Modeling and Simulating Working Processes of the Main Turbocharged Marine Diesel Engine

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Abstract. The modern marine diesel (MDE) always is designed to work together with a turbocharger (TC). The paper presents an integral model (IM) and simulation of the working processes of a complex of the MDE and TC. The MDE as a main engine (ME) drives a propeller on the motor vessel (MV). The IM was received on the basis of the integration of the theoretical and experimental researches to improve the model accuracy. The simulation algorithm was programmed in MatLab/Simulink environment and verified to 8MAK43 engine installed on the PhucHung MV. The received simulation was conducted to study the influences of nozzle cross-section to the engine performances and to optimize the nozzle cross-section in accordance with the deteriorated states of the MDE–TC complex.

Keywords: Modeling working process of marine diesel engine · Modeling working process of turbocharger · Model of the MDE–TC complex · Simulation of MDE-TC complex in MatLab/Simulink

1 Introduction

On medium and large-size diesel engines such as on the MDE, the axial TCs were widely used because their efficiency is higher than radial TC at the same working conditions. The actual working and the standard (designed) conditions of the MDE are quite different, besides that the hull resistance and weather condition affected much on engine operation. After a long operation period, the engine performance indicators would have been reduced. One of the significant causes is the un-enough scavenging air in accordance with the engine loads. The scavenging air (pressure parameter p_i, bar) depends on mainly the turbocharger working.

Watson and Janota [1] given the basic equations for the axial flow turbine. Ranke [2] researching experimentally on a 2.3L engine with an axial turbine at transient regimes shown that with the same centrifugal compressor, the axial turbine attained full boost 25 ÷ 40% faster than the TC with the radial turbine. Pesiridis [3] using MatLab to carry out the thermodynamic analysis of the axial turbine showed that the total to static efficiency (of TC) reached 74.94%.

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The method of this research is to use the integration idea of the theoretical and experimental studies [4] to improve the IM for investigating the working processes of the MDE –TC complex and to optimize the TC works by adjusting the cross-sectional area of the turbine nozzle.

2 Modeling Working Processes of the MDE–TC Complex

2.1 MDE and TC Relationship

The MDE includes combustion chambers (CC), a Scavenging air collector (SAC), and an exhaust gas block (EGB). The TC includes a turbine and a compressor. The working relationship is shown in Fig. 1.

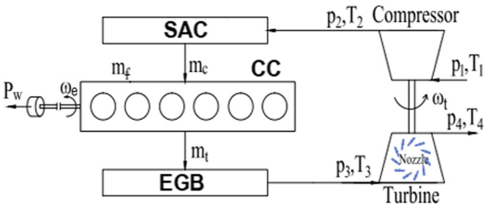

Fig. 1. Relationship between MDE and TC (*m_f, m_c(g/cycle): the amount of fuel provided for a cycle; ω_t, ω_e(rad/s): the turbine and engine speed; p(bar), T(K): pressure and temperature; subscript 1: before the compressor, 2: after the compressor, 3: before the turbine, 4: after the turbine*)

2.2 Models of the TC Working Process

The velocity triangle of the turbine blade is used to make the mathematic model. Figure 2 shows the positions and velocity triangles of the nozzle and working stages of the turbine.

Before and after the working blade: pressure (bar) p3, p4; temperature (°K) T3, T4.

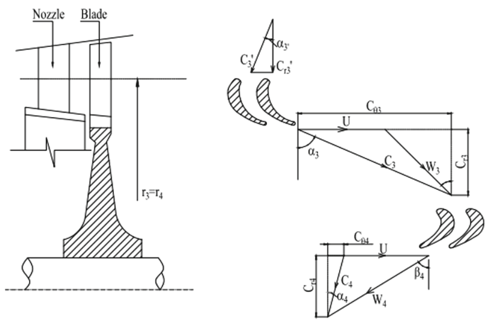

Fig. 2. Velocity triangles of the turbine [1]

The torque produced by the exhaust gas at turbine blades:

$$\tau = \dot{m}_t(C_{\theta 3} r_3 + C_{\theta 4} r_4) \quad (1)$$

The energy transfer:

$$\dot{W} = \omega_t \dot{m}_t (C_{\theta 3} r_3 + C_{\theta 4} r_4); \quad \text{axial turbine}: r_3 = r_4$$

$$\dot{W} = \dot{m}_t U (C_{\theta 3} + C_{\theta 4}) = \dot{m}_t U (C_3 \sin \alpha_3 + C_4 \sin \alpha_4) \tag{2}$$

Where, U (m/s) – speed of rotor; α_3, α_4 - angles of the velocities C_3, C_4; $\dot{m}_t$-mass flow.

