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Possibility of the steam production increase in the selected smoke tube exhaust gas boiler under the low load of the electronically controlled low speed marine prime mover

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Abstract
Modern marine Diesel prime movers are equipped with so called 'common rail' as a part installed in the fuel injection system. This kind of design, gives a possibility to control fuel injection process in ways which were not available to carry out on conventionally designed engines. During the ship operation with a reduced speed and reduced load of the main engine, especially under the "Super Slow Steaming" conditions the waste heat recovery process in exhaust gas boiler is being disturbed. In the article, there is presented a possibility to increase the steam production of the waste heat boiler by interference in the fuel injection pattern for the engine. For the selected system "low speed main engine – smoke tube exhaust gas boiler" the test session has been carried out under the real ambient and operational condition of the ship to verify described possibility. Obtained results have been presented.

Introduction

To provide safe and undisturbed operation of the sea going ships under real ambient conditions it is required to provide significant amount of thermal energy to be utilized by many particular devices and whole systems of the ship engine room. During the so called 'sea passage' the waste heat recovery systems fully meet demand for the thermal energy. On the conventional merchant marine ships the biggest amount of waste heat is being recovered from exhaust gases of ship prime movers by exhaust gas boilers. Typical exhaust gas boiler produces saturated steam to transfer recovered heat. In some special cases, like under ambient condition in tropical areas [1] for example, the overproduction of the steam can be noticed. Such situation may lead to hazardous pressure rise in the ship steam systems and installations. Therefore, it is required that ship is equipped with devices dealing with surplus steam. In contrary to described situation, during operation of the ship with considerably reduced speed which requires decrease of load of the ship's prime mover, shortage of amount of produced steam can happen. Which results from significant drop of the exhaust gas mass flow and temperature. This effect is significantly increased when ship is operated under cold or winter ambient conditions.

The modern ship's propulsion systems making use of low speed long stroke Diesel engines are being designed basing on their versions with electronic systems for control of fuel injection and exhaust valves timing. One of the most important feature of these sophisticated systems is possibility to change the number of injection valves being operated under low load of the engine. It is automatically controlled by combined hardware and software systems, which for example for the Wärtsilä low speed, long stroke engines has been named WECS1 (Wärtsilä Electronic Control System).

Characteristics of the injection system of the electronically controlled engine

The modern, electronically controlled engines do not have typical camshaft, well known from conventionally designed Diesels. Whole process of

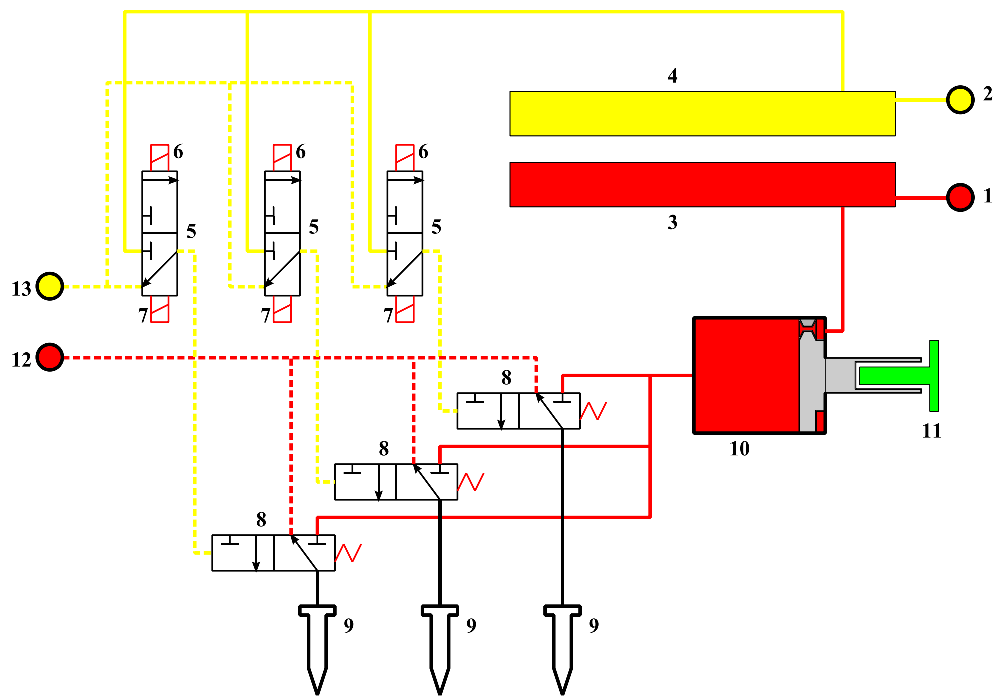

Fig. 1. The simplified injection control system for one cylinder of the large bore common rail RTx engine; 1 – fuel from high pressure fuel pumps, 2 – control oil from high pressure oil pumps, 3 – fuel rail, 4 – control oil rail, 5 – control oil valves, 6 – coil for injection START signal, 7 – coil for injection STOP signal, 8 – fuel injection control valves, 9 – injection valves, 10 – fuel quantity piston, 11 – fuel quantity sensor, 12 – fuel return line, 13 – control oil return line

