Technical Analysis of Organic Rankine Cycle System Using Low-Temperature Source to Generate Electricity in Ship

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Abstract - Nowadays, the shipping sector has growth rapidly as followed by the increasing of world population and the demands for public transportation via sea. This issue entails the large attention on emission, energy efficiency and fuel consumption on the ship. Waste Heat Recovery (WHR) is one of the solution to overcome the mentioned issue and one of the WHR method is by installing Organic Rankine Cycle (ORC) system in ship. ORC demonstrate to recover and exploit the low temperature waste heat rejected by the ship power generation plant. The main source of heat to be utilized is obtained from container ship (7900 kW BHP, DWT 10969 mt) ship jacket water cooling system and use R-134a as a refrigerant. The main equipment consists of evaporator, condenser, pump and steam turbine to generate the electricity. The main objective is to quantifying the estimation of electrical power which can be generated at typical loads of the main engine. As the final result of analysis, the ORC system is able to generate the electricity power ranged from 77,5% - 100% of main engine load producing power averagely 57,69 kW.

Keywords **—Electric Power Generated, Jacket Water Cooling System, Organic Rankine Cycle, R-134a, Waste Heat Recovery**

I. INTRODUCTION

As time went from year to year, the fleet operating at sea increased significantly. Ships are the main transportation in the oceans and recorded in 1985 the total numbers of ship operated is 76.395 ships and in 2010, the total number of vessels reached 103.392 units [1]. It was certainly triggered other related issues concerning to the environment that is caused by the emission of exhaust gas from the ships. IMO (International Maritime Organization) noted the estimated exhaust emission from ship formed in of greenhouse gases (GHG) CO2 by 2050 will reach 2800 Mt CO2 compared with 2015 which ranged from 700 Mt CO2, in other words, these emissions will increase by almost 50% - 270% if there is no treatment to reduce these emissions [2].

IMO (International Maritime Organization) as the main regulator for international shipping take an action to firmly to enact regulations with the aim to reduce the level of greenhouse gases, especially CO_2 and improve the energy efficiency of shipping with introducing to Ship Energy Efficiency Management Plan which came into effect on January 1, 2013. One way to improve efficiency and reduce energy in ship exhaust gas that is using Waste Heat Recovery system. Waste Heat Recovery system is a re-use of waste heat from the wasted fuel combustion process into the environment to be reused for more beneficial purposes. As in this case, waste heat recovery system is used to achieve fuel savings, as an alternative energy to generate electricity on the ship and reducing the exhaust gas emission from the ship.

Organic Rankine Cycles is unpopular until the future of fossil fuels degradation has been main concerning issues at the present times, then the wasted recovery from low-grade / low temperature becomes the main interest. This method allows Rankine cycle heat recovery implemented at a lower temperature sources, in this case, is the temperature heat from the cooling system. The reason why used refrigerant in the cooling system as a heat source is because the refrigeration could boil in below 100^o C. Water has a very small molecular weight and high boiling point of 100^o C. The equipment which is used for this systems contains a pump, evaporator, condenser, and turbine [3].

II. STUDY LITERATURE

A. *Organic Rankine Cycle*

Organic Rankine Cycle is one of the methods to recovering the wasted heat. The problems from the water can be prevented by selecting the most appropriate working fluid.

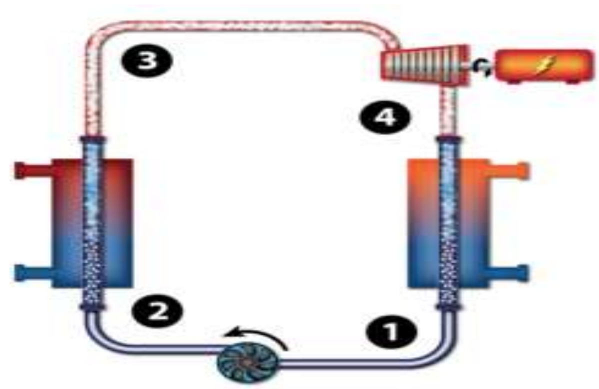

Figure 1. Organic Rankine Cycle Schematics Diagram & Main Equipment **[4]**

The working fluid is use from organic compounds properties and has a high molecular mass and lower boiling point than water. Compared with water, using an organic compound as a working fluid only need low temperature and less heat to evaporate. This method allows Rankine cycle heat recovery implemented at a lower temperature sources, in this case, the temperature heat from the main engine cooling water. The Organic Rankine Cycle uses refrigerant liquid besides water because the refrigerant has a low boiling point. The low temperature itself can be converted into useful work and generates electricity from main engine water cooling temperature outlet after the main engine. The equipment which is used for this systems contains pump, evaporator, condenser and turbine.

