (for each operating point in Fig. 1), energy flow is calculated as presented in [18]:

$$\dot{E}_{\text{en}} = \dot{m} \cdot h, \quad (2)$$

where $\dot{E}_{\text{en}}$ in kW is energy flow of any fluid (operating medium) stream.

HPC developed power in each turbine load is calculated as:

$$P_{\text{HPC}} = \dot{m}_1 \cdot (h_1 - h_2) + (\dot{m}_1 - \dot{m}_2) \cdot (h_2 - h_3), \quad (3)$$

while LPC developed power in each turbine load is calculated as:

$$P_{LPC} = \dot{m}_5 \cdot (h_5 - h_6) + (\dot{m}_5 - \dot{m}_6) \cdot (h_6 - h_7) . \quad (4)$$

Cumulative produced power for the main propulsion propeller drive (cumulative power produced by the main turbine) is:

$$P_{cumulative} = P_{HPC} + P_{LPC} . \quad (5)$$

The share of each cylinder in cumulative main marine propulsion steam turbine developed power is:

$$Z_{HPC}(\%) = \frac{P_{HPC}}{P_{cumulative}} \cdot 100 = \frac{P_{HPC}}{P_{HPC} + P_{LPC}} \cdot 100 , \quad (6)$$

for HPC, while this share for LPC is:

$$Z_{LPC}(\%) = \frac{P_{LPC}}{P_{cumulative}} \cdot 100 = \frac{P_{LPC}}{P_{HPC} + P_{LPC}} \cdot 100 . \quad (7)$$

4. Measured steam operating parameters at different loads

For the accurate and precise analysis of energy flow streams through main marine propulsion steam turbine, at each observed load are required steam mass flow rates, pressures and temperatures in each turbine operating point from Fig. 1. Such steam operating parameters are presented in Table 1 for low turbine load, in Table 2 for middle turbine load and in Table 3 for high turbine load [19]. Presented steam operating parameters are measured during marine steam propulsion plant operation by using calibrated measuring equipment which is mounted inside engine room and is used for power plant regulation and control [20].

Along with steam mass flow rates, pressures and temperatures, in Table 1, Table 2 and Table 3 are presented specific enthalpies for each steam flow stream, calculated by using NIST REFPROP 9.0 software [21]. Analysis of energy flow streams is not dependable on the conditions of the ambient in which observed steam turbine operates, therefore the ambient temperature and pressure do not have to be defined [22, 23].

Table 1. *Steam operating parameters at low turbine load*

Low load (Operating points - Fig. 1.)	Temperature (°C)	Pressure (MPa)	Mass flow rate (kg/h)	Specific enthalpy (kJ/kg)
1	488.0	6.190	16605	3392.2
2	-	-	0	-
3	243.0	0.151	16605	2958.8
4	-	-	0	-
5	243.0	0.151	16605	2958.8
6	-	-	0	-
7	32.50	0.00489	16605	2531.7

Table 2. *Steam operating parameters at middle turbine load*

Middle load (Operating points - Fig. 1.)	Temperature (°C)	Pressure (MPa)	Mass flow rate (kg/h)	Specific enthalpy (kJ/kg)
1	513.5	6.020	65012	3454.9
2	-	-	0	-
3	256.0	0.467	65012	2974.6
4	256.0	0.467	4690	2974.6
5	256.0	0.467	60322	2974.6
6	156.0	0.097	2032	2788.7
7	29.47	0.00412	58290	2390.0

Table 3. *Steam operating parameters at high turbine load*

High load (Operating points - Fig. 1.)	Temperature (°C)	Pressure (MPa)	Mass flow rate (kg/h)	Specific enthalpy (kJ/kg)
1	500.0	5.899	96474	3424.3
2	350.0	1.565	3268	3146.7
3	256.0	0.593	93206	2970.4
4	256.0	0.593	13609	2970.4
5	256.0	0.593	79597	2970.4
6	153.0	0.121	3355	2781.1
7	34.92	0.00561	76242	2373.4

5. Results and discussion

All energy flow streams (energy of steam and each cylinder produced power) for the main marine propulsion steam turbine at low load are presented in Fig. 2. The steam energy flow stream which enters in the main turbine from marine steam generators at low load is equal to 15646.52 kW. That steam energy flow stream at low load is used only for power production in HPC and LPC, because all steam extractions (from HPC, from LPC and between cylinders) are closed and energy flow through each extraction is equal to 0 kW. Therefore, it can be concluded that at low load, steam generators produce steam energy flow stream sufficient only for power production by both main turbine cylinders.