C_3 is the outlet velocity of the nozzle, from the first energy conservation law:

$$\dot{m}_t c_{pe} (T_3 + T_{3'}) = \frac{1}{2} \dot{m}_t C_3^2 \tag{3}$$

Assuming the isentropic process in the nozzle we have an isentropic relationship:

$$T_3 / T_{3'} = (p_3 / p_{3'})^{(k_e - 1)/k_e} \tag{4}$$

$$C_3 = \sqrt{2 c_{pe} T_3 \left[1 - (p_{3'}/p_3)^{(k_e-1)/k_e}\right]} = \sqrt{2 c_{pe} T_3 \left[1 - \pi_{t,noz}^{(k_e-1)/k_e}\right]}; \pi_{t,noz} = p_{3'}/p_3 \tag{5}$$

The outlet velocity of the turbine blade can be obtained as below:

$$C_4 = \sqrt{2 c_{pe} T_3 \left[1 - (p_4/p_3)^{(\gamma_e-1)/\gamma_e}\right]} = \sqrt{2 c_{pe} T_3 \left[1 - \pi_t^{(\gamma_e-1)/\gamma_e}\right]}; \pi_t = p_4/p_3 \tag{6}$$

Where, $\pi_{t,}(-)$ is the pressure ratio through the turbine; $\pi_{t,noz}(-)$ is the pressure ratio through the nozzle; γ (−) is the specific heat capacity ratio; k_e (−) is the isentropic exponent index; c_{pe} (J/kg.K) is the specific heat at constant pressure.

The mass flow through the turbine depends on the gas states before the turbine, nozzle cross-sectional area, and expansion ratio, and modeled as below [1]

$$\dot{m}_t = \frac{p_3}{\sqrt{T_3 R_e}} A_T f(\pi_t) \tag{7}$$

Where R_e (J/kg.K) - exhaust gas constant, and the function $f(\pi_t)$ is modeled below [5]:

$$f(\pi_t) = \sqrt{1 - \pi_t^{k_\pi}} \tag{8}$$

Where $k_\pi(-)$ is the tuning parameter, according to [5], $k_\pi \approx 2$.

2.3 Models of the Diesel Engine Working Processes

Working processes in the combustion chambers of the diesel cylinders are modeled in accordance with the thermodynamic law, the mass conservation law, Weibe equations for the fuel oil burning and spread heating in the firing process, Woschni equations for the heat exchanging with the cylinder walls. The mathematic models with corrected coefficients according to the relative real processes are conducted and shown in [4].

3 Simulating the MDE-TC Models in MatLab/Simulink

The blocks in Simulink for TC are shown in Fig. 3, and in Fig. 4 – for MDE-TC.

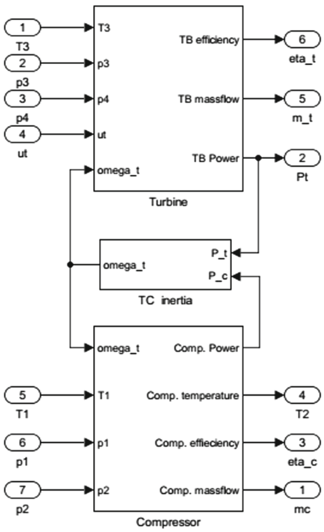

Fig. 3. Block model of the TC in MatLab/Simulink

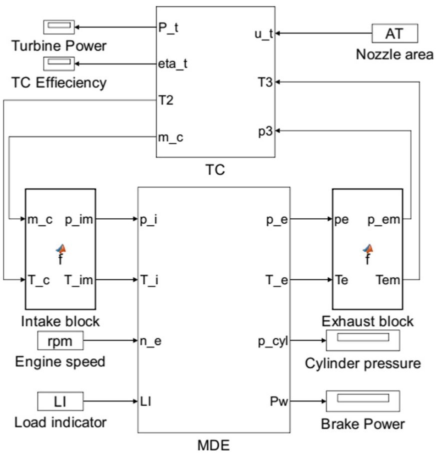

Fig. 4. Block model of the MDE-TC in MatLab/Simulink

The simulation object is a 4-stroke MDE, installed on the MV PhucHung, GLS Co. Ltd (Viet Nam). The features of the object are given in Table 1.