B. Organic Rankine Cycle Processes

Organic Rankine cycles is a Rankine Cycles where the organic fluid is used replacing the steam in Rankine cycles. The Organic Rankine process is similar with the Rankine cycles. In this cycle the use of organic fluid is selected to optimize the output from heat source which have low temperature and low pressure and this problem which cannot be solved with Rankine cycle and water is used as a working fluid in the system.

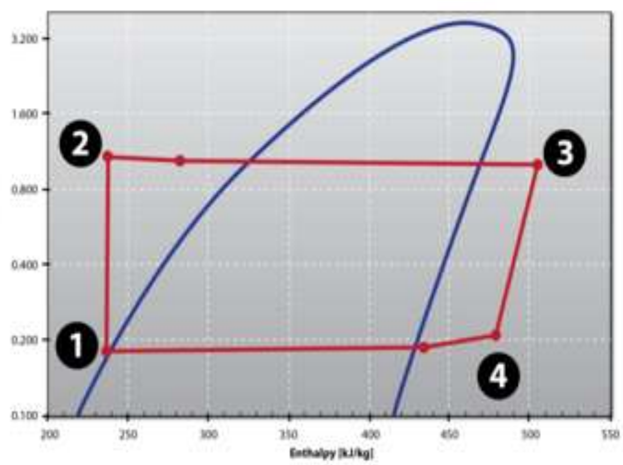

Figure 2. P-h Diagram of Organic Rankine Cycle **[4]**

Process 1 - 2 (showed in point 1 and point 2) is an isentropic compression from pump. The ideal pump work is given by:

$$W = m\,(h_2 - h_1) \quad (1)$$

Process 2 - 3 (showed in point 2 and point 3) is a heating process of organic working fluid with constant pressure in evaporator. The heat absorbed by organic working fluid is given by:

$$Q = m\,(h_3 - h_2) \quad (2)$$

Process 3 - 4 (showed in point 3 and point 4) is an expansion process with isentropic expander. Isentropic expansion is given by:

$$Q = m\,(h_4 - h_3) \quad (3)$$

Process 4 - is a subcooled condensation of organic working fluid in constant pressure inside a condenser. The heat released by the organic working fluid is given by:

$$Q = m\,(h_4 - h_1) \quad (4)$$

C. Working Fluid Selection for Organic Rankine Cycle

The organic working fluids selection is a key vital to design the Organic Rankine Cycle system. Different organic working fluids will result different electricity power generated and the temperature of this organic working fluids is relatively low. For selecting the working fluids for organic Rankine cycle, the analysis was limited to non-flammable, non-toxic having no potential to ozone layer depletion potential, refrigerant has a high thermal conductivity and have low cost and has a high availability.

D. Main Equipment for Organic Rankine Cycle

The main equipment is required to design the simple organic Rankine cycle consist of condenser, pump, evaporator and expander.

1) Pump

Pump is the equipment that have a function to transfer fluid within the pipe from one location to another location. In this organic Rankine cycle, pump is used to flow the refrigerant that has been cooled from the condenser in liquid phase forms back to the evaporator. Another function of this pump is to creates the pressure for the refrigerants as the working fluid.

2) Condenser

A condenser is an equipment (heat exchanger) or unit used to condense a working fluid. In this organic Rankine cycle system, condenser is used to return refrigerant steam phase from turbine back to the liquid phase so the refrigerant can be use again.

3) Evaporator

The evaporator is a heat exchanger equipment to evaporate the phase from the liquid phase into steam phase. Evaporator has a basic function such as heat exchangers and for separating the vapor formed from the liquid. Different heat transfer applications require different types of hardware and different configurations of heat transfer equipment and the common used type from evaporator is shell and tube heat exchanger type and compact heat exchanger type [5]

4) Turbine

The turbine will be used to rotate the motor generator. The principal is that the prime mover in the power field generating of electric power generation. Rotation in the turbine is generated from the vapor which resulted by the expansion to the turbine impeller with significantly pressure drop and the kinetic energy different is happen. The rotation of the turbine is generated from the vapor which resulted by the evaporator. After the vapor passed the turbine, the vapor will flow back again to the condenser where this vapor from the refrigerant will be converted again back to the liquid phase [6].

