Istrazivanja i projektovanja za privredu
Journal of Applied Engineering Science

Preliminary Report

doi:10.5937/jaes18-25189

Paper number: 18(2020)2, 684, 251 - 256

COST EFFICIENCY OF OPTIMIZING AUTOMATIC TEMPERATURE CONTROL PARAMETERS IN A DIESEL ENGINE COOLING SYSTEM ON A CRUISING VESSEL – A CASE STUDY

Radoslav Radonja, Vladimir Pelić, Davor Pavić, Nikola Tomac*
University of Rijeka, Faculty of Maritime Studies, Rijeka, Croatia

With the enforcement of international regulations aimed at reducing environmental pollution, various measures and procedures have been proposed to reduce fuel consumption and increase energy efficiency of ships. Cruising ships that are commonly visiting some of most sensitive and protected sea areas are of particularly interest.

This case study outlines measure that can be applied tocruising vessels without installing new or modifications of existing systems and will require somewhat increased attention of chief engineer during voyage.

Modern medium speed marine diesel engines, out of the total energy contained in the fuel, utilize slightly less than half while the rest is a thermal loss.Therefore, ships are equipped with waste heat recovery systems utilizing the excessive heat of diesel engine exhaust gases and cooling water. The findings in this paper shows that correct selection of parameters in automated control of cooling water temperature results with a significant improvement of diesel engine thermal efficiency, reduced fuel consumption and improved costs efficiency. The results are applicable for all similar marine or industrial power systems as well.

Key words: cruising vessels, ship energy efficiency, waste heat recovery, diesel engines

INTRODUCTION

Amendments to the MARPOL 73/78 Annex 6 [1] impose new requirements primarily focused on reduction of harmful emissions from ships and increasing their energy efficiency. The Ship Energy Efficiency Management Plan (SEEMP), International Energy Efficiency Certificate (IEEC) and the Energy Efficiency Design Index (EEDI) are required for new ships.

The SEEMP contains a set of measures aimed to improve energy efficiency. The plan also enables a non-mandatory Energy Efficiency Operational Indicator (EEOI) as a possibility for companies to manage whole fleet.

EEDI is a technical measure used to promote energy-efficient and environmentally-friendly power plants onboard vessels. EEDI is not required for existing engines.

Relevant publication [2] that is addressingenergy efficiency of the ships recognize many possibilities but most commonly such as: voyage optimization, energy consumption management, hull propulsion and plant maintenance, structural alteration or the use of alternative fuels [3].

This paper shows that significant savings in fuel costs can only be achieved by optimizing of automatic temperature control parameters in the diesel engine cooling system. The calculations and results presented here are based on the real data gathered on board cruise ship built in ‘Voyager’ class and they are applicable for entire class, but not limited to that class exclusively.

General characteristic of the ship

The ship was built in the "Kvaerner Masa" shipyard (Turku, Finland) in the "Voyager" class. With a length overall of 311 m, a beam of 38.6 m at the waterline (48 m max), draft of 8.6 m and 139,570 BT today is among the largest passenger vessels in the world.

The concept of a "fully integrated electrical system" was applied to the ship. The six diesel generators (6 × Wärtsilä 12V46; 6 × 12,600 kW) producing high-voltage electricity (11 kV) that is being distributed to consumers. It is used primarily for propulsion engines, bow and stern thrusters, and through 11 kV / 440 V transformers for power supply of engine room and other ship requirements (in ex.hoteling).

The ship diesel electric propulsion includes two ABB azipods, one fixipod and four bow thrusters. Maximum passenger capacity is 3.807 and crew of 1.213. Maximum speed 24 knots.

The ship has built-in waste heat recovery system utilizing the excessive heat from diesel generator water cooling and charged air from turbo-chargers (scavenging air) and it is consisting of:

- sanitary hot water heating system
- fresh water generator heating system
- air-conditioning water heating system.

Use of waste heat of cooling water of diesel engine improves thermal efficiency and reduces fuel consumption.

Waste heat recovery system

Modern large cruise ships have large energy needs to be used for various technological processes on board. Table 1 shows typical values, depending on the operational conditions, i.e.:

*radonja@pfri.hr

1. maximum consumption – all diesel generators at 100 % load
2. winter time in port – one diesel generator at 80 % load
3. winter time at sea – four diesel generators at 80 % load
4. summer time in port – one diesel generator at 80 % load
5. summer time at sea – four diesel generators at 80 % load
6. summer time at sea, cruising speed of 16 knots – three diesel generators at 72 % load.