fuel pressurizing and governing of the fuel injection is being maintained by so called "common rail system" (Fig. 1) which utilizes electronically processed signals from crank angle sensors. Typical Wärtsilä large bore RTx [2] (so called RT-flex) engine common rail system consists of:

- high pressure oil and fuel pumps;
- high pressure oil and fuel rails;
- fuel injection control valves;
- control oil valves;
- fuel quantity piston and sensor units.

The new design high pressure fuel pumps supply the fuel for the fuel rail. Among the injection periods, pressurized fuel is sealed from the injection line by fuel injection control valves. During injection sequence electrically activated control oil valves are activating by the control oil from the oil rail injection control valves to open fuel to the injection valves. Amount of the injected fuel is controlled by unit consisting the fuel quantity piston and sensor. Design of fuel injection system described as above, gives possibility to individually control of each of injection valve. By triggering START/STOP injection signals by the electronic control modules it is possible to run the engine with either three or two, or even only one injection valve. The number of the those being in use during operation of the engine is load dependent. To ensure even distribution of load of each of injection

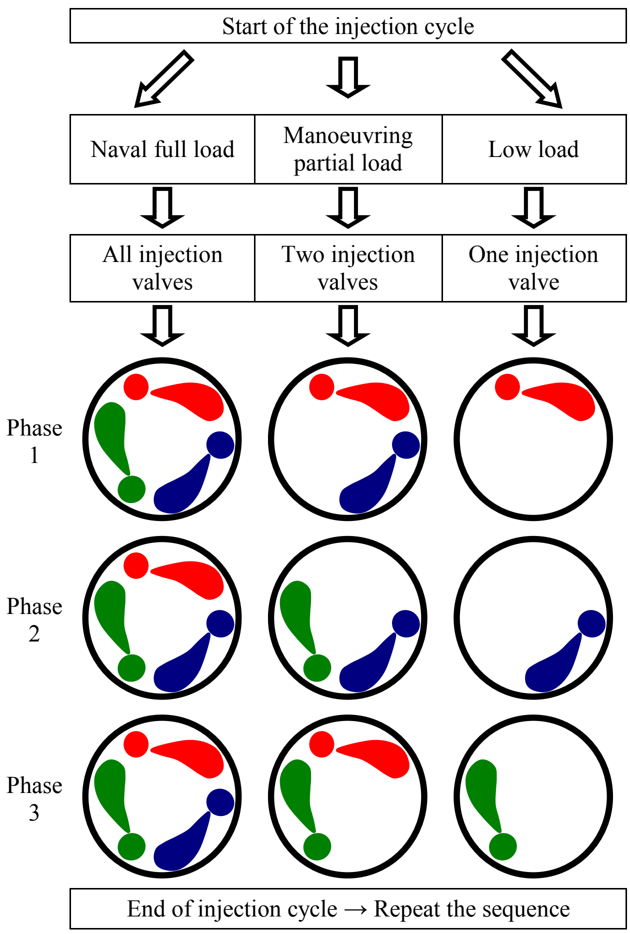

Fig. 2. The injection valves activation during one injection cycle of the large bore common rail RTx engine

valve the control unit is activating all of them or in groups respectively. Time of group activation is split into 3 phases (Fig. 2). Such a feature was not possible to be ran on the camshaft controlled Diesels equipped with standard injection pumps.

However, there is a possibility to force the engine to change the number of active injection valves to maximum even during low load of the engine (one injection valve active).

Steam production in the marine waste heat boiler

The amount of the recovered heat (q_{EB}) in the exhaust gas powered boiler by heated medium describes following equation:

$$q_{EB} = D_{EB} \cdot (i_2 - i_1) \text{ [kJ/h]} \tag{1}$$

where:

- D_{EB} – steam output of the waste heat boiler [kg/h];
- i_1 – enthalpy of the heated medium – inlet to the boiler [kJ/kg];
- i_2 – enthalpy of the heated medium – outlet from the boiler [kJ/kg].