Table 1. Engine specifications [6]

Parameters	E.Unit	Giá trị
Bore x stroke	mm	430 × 610
Nominal speed	rpm	500
Number of cylinders	–	8
SFOC at nominal	g/kW.h	175–178
Nominal power	kW	7200
Turbocharger type	–	TPL76C (ABB)
Turbine blade diameter	mm	520
Number of nozzles	–	24

The Interface Design of the Simulation. In MatLab/Simulink environment, the interface design consists of: input controls, load (%), engine speed (rpm), and nozzle area (%)) and get results (Indicator diagram (p-φ), brake power, specific fuel consumption (g_e), exhaust temperature…). The interface is shown in Fig. 5 after running the simulation.

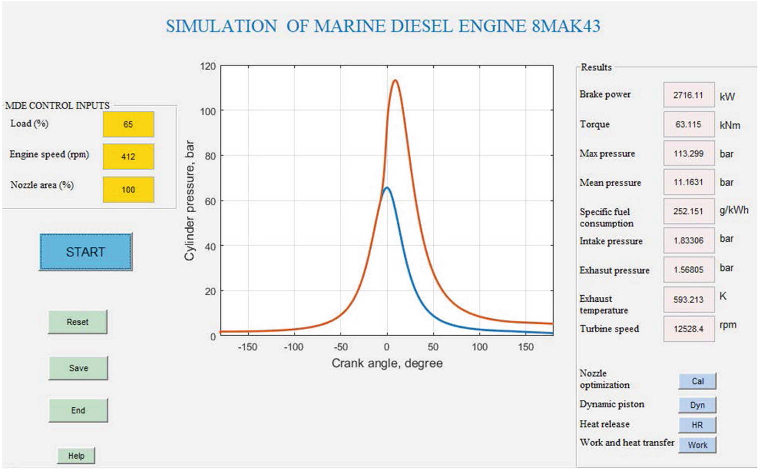

Fig. 5. Simulation program (at speed 410 rpm, load 65%)

This is simulated for the MDE at working condition, the input parameters gathered from engine room (pressure and temperature values), and some key output parameters (exhaust temperature, intake, and maximum pressure) can be compared with the ones in the ship diary for tuning parameters of the modelling.

The optimization of the nozzle area is determined from the simulation as below:

According to Fig. 6 and Fig. 7, the optimization point of the nozzle area is around 91%A_{Tmax}. At this point, the nozzle area was optimized.

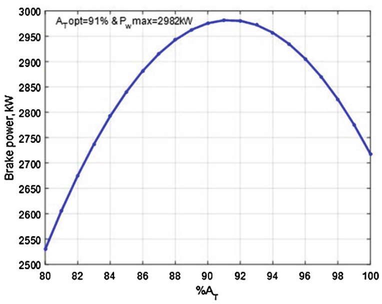

Fig. 6. Varies engine power P_w with nozzle area (%A_{Tmax})

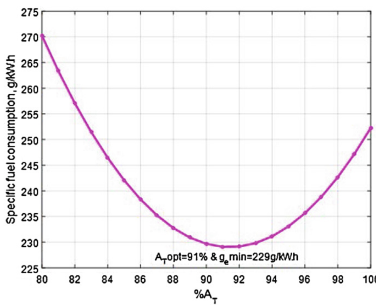

Fig. 7. Varies engine g_e with nozzle area (%A_{Tmax})

4 Experiments on the MDE 8MAK43

The MDE of the MV PhucHung after a long time in using, its technical parameters were gradually worse, especially SFOC and exhaust temperatures. Based on the above simulation results, the turbine nozzle ring was removed and repaired.

After repairing the nozzle ring was re-assembled and tested. The quality working of the MDE increased significantly, and some parameters were shown in Table 2.

Table 2. Evaluation of nozzle adjustment (65% load, speed 411 rpm)

Parameters	Before repairing	After repairing	Changed
Max. pressure (bar)	114	127	Δp_z = 13; (11.3%)
Turbine speed (rpm)	11165	13341	Δn_t = 2176; (19.5%)
Intake pressure (bar)	1.83	2.29	Δp = 0.46; (25.1%)
Exhaust temperature (°C)	379,1	343,6	ΔT = 35.5 °C; (9.4%)

5 Conclusion

The case study on the MDE 8MAK43 uses the integration method of the simulation and real experiment to increase its power, decrease its specific fuel consumption, and exhaust temperature of the old MDE in practice. The simulation research conducts the optimization of the nozzle area to carry out the experimental study for repairing the nozzle ring of the TC in practice. The experiment was carried out and has positive results, with adjusted nozzle area, engine performance improved significantly (See in Table 2, increase max. Pressure with + 11.3%, turbine speed + 19.5%, intake pressure + 25.1%, and decrease exhaust gas temperature −9.4%). This is a relatively simple method and affordable cost which can be applied in the maintenance and improvement of the marine diesel engine field.

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