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INFLUENCE OF THE CRUISING SPEED OF A SHIP ON EXHAUST GAS BOILER EFFICACY

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Abstract

The paper presents simulation calculations for a ship's power transmission system and the associated exhaust gas boiler with the aim of assessing the boiler's efficacy. Increasing prices of marine fuels force ship owners to limit the cruising speed of ships. This has negative impact on the operation of an exhaust gas boiler powered with exhaust fumes from the main engine. The boiler's capacity decreases, seriously limiting the tasks ascribed to vapour. Simulation calculations were conducted for the most typical system used on sea ships, i.e. a multi-turn engine and the associated exhaust gas boiler which generates saturated vapour. Adopting several values of ship cruising speed, which were smaller than the nominal speed, was a starting point for the calculations. Main engine powers were calculated with partial loads. Next, relevant values of excess air number were assigned to those powers and classic combustion calculations were conducted with the use of stochiometric combustion equations. For assumed fumes temperatures in front of and behind the boiler drops in fumes enthalpy were noted. It enabled to calculate the values of heat fluxes released by the fumes in the boiler. After adopting relevant vapour parameters boiler capacities were evaluated as appropriate. Results of those calculations are shown in tables and on the graphs. The summary of the paper includes conclusions and suggestions which may be helpful as far as designing waste heat recovery systems is concerned.

Keywords: *thermodynamics, heat transfer, marine power plants, marine steam boilers, marine diesel engines*

1. Introduction

In recent years a systematic, or at times even a sudden, increase of marine fuels has been observed. With varying intensity, this phenomenon occurred before as "fuel crises" in the years 1973, 1979 and a number of subsequent years. It was characteristic that when fuel prices increased, ship owners resorted to recovery systems to increase power plant's efficiency and thus reduce the consumption of ever more expensive fuel. Over time, more and more advanced, and hence more expensive, deep waste heat recovery systems were introduced. Amortization period for such systems is calculated not in months but in years, sometimes even many years. The systems have been developing mainly towards recovering waste heat generated by fumes from the main engine.

The recent fuel crisis in the first decade of the 21st century caused unprecedented reaction among the majority of ship owners. Expensive deep waste heat recovery systems were replaced by another method of reducing operating costs, that is reducing the cruising speeds of ships. In effect, efficiency of all waste heat recovery systems has deteriorated, and in some cases the systems have been fully or partly exempt from operation.

Exhaust gas boilers are being matched with an engine operating at a nominal load or with any partial load as indicated by the ship owner [1,2].

Below, simulation calculations are presented, which were made for the assumed main engine cooperating with the most typical exhaust gas boiler, i.e. the boiler generating saturated vapour for heating and technological purposes. Those calculations are based on the assumption that the boiler was matched with the nominal load of the main engine to ensure the nominal speed of the ship. Subsequent calculation points reflect decreasing cruising speeds, and thus a decreasing power of the main engine.

2. Combustion calculations

Calculations were made for engine 8S50MC by MAN Diesel & Turbo. It is a dual stroke, crosshead, supercharged engine operating at low-speed, with the following technical parameters [6]:

- number of cylinders…………………………….….8,
- nominal power……………………………….....11,140 kW,
- nominal rotational speed……………….............127 rpm

The engine, coupled with a screw by a shaft line, constitutes a direct power transmission system. An assumption was made that while working at a nominal power and nominal rotational speed the engine powers the ship at a speed of 20 knots.

Simulation calculations were made for the following six cruising speeds of the ship: 20 k, 19 k, 18 k, 17 k, 16 k, 15 k. It was assumed that when the ship’s speed is being gradually decreased, sailing conditions remain the same, which means that all the time the power screw is operating at a fixed value of advance coefficient. Therefore, the ship's forward speed is proportional to the screw's rotational speed. It was assumed that the power developed by the engine is proportional to the rotational speed of the engine (screw) to the third power. Table 1 shows relevant powers for adopted cruising speeds.

Tab.1. Relationship between power of the main engine and the ship's speed

No.	V [k]	N [kW]	N [%]
1	20	11,140	100
2	19	9,551	85,7
3	18	8,121	72,9
4	17	6,840	61,4
5	16	5,703	51,2
6	15	4,678	42

where:

No. – ordinal number,
V – ship's speed,
N – engine’s power.