Assuming that typical marine boilers were designed and installed on ships to produce saturated steam, above equation (1), the boiler's output can be described by formula following (2), which finally can be presented as equation (3):

$$D_{EB} = \frac{q_{EB}}{(i'' - i_{FW})} \text{ [kg/h]} \tag{2}$$

where:

- i'' – enthalpy of the produced saturated steam [kJ/kg];
- i_{FW} – enthalpy of feed water [kJ/kg].

$$D_{EB} = \frac{3.6 \cdot F_{EB} \cdot k_{EB} \cdot \delta_T}{(i'' - i_{FW})} \text{ [kg/h]} \tag{3}$$

where:

- F_{EB} – heat exchange area [m^2];
- k_{EB} – overall heat transfer coefficient [W/m^{2}K];
- δ_T – logarithmic mean temperature difference [K].

Under stabile conditions of the waste heat boiler operation the overall heat transfer coefficient (k_{EB}) mainly depends on the heat exchange coefficient (α) from exhaust gases to tube material (4). The empirical equations describing the heat exchange coefficient have been formulated by boilers manufacturers, for example by BABCOK [3] as follows:

$$\alpha = 0.287 \lambda^{0.635} c_{\text{exh}}^{0.364} \nu_{\text{exh}}^{-0.236} \dot{m}_{\text{exh}}^{0.6} \phi^{-0.4} \text{ [W/m}^2\text{K]} \tag{4}$$

where:

- c_{exh} – specific heat of exhaust gases [kJ/kgK];
- λ – thermal conductivity of the tube material [W/mK];
- $\dot{m}_{\text{exh}}$ – mass flow of exhaust gases [kg/h];
- ν_{exh} – kinematic viscosity of exhaust gases [m^2/s];
- ϕ – inner diameter of tubes [m].

During sea passages all main parameters of the "marine prime mover – exhaust gas boiler" system are stabile and mainly constant. Assuming constant temperature of the boiler feed water and pressure of the saturated steam only changes of the exhaust gas parameters can exert influence on steam production.

Exhaust gas parameters depend on many operational conditions and design factors of the engine itself, and the structure of the whole ship as well. Also the ambient conditions exert significant influence on these parameters [4]. Marine Diesel engines producers in their publications (Engine Selection Guide, Project Guide, etc.) presented empirical equations [5] allowing to evaluate temperature (5) and mass flow (6) of the exhaust gases (accordingly to MAN Diesel&Turbo).

$$T_{\text{exh}} = T_{L1} + \Delta T_O + \Delta T_{amb} + \Delta T_S + \Delta T_{TCS} \text{ [°C]} \tag{5}$$

$$M_{\text{exh}} = M_{L1} \frac{P_O}{P_{L1}} \frac{m_{O\%}}{100} \left(1 + \frac{m_{amb\%}}{100}\right) \cdot \left(1 + \frac{\Delta m_{S\%}}{100}\right) \frac{P_{S\%}}{100} \left(1 + \frac{\Delta m_{TCS}}{100}\right) \text{ [kg/h]} \tag{6}$$

where:

- M_{L1} – nominal mass flow of the exhaust gas [kg/h];
- T_{L1} – nominal temperature of the exhaust gas [°C];
- P_O, $P_{S\%}$ – engine load correction factors;
- ΔT_O, ΔT_{amb}, ΔT_S, ΔT_{TCS} – temperature correction factors;
- $m_{O\%}$, $m_{amb\%}$, $\Delta m_{S\%}$, Δm_{TCS} – mass flow correction factors.

Above presented equations are based on tabular values of exhaust gas flow and temperatures recorded for engines running at nominal MCR (M_{L1}, T_{L1}) and under ambient conditions in accordance with ISO3046-1. Procedures describing ways of calculation of particular corrections of temperature, (ΔT_O, ΔT_{amb}, ΔT_S, ΔT_{TCS}), mass flow ($m_{O\%}$, $m_{amb\%}$, $\Delta m_{S\%}$, Δm_{TCS}) and engine load (P_O, $P_{S\%}$) resulting from engine setup, partial load, variable ambient condition and eventually assembled turbo compound system were presented in engine manufacturer publications as well [5]. Adequate equations have been formulated by Wärtsilä for their types of long stroke marine prime movers [6, 7]. Conclusion arising from presented equations is, that under ambient and operational condition remaining constant with time, production of the steam by the waste heat boiler can be controlled by change of the temperature or mass flow of the exhaust gases.

As described before, electronically controlled engines can be operated with different number of activated injection valves. This number is automatically corrected by control software depending on the engine load. Under low, load of the engine it is possible to run the engine with higher number of activated injection valves than preset by manufacturer. It may be assumen, that an increase in activated injection valves will change the pattern of injection and combustion conditions, leading to taken into account the effect of change in temperature of the exhaust gases produced by Diesel engine with unchanged fuel consumption. As a result, controlling number of activated injection valves, increased steam production by the exhaust gas boiler should be achieved.