It is almost commonly known that modern marine four stroke diesel engines transform in to mechanical work only about 45-48% of total energy contained in the fuel while the rest of 52-55% is heat loss (exhaust gases, scavenging air cooling, cylinders cooling, lubrication oil cooling, cooling and radiation in the engine room).

In order to prevent such loss waste heat recovery systems (WHRS) are widely in use in modern vessels. In that manner the heat of exhaust gases is recovering in exhaust gas boilers to produce the steam for different purposes onboard. On this particular type of passenger ship the heat produced from scavenging air and from high temperature (HT) cooling system are recovering for:

- Distillated water production (evaporator)
- Heating of sanitary hot water
- Heating of air conditioning system (AC re-heating).

HT water cooling system on board particular vessel is used for cooling of cylinder liner, cylinder heads, turbo chargers (TC), scavenging air cooler (1st stage) and then to heating of evaporator, sanitary hot water andAC re-heater). Finally, the water is returning to engine or mixed with low temperature (LT) cooling system depending on outlet temperature after waste heat recovery. LT cooling water system is used for cooling of generators, scavenging air (2nd stage), lub-oil cooling and cooling of HT water system over mixing valve.

Although some heat is recovering in that systems it can be seen that automatic temperature control parameters in the diesel engine cooling system might be optimized to increase energy efficiency and fuel economy.

Methodology

The cooling system of each of the six Wärtsilä 12V46 diesel engines consists of the following components (Fig. 1):

Red line – HT water cooling system

Violet line – preheating

Blue line – LT water cooling system

Light blue line – connections to expansion tank

Table 1: The power load needs of a modern cruise ship for different operational conditions [3]

	Operational condition						Unit
	1	2	3	4	5	6	
Tank heating	2725	1090	1090	545	545	545	kW
Fuel trace (piping) heating	80	80	80	40	40	40	kW
Diesel engine fuel heating	494	66	264	66	264	178	kW
Boiler fuel heating	37	70	68	54	53	72	kW
High temp. water heating	0	360	144	360	144	216	kW
Fuel oil purifier heating	596	99	397	99	397	298	kW
Lub-oil purifier heating	557	93	372	93	372	279	kW
Air conditioning (pre-heating)	0	0	0	0	0	0	kW
Air conditioning (re-heating)	4350	4350	4350	1088	1088	1088	kW
Hot water heating (sanitary)	6000	4980	4980	4980	4980	4980	kW
Evaporator 1	0	0	267	0	267	957	kW
Evaporator 2	0	0	3836	0	3836	5620	kW
Galley	2000	2000	2000	2000	2000	2000	kW
Laundry	5100	5100	5100	5100	5100	5100	kW
Spa	120	120	120	120	120	120	kW
Swimming pools	500	500	500	500	500	500	kW
Total	22560	18908	23568	15045	19705	21991	kW
Steam consumption	34790	28982	36462	23145	30625	34182	kg/h