For combustion calculations, heavy fuel with the following working composition was used (mass contents): C=85.44%; H=10.85%; O=0.39%; S=1.18%; N=1.14%; W=1.00%.

where:

C – coal content,
H – hydrogen content,
O – oxygen content,
S – sulphur content,
N – nitrogen content,
W – humidity content.

When calculating fumes enthalpy, a change in the excess air number λ, which occurs when the engine load is changed, was taken into account. Experimental data obtained in the combustion engine laboratory in the Department of Maritime Power Plants in the Gdynia Maritime University were used. The relationship shown in Figure 1 was created based on the balance of carbon dioxide contained in fumes.

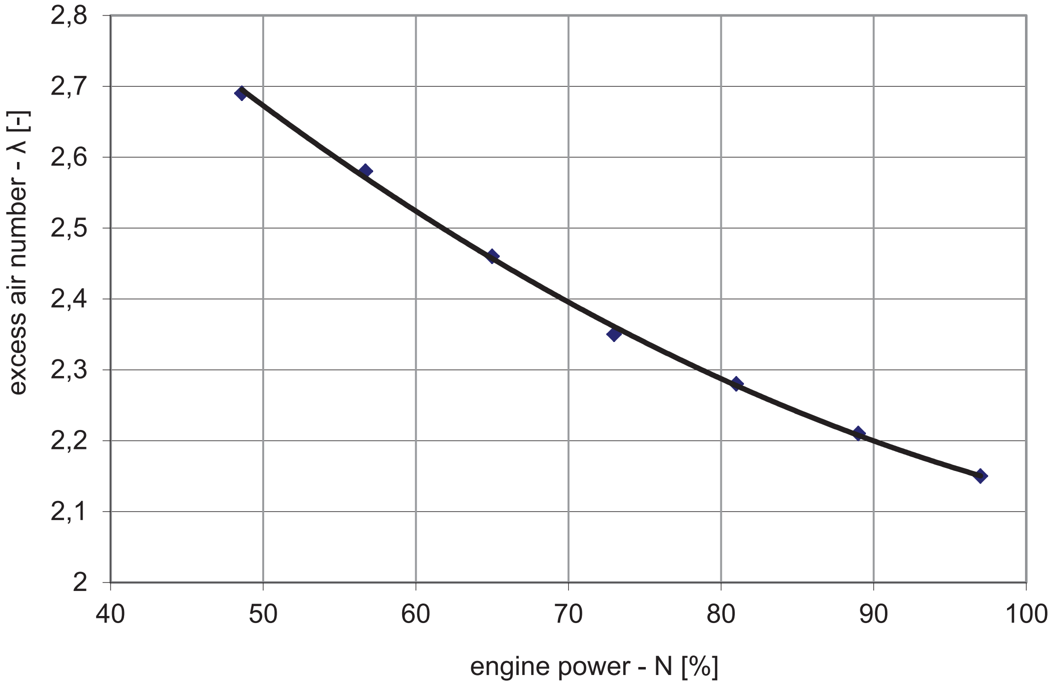

Fig. 1. Relationship between excess air and engine power

For further calculations, it was assumed that the nature of excess air number λ changes is as shown in Figure 1. Relevant values λ were calculated based on the experimental data approximating equation. Λ values reflecting relevant cruising speeds of the ship were show in Table 2.

Tab.2. Relationship between excess air number λ and the ship's speed

No.	V [k]	λ
1	20	2,11
2	19	2,22
3	18	2,35
4	17	2,49
5	16	2,64
6	15	2,80

To calculate the values of heat fluxes allowing for utilization, fumes enthalpy graphs in the function of fumes temperature were developed for six λ values as specified in Table 2. Fumes enthalpy was calculated based on equation (1) [3].

$$I = V_{CO2}i_{CO2} + V_{SO2}i_{SO2} + V_{N2}i_{N2} + V_{O2}i_{O2} + V_{H2O}i_{H2O} \quad [kJ/kg\ fuel], \tag{1}$$

where:

I [kJ/kg fuel] – fumes enthalpy produced by using up one kilogram of fuel,
V [Nm^3/kg fuel] – volume of one fumes component,
i [kJ/Nm^3] – enthalpy of a given fumes component.