E. Sankey Diagram

Sankey Diagrams are kind of a flowcharts that representing the distribution of an energy process and also the losses of a material or even and energy. In the terms of the main engine of the ship (i.e MAN B&W), Sankey diagrams is representing that from 100% energy combusted from fuel, cannot be delivered 100 % into the effective energy. The energy cannot be delivered up to 100% from fuel energy into effective energy because the energy is transformed to the heat in several percent regarding to the operation and the engine itself.

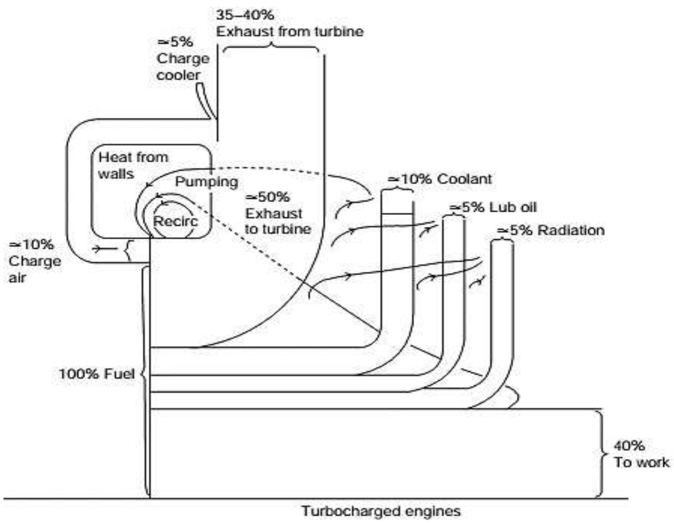

Figure 3. Sankey Diagram for Turbocharged Engines **[7]**

F. Estimating the Engine Load Based on RPM

To estimate the engine load based on RPM of main engine is using a formula:

$$\frac{n_1}{n_2} = \frac{(P_1)^3}{(P_2)^3} \qquad (5)$$

III. RESEARCH METHODS

The overall step of the research methods has a total 10 steps start with identifying the problem come out with literature study from the previous research and fundamental of theories from book, journal, internet and thesis. The next step is to collect the data of engine log book and cooling system drawing from ship. The third step is to analyze the data that already collected to find out the parameters as describe at the flowchart. After the data has been analyzed, the ORC system is ready to be designed at the cooling system followed by modelling the ORC system equipment. The sixth step is to do the simulation to find the most suitable refrigerant with the operating condition and find out the electricity power generated by the turbine. To make sure that the data from the simulation are correct and also to make selection and sizing of the ORC equipment, the next step is to do the manual calculation and this is the last step of the technical analysis. The eighth step is to make the analyze to find how much the fuel can be saved at typical main engine load and do the economic calculation in order to find out the break-event point from the price of installing the ORC equipment include with financing scenario in this report versus fuel which can be saved. The final result will give the how many electricity power that can be generated from the ORC system in the ship and how many years that the break-event event can be achieved from the economic analysis that has already been obtained from previous data.

IV. DATA ANALYSIS

A. Ship Particular

The implementation of the ORC system is proposed to be installed in the ship as the data is described in Table 1.

Table 1 Ship Particular

Parameters	Remarks
Ship Type	Container
Port of Registry	Jakarta
Nationality	Indonesia
Gross Tonnage	9030
Net Tonnage	4222
Length Overall	135,6 m
LPP	124,97 m
Breadth Moulded	22,49 m
Depth Moulded	11,21 m
Design Draft	7,6 m
Bunker Capacity	962,5 mt
Block Coefficient	0,636
Deadweight	10969,0 mt
Displacement	15703,3 mt
Container Capacity	820 TEU's
Main Engine Type	MHHM MAN B7W-Type 5S-50MC-C (7900 kW)
Auxiliary Engine Type	3xZMDW type 5L23/30H
Service Speed	17,0 knots.
Classification Society	B.V.