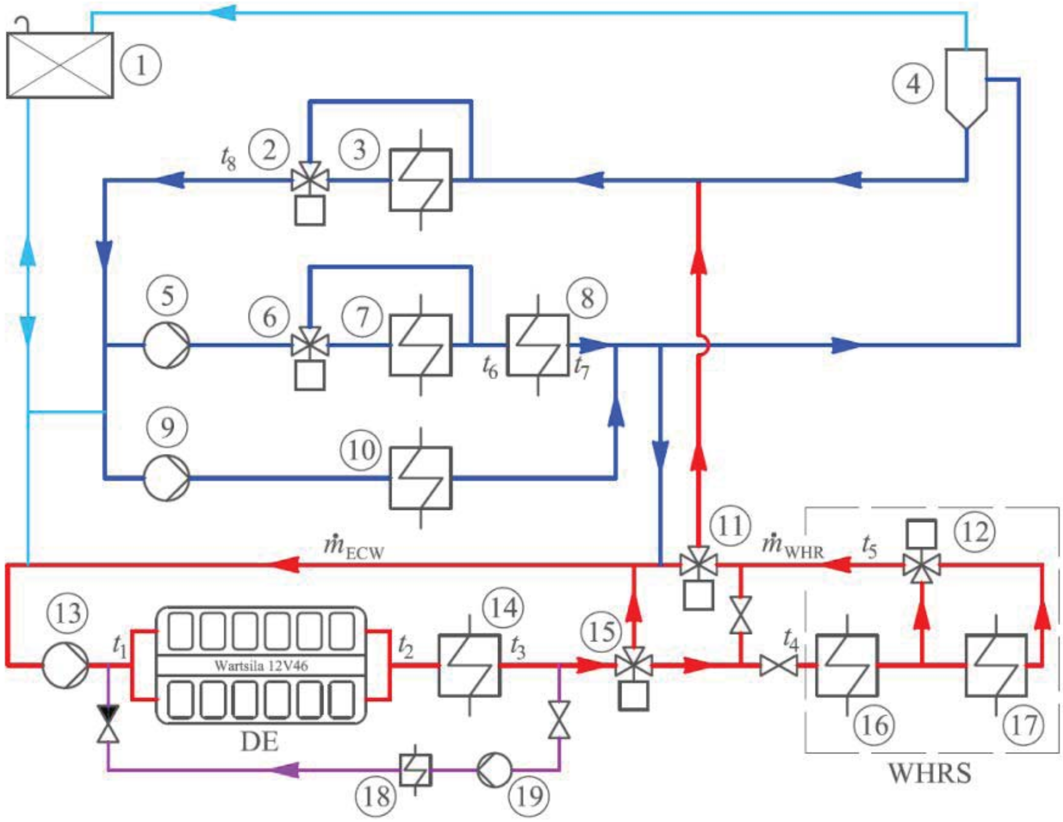

Figure 1: Diesel engine fresh water cooling system (Source: authors - adopted from [4], [5])

1. expansion tank
2. automatic three-way valve for regulation of LT water temperature 1
3. fresh water (FW) cooler
4. air vent tank
5. LT water circulation pump for scavenging air and lubricating oil cooling (attached to the engine)
6. automatic three-way valve for regulation of LT water temperature 2
7. LT scavenging air cooler (2nd stage)
8. lubricating oil cooler
9. LT water circulation pump for generator cooling (driven by electromotor)
10. LT generator cooler
11. automatic three-way valve for regulation of HT water temperature 1
12. automatic three-way valve for regulation of WHRS
13. HT water circulation pump (attached to the engine)
14. HT scavenging air cooler (1st stage)
15. automatic three-way valve for regulation of HT water temperature 2
16. evaporator (1st stage of WHRS)

hot water heating (2nd stage of WHRS).

The thermal efficiency of the diesel engine cooling system is (Fig. 1):

$$\eta_{\mathrm{WHR}} = \frac{\textit{Heat taken from DE cooling system}}{\textit{Total heat energy contained in DE cooling system}} \tag{1}$$

$$\eta_{\mathrm{WHR}} = \frac{\dot{m}_{\mathrm{WHR}} \cdot c_{\mathrm{w}} \cdot \Delta t_{\mathrm{WHR}}}{\dot{m}_{\mathrm{ECW}} \cdot c_{\mathrm{w}} \cdot \Delta t_{\mathrm{ECW}}} \tag{2}$$

where:

$\dot{m}_{\mathrm{WHR}}$ – mass flow through waste recovery system

$\dot{m}_{\mathrm{ECW}}$ – mass flow through engine cooling system

c_W– specific heat capacity of cooling water

Δt_{WHR} – temperature difference WHR system

Δt_{ECW}– temperature difference HT/LT cooling system

Due to equal mass flow ($\dot{m}_{\mathrm{WHR}}$ = $\dot{m}_{\mathrm{ECW}}$) the relevant formula is:

$$\eta_{\mathrm{WHR}} = \frac{\Delta t_{\mathrm{WHR}}}{\Delta t_{\mathrm{ECW}}} = \frac{t_4 - t_5}{t_3 - t_1} \tag{3}$$

Useful power (P) or thermal heat recovered (THR):

$$P = THR = P_{\mathrm{HT}} \cdot \eta_{\mathrm{WHR}} \tag{4}$$

Where P_{HT} is power from engine HT cooling system (jacket water and charge air HT circuit).

The waste heat in the HT cooling water can be used for fresh water production, central heating, fuel tank heating etc. The heat available from HT cooling water is affected by engine load and ambient conditions. Recoverable heat is reduced by circulation to the expansion tank, radiation from piping and leakages in temperature control valves. Data provided by the manufacturer for heat bal-