Volume of each fumes component was calculated based on stoichiometric combustion equation. Results of fumes enthalpy calculations in the function of fumes temperature for six different values of excess air number are shown in Figure 2.

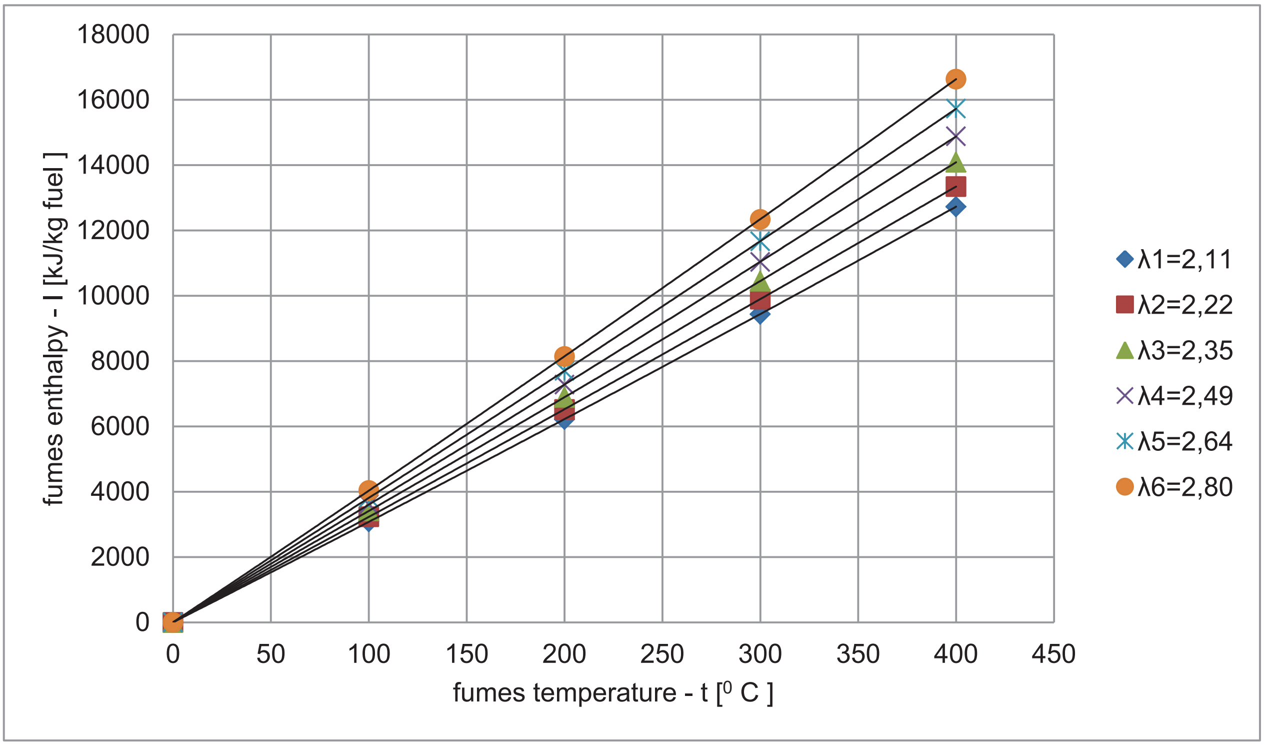

Fig. 2. Relationship between fumes enthalpy and fumes temperature for selected values of excess air number

3. Heat transfer calculations

Engine specifications provided by manufacturers and numerous performance measurements [5] made on ships point out that within the 50% - 100% range of engine load changes fumes temperature behind the turbocharger is very stable. Based on specifications of a given engine [6] the adopted value of fumes temperature behind the turbocharger was t_s=230 ^oC, The same temperature was adopted for further calculations as temperature at the front of the boiler.

It was assumed that the boiler produces saturated vapour with working pressure p_r=0.7 MPa. This pressure corresponds to the temperature saturated vapour t_n=170 ^oC. It was assumed that the minimum temperature discrepancy between heat transferring factors (pinch point) is 10 ^oC. Thus, temperature of exhaust fumes released by the boiler (behind the last heating surface) is t_{wyl}=180 ^oC. Decrease in the fumes temperature in the boiler is: $\Delta t_{sp} = t_s - t_{wyl} = 230 – 180 = 50$ ^oC.