B. Operating Conditions of Jacket Water Cooling System

The temperature inlet and outlet of the main engine data is required to obtain how much the waste heat that can be utilized. In this case, the available heat for jacket water cooling system is 10% from typical main engine load [7]. It is assumed from RPM 100 -127 the temperature outlet of jacket water is constant at 83,1 ^{o}C. The result of temperature inlet & outlet and heat available from jacket water cooling system than can be utilized in each engine load are written on Table 2.

Table 2 Inlet and Outlet of Jacket Water Cooling

No	RPM	Load	kW	Qht [kW]	dT	Toutlet	Tin
1	77	22,3%	1761,7	185,82	2,28	73,8	69,0
2	90	36,0%	2844,0	299,98	3,68	76,0	68,0
3	95	42,0%	3318,0	349,97	4,30	78,0	69,0
4	97	45,0%	3555,0	374,97	4,60	81,6	73,3
5	100	48,8%	3856,8	406,63	4,99	83,1	76,0
6	100,5	49,6%	3914,5	413,30	5,07	83,1	78,03
7	107	60,0%	4740,0	499,96	6,14	83,1	76,96
8	115,5	77,5%	6122,5	624,95	7,67	83,1	75,43
9	120,5	85,4%	6748,2	711,61	8,74	83,1	74,36
10	122,5	90,0%	7110,0	749,94	9,21	83,1	73,89
11	127	100,0%	7900,0	833,27	10,23	83,1	72,87

The RPM and main engine load are calculated according to (5). The actual data from engine log book obtained only from RPM 77 – RPM 100, then the rest of temperature inlet should be calculated. Heat flow formula is used to calculate temperature different at typical load of main engine using the Equation (6):

$$Qht = \dot{m}\ x\ cp\ x\ \Delta t \quad (6)$$

C. *Refrigerant Selection*

The refrigerant is used as a working fluid to generate electricity in ship through the expander. In this research the refrigerant which being used is R-152a & R-134a. Based on the simulation, different type of refrigerant gives an effect to the different electric power that will be produced while the best result is achieved using R-134a as a working fluid in the organic Rankine cycle.

D. *Organic Rankine Cycle Design in Ship*

As mentioned before, the organic Rankine cycle system proposed to be installed at cooling system in jacket water cooling system. The equipment of organic Rankine cycle is to be installed after the jacket water cooling system leaving from the main engine.

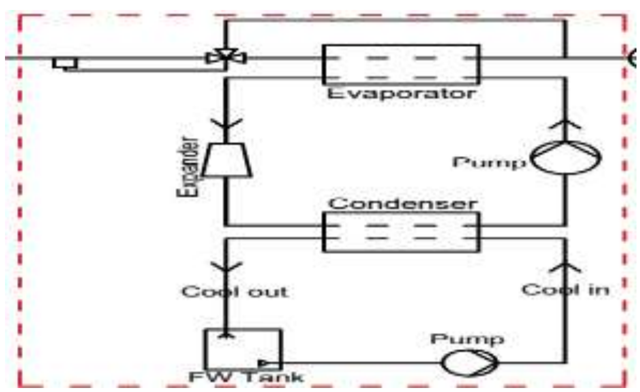

Figure 4. Proposed ORC System

E. *Simulation*

After the complete data and the data analysis calculation has been collected, then the simulation process can be start with inputting the data to the software. By varying the mass flow rate of jacket water cooling water at typical engine load, the generated electrical output power will have differences. The maximum mass flow rate of jacket water cooling is 19,44 kg/s. The mass flow rate of each different main engine load will also be different in order to keep the organic Rankine cycle component well-performed.

F. *Manual Calculation*

The process of manual calculation act as a comparison to show that the result from simulation stage can be use if the result from the manual calculation also show the same result with some tolerable error and also act as a tools to make sizing and selection for each organic Rankine cycle equipment (heat exchanger, pump, expander) that will be used. The aims at this stages is to show that the result from simulation stage can be use if the result from the manual calculation also show the same result with some tolerable error. The result from the manual calculation are shown in the Table 3.