Tests under real ambient and operational conditions of the ship

On the 7200 TEU (twenty foot equivalent unit) container ship equipped with prime mover Wärtsilä 8RTx96C (P_{NMCR} = 35,006 kW, n = 93 rpm), smoke-tube exhaust gas boiler of type MISSION XS-2V (p_R = 0.75 MPa, D_n = 3700 kg/h) and oil fired boiler UNEX CHB (p_R = 0.75 MPa, D_n = 4500 kg/h) test session has been carried out. The load of main engine was lower than 20% of nominal power and constant during whole session. Due to very low load of the main engine, the oil fired boiler was permanetntly in operation. To avoid the unfavorable steam consumption changes the overproduction steam condenser have been switched off. Automatic temperature controlers for the tanks heating coils and additional heaters have been set to manual mode and fixed in one position. Therefore, it may be asumed that the ship's steam demand was kept on constant level during carried out test session. At intervals of five seconds following parameters have been recorded:

- main engine load [MW] and [% of P_{NMCR}];
- fuel setting command for main engine;
- temperatures of the exhaust gases before turbochargers [°C];
- temperatures of the exhaust gases before exhaust gas boiler [°C];
- load of burner of the oil fired boiler [%];

Measures have been split in two groups:

- taken with two injection valves in operation starting from the moment when all recorded parameters were stabile;
- taken with three injection valves in operation after change from two of them until stabilisation of recorded parameters.

Main engine power parameters during whole session have been constant except short period of activation of additional injection valve (Fig. 3). The most important fact is, that after stabilising of combustion process in the engine, the fuel command which is a control parameter for the fuel quantity piston (Fig. 1, pos. 10) remained on the same level as before the third injection valve have been engaged into injection cycle. Therefore it may be assumed that the fact of activation of the third injection valve did't change the fuel consumption of the main engine.

Exhaust gas temperatures after activation of the third injection valve began to decrease. Time of stabilisation of these parameters was longer than corresponding period for main engine power parameters (Fig. 4). The exhaust gas temperature before exhaust gas boiler kept on the same level even for a longer period after activation of the third injection valve due to transferring of accumulated heat from material of the exhaust gas manifold and pipeline (steel) connecting turbochargers and exhaust gas boiler.