At low propulsion plant loads, steam required for all marine elements operation is delivered from steam generators (auxiliary steam), not from main turbine [24]. Steam energy flow stream which is, at low load, delivered to the main marine steam condenser (at the LPC outlet) equals 11677.46 kW and can be calculated as inlet steam energy flow stream (delivered from steam generators) reduced for the produced power of both main turbine cylinders.

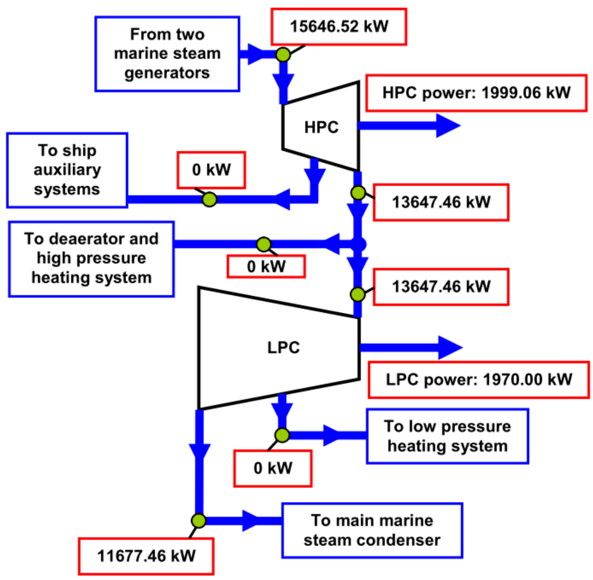

Fig. 2. *Energy flow streams through main marine propulsion steam turbine - low load*

The steam energy flow stream which enters in the main turbine from marine steam generators at middle load is significantly higher in comparison to low load (62391.66 kW in comparison to 15646.52 kW), Fig. 3. Such higher steam energy flow stream is used for much higher power production of both steam turbine cylinders when compared to low load. In addition, at middle load are open two of three steam extractions.

HPC steam extraction is still closed at middle load, so steam for ship auxiliary systems is still delivered from steam generators (auxiliary steam). Steam extractions between two main turbine cylinders as well as LPC extraction are open and cumulative steam energy flow stream extracted from the main turbine at low load is equal to 5449.31 kW, Fig. 3. From Fig. 3 should be noted that deaerator and high pressure feed water heating system requires more than double steam energy in comparison to low pressure condensate heating system at middle load. Steam energy flow stream delivered to main marine steam condenser at middle load is equal to 38698.09 kW.

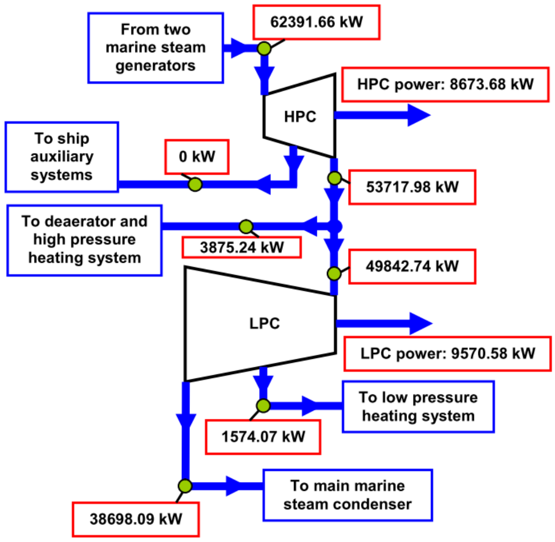

Fig. 3. *Energy flow streams through main marine propulsion steam turbine - middle load*

At high propulsion plant load, steam energy flow streams delivered into the main turbine form steam generators (91765.53 kW) and delivered from main turbine to main marine condenser (50264.66 kW) are the highest in comparison with lower loads, Fig. 4. Also, at high load both main turbine cylinders produce significantly higher power when compared to lower loads.

High propulsion plant load is characterized with a fact that all of three steam extractions are open, and steam is delivered to almost all steam plant components directly from the main steam turbine. Comparison of steam energy flow steams extracted through each main turbine extraction at high load shows that the highest steam energy flow consumers are deaerator and high pressure feed water heating system elements which uses four (or more than four) times higher steam energy flow stream than other extractions. At the same time, ship auxiliary systems and low pressure condensate heating system use steam energy flow streams equal to 2856.50 kW and 2591.83 kW, respectively.