1) *Operating Conditions*

Operating conditions for this research is acquired from patented technology that already built. The operating conditions are described below on the table:

Table 3 Proposed Operating Condition of ORC System

Parameters	Value
Pressure inlet turbine	21,6 bar
Pressure inlet evaporator	22 bar
Pressure inlet condenser	7,5 bar
Mass flow rate of working fluid	2.811 kg/s

2) *Mass Flow Rate of Working Fluid*

The value of mass flow rate which is used in this system are valued 2,833 kg/s and with this mass flow rate the ORC system still could be activated at 77,5% - 100% of the main engine load. Conversely, if the mass flow rate increase to 2,833 kg/s could be activated at 77,5%-100% of the main engine load with more electricity that could be produced by the system. For the lower mass flow rate, the power that will be generate also will be lower, but the ORC system could be used in lower engine load. In the other hand, the higher mass flow rate of the refrigerant in ORC system will generate more electrical power, but the ORC system could be used in higher engine load.

3) *Refrigerant Temperature After Leaving Evaporator*

The refrigerant temperature outlet of the evaporator should be determined to obtain the temperature after the refrigerant leave the expander and can be calculated using the heat balance formula as it described below as the result is shown on the Table 4:

$$Q_{Evaporate} = \dot{m}.c_p.(T_{in} - T_{sat}) \quad (7)$$

$$Q_{\mathrm{Saturated}} = \dot{m}.Lv \quad (8)$$

$$Q_{\mathrm{Subcooled}} = \dot{m}.c_p.(\mathrm{T_{sat}} - \mathrm{T_{out}}) \quad (9)$$

Table 4 Temperature Outlet After Evaporator

Main Engine Load (kW)	Temperature (°C)
77,50	73,77
80,00	75,96
85,00	76,55
90,00	77,61
95,00	77,84
100,00	77,98

4) *Pressure Drop*

Pressure drop is occurred when the fluid entering the heat exchanger (condenser and evaporator). The type of the heat exchanger which is used for this system is brazed type plate heat exchanger. Brazed PHE give a number of critical advantages: a sealed, compact system, less space, high temperature and pressure capability, gasket-free construction, high thermal efficiency, and ideal for refrigeration and process applications. [8]. The formula to calculate the pressure drop in brazed plate heat exchanger as show in (10) and the result of the pressure drop in all heat exchanger shown in the Table 5.

$$\Delta p = \frac{1{,}5{G_p}^2 n_p}{2 g_c \rho_i} + \frac{4 f L G^2}{2 g_c D_e}\left(\frac{1}{\rho}\right)_m \pm \frac{\rho_m g L}{g_c} \qquad (10)$$

Table 4 Pressure Drop in Installed Heat Exchanger

Parameters	Pressure Drop (Bar)
Refrigerant Flow (Evaporator)	0,3
Jacket Water Flow (Evaporator)	0,2
Refrigerant Flow (Condenser)	0,02
Jacket Water Flow (Condenser)	0,45

5) *Electrical Power Generated of the Turbine*

The temperature outlet of the turbine is required to calculate how much electricity that will be generated by the turbine by assuming that the outlet pressure from the turbine is 7,5 bar. Electrical power will be generated by the rotating of the turbine. Before the calculations begin, the operating conditions in the turbine should be determined first. After the operating conditions already completed, the outlet turbine outlet temperature is able to calculated by using Formula (11) as the final result shown in Table 5:

$$T_2 = T_1 \left(\frac{P_2}{P_1}\right)^{\frac{\gamma - 1}{\gamma}} \qquad (11)$$

Table 5 Refrigerant Temperature Outlet After Turbine

Main Engine Load (kW)	Temperature (°C)
77,50	73,77
80,00	75,96
85,00	76,55
90,00	77,61
95,00	77,84
100,00	77,98

Then the electrical power produced by the generator is able to determine by using the Formula (12) and the result is shown in Table 6.

$$kW_{generated} = \dot{m}.c_p.(T_{in} - T_{out}) \qquad (12)$$

Table 6 Power Produced by Turbine at Typical Main Engine Load

Load [%]	ṁht average [kg/s]	ṁref [kg/h]	Power Produced [kW]
77,5	19,44	10200	55,545
80	18,50	10200	57,197
85	17,40	10200	57,640
90	16,63	10200	58,436
95	15,78	10200	58,612
100	15	10200	58,714

After the result already obtained from the manual calculation then the next step is to compare the electricity power generated result between the manual calculation result and the result from the simulation. The final result from both source is written in the Table 7.