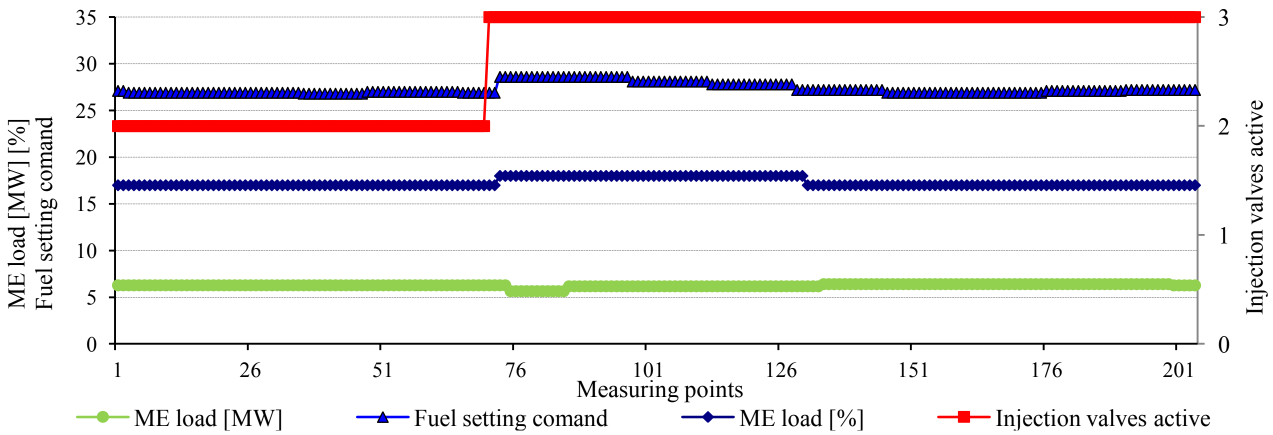

Fig. 3. The main engine power parameters

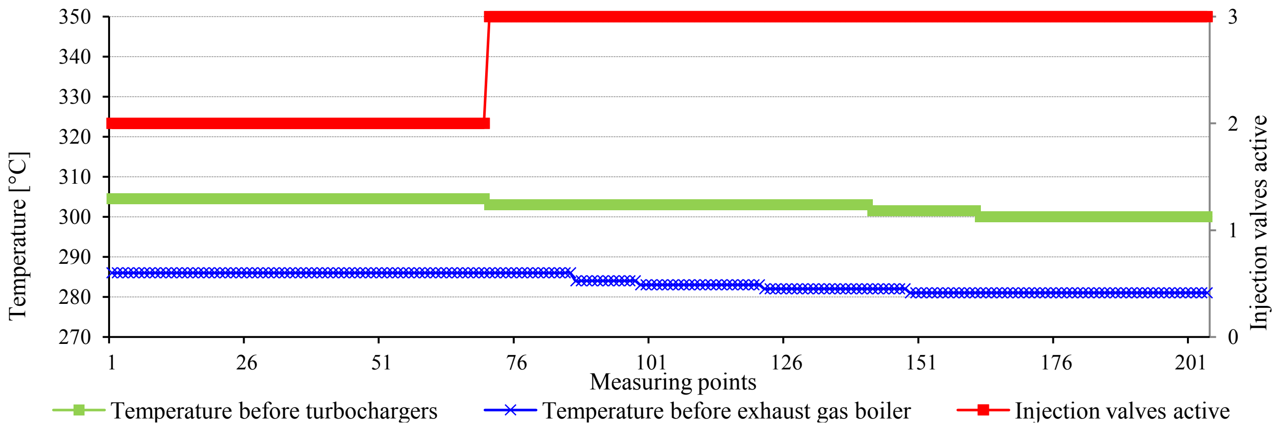

Fig. 4. The exhaust gas temperatures

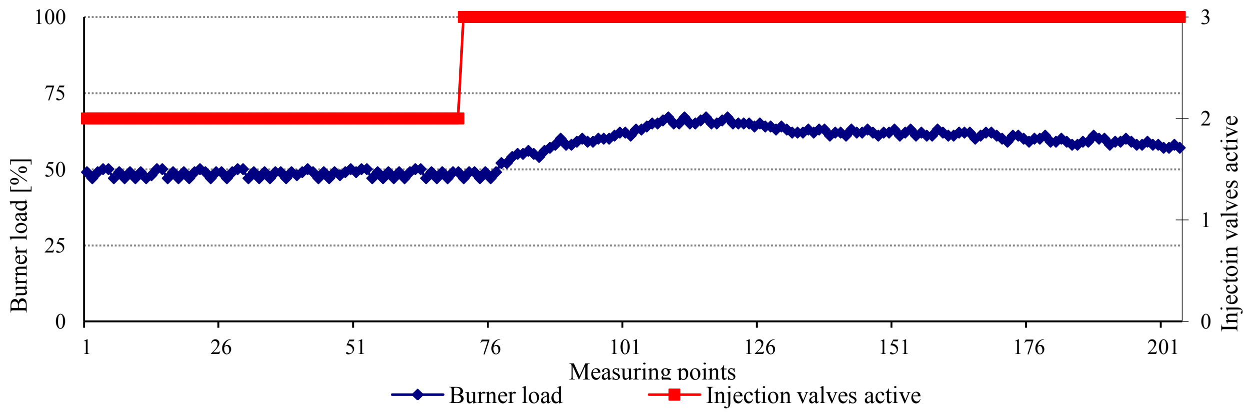

Fig. 5. The injection valves in operation and oil fired boiler load during testing session

On merchant marine ships it is not possible to directly measure amount of steam produced by exhaust gas boiler. As indication for increase or decrease of this parameter the burner load of the fired gas boiler may be used. The ship, where the tests were carried out was equipped with electronically controlled oil fired boiler enabling continuous monitoring and recording selected parameters. Therefore, boiler burner load was controlled along with the other recorded parameters of the main engine. It was clearly visible, that the load of the burner increased after activation of the third injection valve (Fig. 5). Time of the boiler burner load stabilising was longer that adequate time for the other recorded parameters because it depends on controller settings the software controlling boiler's parameters.

Conclusions

Using a new proposal electronically controlled marine engine, the lower operating load rangeit is possible to change the number of active injection valves.

Presented above results of tests carried out on the ship operated under real ambient condition are clearly pointing decrease of the exhaust gas temperature after activation of the third injection valve while fuel consumption of marine low speed large bore Diesel engine remained unchanged. As a result, increased load of the oil fired boiler burner have been observed.

Extending of range of activation of only two injection valves may be considered as a way to increase steam production by the exhaust gas boilers. The advantage will be achieved by reducing fuel consumption by oil-fired boilers, especially during prolonged maneuvers, with a much reduced load at low speed main engine.

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