On the I = f(t) graph relevant values of fumes enthalpy were read for temperatures t_s i $t_{wyl.}$ Table 3 shows relevant values of fumes enthalpy and discrepancies for individual values of excess air number.

Tab.3. Fumes enthalpy for fumes temperatures in the front of and behind the boiler, with different values of excess air number λ

No.	λ	I_s [kJ/kg fuel]	I_{wyl} [kJ/kg fuel]	ΔI [kJ/kg fuel]
1	2.11	7,180	5,588	1,591
2	2.22	7,532	5,862	1,670
3	2.35	7,957	6,194	1,763
4	2.49	8,404	6,542	1,861
5	2.64	8,885	6,918	1,967
6	2.80	9,401	7,319	2,081

where:

I_s – fumes enthalpy in front of the boiler,
I_{wyl} – fumes enthalpy behind the boiler,
ΔI – difference between fumes enthalpy in front of and behind the boiler.

The next stage of calculations is to calculate fuel consumption with relevant forward speeds. Unit fuel consumption was adopted based on specifications [6]. Relevant values of fuel consumption are shown in Table 4.

Tab.4. Fuel consumption for individual cruising speeds

No.	V [k]	g_e[g/kWh]	B[kg/h]	B_s[kg/s]
1	20	171	1,956	0,5433
2	19	170	1,666	0,4627
3	18	169	1,409	0,3913
4	17	170	1,194	0,3316
5	16	171	1,001	0,2780
6	15	172	702	0,1950

where:

g_e – unit fuel consumption,
B – fuel consumption per hour,
B_s – fuel consumption per second.

Heat flux released by fumes in exhaust gas boiler was calculated based on equation (2).

$$Q_{sp} = B_s \Delta I \text{ [kW]} \tag{2}$$

where:

Q_{sp} – heat flux released by fumes in the exhaust gas boiler.

Relevant values of heat fluxes Q_{sp} are show in Table 5.

Tab.5.Heat fluxes released by fumes in the boiler at individual cruising speeds

No.	V [k]	Q_{sp}[kW]
1	20	864
2	19	772
3	18	689
4	17	617
5	16	546
6	15	405

Heat received by water in the boiler reduced by losses of heat released to atmosphere. That loss is accounted for by heat keeping coefficient φ. The adopted value was φ=0,9. Therefore, fluxes of heat intercepted by water Q_w may be calculated based on equation (3).

$$Q_w = \varphi\, Q_{sp}\ [kW] \tag{3}$$

Relevant values of heat fluxes Q_w are show in Table 6.

Tab.6. Fluxes of heat intercepted by water at individual cruising speeds

No.	V [k]	Q_w[kW]
1	20	855
2	19	764
3	18	682
4	17	610
5	16	540
6	15	401

The boiler's capacity, with relevant heat fluxes Q_w may be calculated based on equation (4).

$$D = \frac{Q_w}{i_p - i_{wz}}\ [kg/s] \tag{4}$$

where:

D[kg/s] – boiler's capacity per second.
i_p[kJ/kg] – vapour enthalpy,
i_{wz}[kJ/kg] – enthalpy of the water powering the boiler.

The boiler's capacities for relevant cruising speeds are shown in Table 7.

Tab.7. Boiler's capacity at individual cruising speeds.

No.	V [k]	D[kg/s]	D_h[kg/h]
1	20	0.350	1,264
2	19	0.313	1,130
3	18	0.280	1,080
4	17	0.250	902
5	16	0.221	789
6	15	0.164	593

where:

D_h[kg/h] – hourly capacity.

Capacity per second, taken directly from equation (4) is provided here, along with the so called hourly capacity, in other words capacity provided by the manufacturer in specifications. The results are shown in tables and on the graph in Figure 3. The graphic representation of data involves only hourly capacity, which is often used to show boiler performance.

Relationship between the boiler's capacity and the cruising speed is shown in Figure 3.