Table 7 Power Produced by ORC System at Each Main Engine Load

Load [%]	ṁht from simulation [kg/s]		ṁht average [kg/s]	ṁref [kg/h]	Power Produced [kW]	Power Produced from Simulation [kW]	Error
	Min	Max					
75	19,44	19,44	19,44	10200	55,55	57,54	3,47
80	18,1	18.09	18,5	10200	57,20	61,11	6,40
85,4	17	17,8	17,4	10200	57,64	61,32	6,00
90	16,15	17,1	16,63	10200	58,44	61,49	4,97
95	15,45	16,1	15,78	10200	58,61	61,68	4,97
100	14,6	15,4	15	10200	58,71	61,72	4,87

6) *Condenser & Evaporator Exchanger Heat Load*

The purpose of calculate the heat load of both heat exchanger is to select the most suitable heat exchangers product from the manufacturers in order to withstand at the maximum operating conditions within the installed system. By referring to the equation (7), (8), (9) the result of each heat exchanger heat load are written in the table below:

Table 8 Condenser & Evaporator Heat Load

Load (%)	Condenser Heat Load (kW)	Evaporator Heat Load (kW)
77,50	560,21	625,25
80,00	589,78	634,68
85,00	590,90	637,24
90,00	592,83	641,65
95,00	593,26	642,67
100,00	593,51	643,26

Since the heat load of the evaporator has already known, then the evaporator can be selected according to the operating conditions which has been determined based on the previous calculation.

7) *Pump Selection for Fluid*

The pump is selected to fit the operating conditions of the system. Actually, two pumps should be selected in order to pump the refrigerant fluid and to pump the water as a refrigerant cooler to become liquid phase again. The operating conditions of the pump that will be installed in organic Rankine cycle system is written in Table 9:

Table 9 Operating Conditions of Refrigerant in Pump

Parameters	Remarks
Refrigerant Type	R-134a
Fluid Density	1197 kg/m^3
Mass Flow Rate	2,833 kg/s (8,521 m^3/h) (37,5184 Gpm)
Temperature inlet	28 °C
Pressure Inlet	7,48 Bar
Pressure Outlet	22 Bar
State of Aggregation	Liquid

The head required by the pump should be calculated first. The head loss, head static and head velocity is assumed to be zero. So the head pressure is still remaining to be calculated by using Equation (12). The result is 124,0.32 m (406,929 ft) required by the refrigerant pump in order to fulfill the required operating conditions.

$$Hreq = \frac{P_2 - P_1}{\rho g} \tag{13}$$

Water cooler pump is used to pump the freshwater as cooler to cooling down the refrigerant in vapor phase to becomes liquid phase. The operating conditions of the pump is written below. Mass flow rate of the water is set up at 150 m^3/h to make the refrigerant vapor is turned back again to the liquid phase. After the water cooling down the refrigerant, the temperature of the water cooler is increase. The temperature of the increased water cooler can be calculated by using the heat balance formula. Assuming the temperature inlet to the condenser of the freshwater is always set to 25^oC after the tank entering the condenser. Main engine load will increase the temperature of the water cooler gradually

8) Selected Equipment

After the operating conditions already obtained for all equipment based on the operating conditions, hence the selection of the equipment can be done as the list is figured on the Table 10.

Table 10 List of Equipment for ORC System

Equipment	Manufacturer
Refrigerant Pump	CLARK SOLUTIONS (Rotary Gear Pump - 1000 SSU - NO. 557 Pump)
Evaporator	Funke ViFlow TPL
Water Cooling Pump	BBA Pumps - B100 Electric Drive
Condenser	ALVA LAVAL CB400
Expander	Micro Steam Turbine Generator G-Team (TR-Hi 150)
Three Way Valve	Samson Valve

V. CONCLUSION

Based on data analysis and result which has been done in the previous section can be concluded as the electricity power generated by the ORC system is different depends on main engine load. The equipment consists of pump, condenser, evaporator and turbine. As the main engine load increase, the electricity power generated also increase. The best working fluid to use is R-134a. At 77,5% of main engine load electricity power generated reach 55,55 kW, at 80% of main engine load electricity power generated reach 57,20 kW, at 85% of main engine load 57,64 kW, at 90% of main engine load electricity power generated reach 58.,44 kW, at 95% of main engine load electricity power generated 58,61 kW and at 100% of main engine load electricity power generated reach 58,71 kW. Averagely, the electricity power that can be generated is 57,69 kW.

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