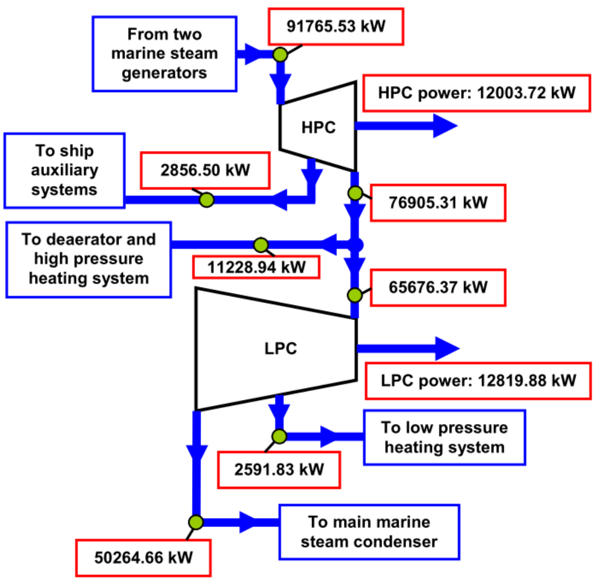

Fig. 4. *Energy flow streams through main marine propulsion steam turbine - high load*

From the previous observations can be concluded that power produced by main marine propulsion steam turbine cylinders increases in each cylinder during the increase in steam plant load. It is interesting to observe the share of each main turbine cylinder in cumulative produced power. In Fig. 5 is presented that at low propulsion plant loads, the dominant power producer inside the main turbine is HPC, while an increase in steam plant load resulted with a fact that at middle and high loads the dominant power producer is LPC. The highest difference between the main turbine cylinders share in cumulative produced power can be seen at the middle power plant load where HPC takes a share of 47.54%, while the LPC takes a share of 52.46%.

Proper main steam turbine operation significantly depends on the proper operation of the main steam condenser. Steam in each operating point of main marine steam turbine from Fig. 1 is superheated with an exception of operating point 7 (entrance into the main condenser) where the steam is saturated, regardless of the observed steam plant load. For the proper main condenser operation is interesting to note that an increase in steam propulsion plant load resulted with a decrease in steam content at the main condenser entrance (LPC outlet). This element resulted with a fact that increase in steam propulsion plant load resulted with higher amount of water droplets inside steam at the last LPC stages and at the main condenser inlet, which is valuable information for designing and maintenance of both main steam turbine and main steam condenser.

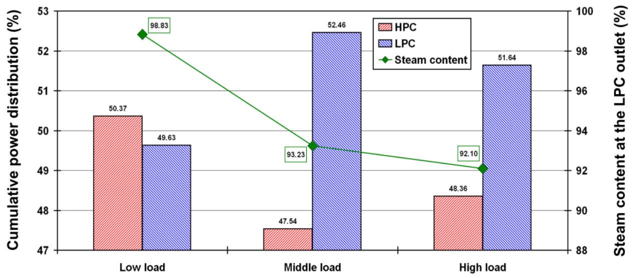

Fig. 5. *Cumulative produced power distribution on both main marine propulsion steam turbine cylinders and steam content at the LPC outlet for all observed loads*

Based on the previous researches of the same authors, further improvement and possible optimization of presented main marine propulsion steam turbine will be performed by using advanced artificial intelligence methods and algorithms [25, 26].

6. Conclusions

This paper presents an analysis of energy flow streams through the main propulsion steam turbine at three different loads. The analysis is based on measured steam operating parameters from conventional LNG carrier on which observed turbine operates (the main turbine is used for LNG carrier propulsion). The main conclusions obtained in this analysis are:

- Energy flow streams notably increases during the increase in propulsion plant load.
- At low propulsion plant loads, all steam extractions from the main turbine are closed. Increase in propulsion plant load resulted with the opening of some steam extractions (middle loads), while at high loads all steam extractions from the main turbine are opened.
- Energy flow streams delivered from main turbine to the steam consumers (through extractions) significantly differs. The highest energy flow stream consumers are deaerator and high pressure feed water heating system.
- At low propulsion plant loads the highest share in cumulative main turbine produced power takes High Pressure Cylinder (HPC), while the dominant power producer at other loads is Low Pressure Cylinder (LPC).
- Increase in propulsion plant load resulted with higher amount of water droplets inside steam at the LPC outlet (main condenser inlet).
- This analysis will be used as a baseline for further research of presented main propulsion steam turbine and for the possible

improvement of the whole propulsion plant in which main turbine operates.

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