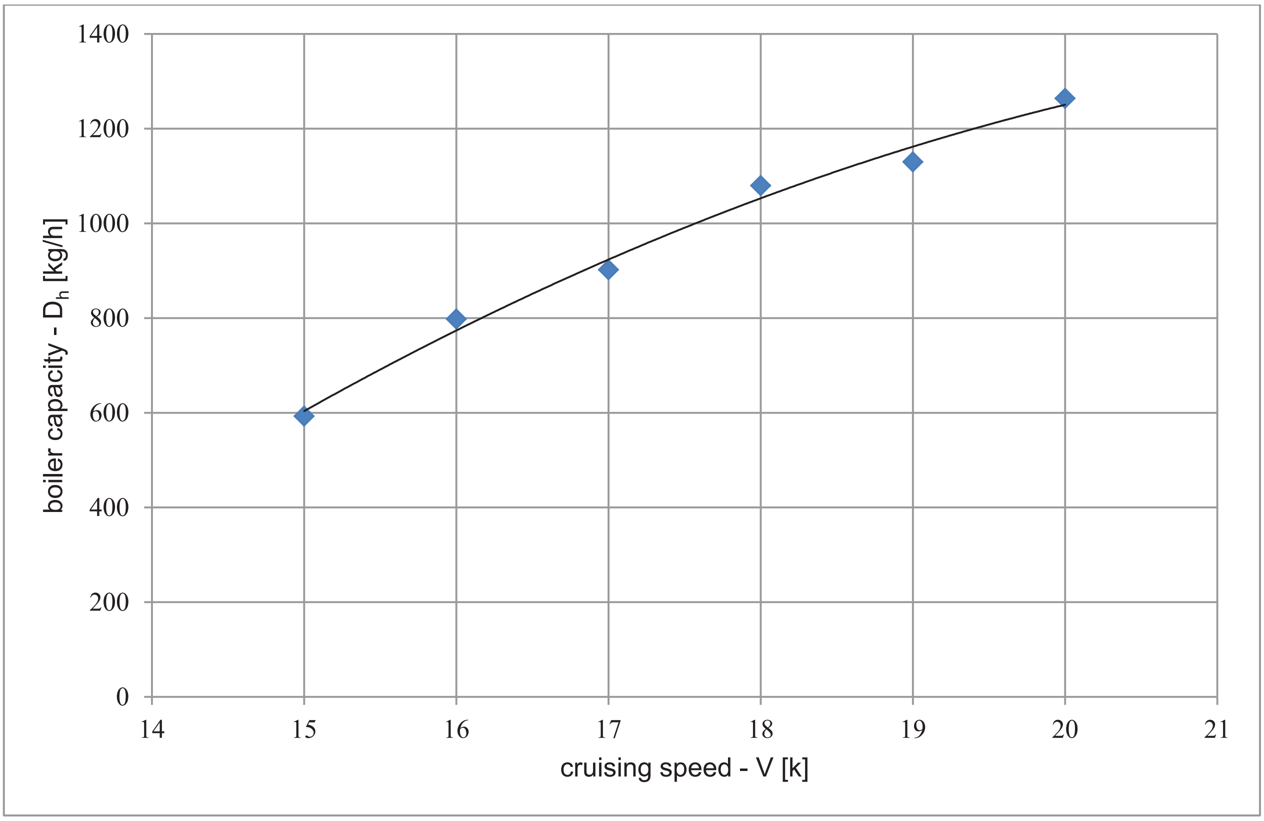

Fig.3. Relationship between boiler's capacity and cruising speed

4. Summary

Results of simulation calculations point out that even the slightest decrease in cruising speed leads to significant decrease in the boiler's capacity. So, reducing the speed by 5 knots, from 20 to 15, i.e. by 25%, causes a drop in the boiler's capacity by as much as 53%.

Such a serious drop in vapour production may be associated with the necessity to launch a fired boiler. This is an completely normal procedure during manoeuvres, river or canal crossing, or in other situations where the time is limited, which may be encountered by a sea ship. Nevertheless, during long-term sea or ocean cruises, such a situation may be considered pathological.

A power plant designed for a contemporary sea ship equipped in waste heat recovery system should account for emergency situations when sometimes even for long periods of time a ship will be cruising at lower speeds that the nominal speed. To maintain the appropriate efficiency of waste energy recovery processes, possibilities of heat recovery from other sources, e.g. by cooling powering air, should be considered. Such solutions may be autonomous or may be closely connected with a classic exhaust gas boiler, ensuring production of required amount of vapour on a ship.

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