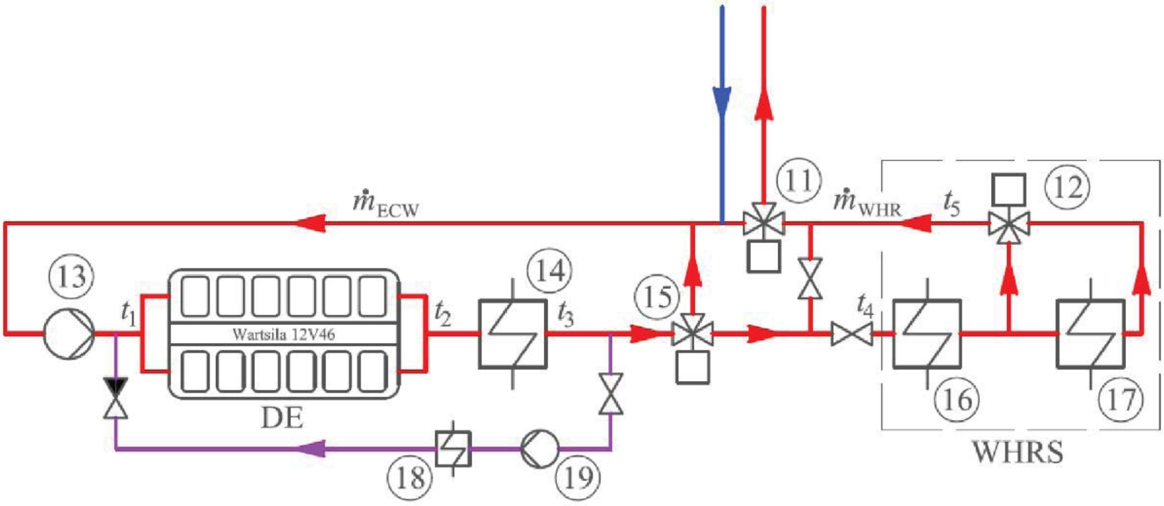

Figure 2: Diesel engine HT fresh water cooling system (Source: authors - adopted from [4], [5])

ance at 100% load for diesel engine 12V46F taken from [6], and recalculated for engine load at operational condition – 6 (three diesel generators at 72 % load).

P_H - power required for water production, hot water heating (sanitary) and air conditioning (re-heating) in operational condition – 6 are taken from Table 1.

Optimization

It is common practice on board that there is no any intention of the engine crew to optimize waste heat recovery system of scavenging air cooling or HT/LT fresh water cooling. With correct selection of parameters ("set points") in automated control of automatic three-way valve (11,12 and 15), (Fig. 2) it is possible to optimize the system.

Improvement in the thermal efficiency and reduced fuel consumption might be achieved through temperature adjustment as shown in the following tables (Table 2, 3 and 4).

*Table 2: Thermal efficiency calculated **before** optimization (only 1st stage of WHRS in use)*

Temperatures recorded on board:			
Temperature before cylinders	t_1	72	°C
Temperature after cylinders	t_2	83	°C
Temperature after HT charge air cooler	t_3	93	°C
Temperature before WHRS	t_4	92	°C
Temperature after WHRS	t_5	84	°C
Temperature after LT charge air cooler	t_6	40	°C
Temperature after lubricating oil cooler	t_7	45	°C
Temperature before engine	t_8	37	°C
	P_H	12645	kW
Calculated values:			
Thermal efficiency	η_{WHR}	0,38	
Heat recovery at 100% load per DE	THR_1	1770	kW
Heat recovery at 72% load per DE	THR_2	1274	kW
Heat recovery for three DE at 72% load	THR_3	3822	kW

*Table 3: Thermal efficiency calculated **before** optimization (1st and 2nd stage of WHRS in use)*

Temperatures recorded on board:			
Temperature before cylinders	t_1	72	°C
Temperature after cylinders	t_2	83	°C
Temperature after HT charge air cooler	t_3	93	°C
Temperature before WHRS	t_4	92	°C
Temperature after WHRS	t_5	81	°C
Temperature after LT charge air cooler	t_6	40	°C
Temperature after lubricating oil cooler	t_7	45	°C
Temperature before engine	t_8	36	°C
	P_H	12645	kW
Calculated values:			
Thermal efficiency	η_{WHR}	0,52	
Heat recovery at 100% load per DE	THR_1	2433	kW
Heat recovery at 72% load per DE	THR_2	1752	kW
Heat recovery for three DE at 72% load	THR_3	5256	kW

*Table 4: Thermal efficiency calculated **after** optimization (1st and 2nd stage of WHRS in use)*

Temperatures recorded on board:			
Temperature before cylinders	t_1	75	°C
Temperature after cylinders	t_2	86	°C
Temperature after HT charge air cooler	t_3	95	°C
Temperature before WHRS	t_4	94	°C
Temperature after WHRS	t_5	77	°C
Temperature after LT charge air cooler	t_6	40	°C
Temperature after lubricating oil cooler	t_7	45	°C
Temperature before engine	t_8	36	°C
	P_H	12645	kW
Calculated values:			
Thermal efficiency	η_{WHR}	0,90	
Heat recovery at 100% load per DE	THR_1	3948	kW
Heat recovery at 72% load per DE	THR_2	2843	kW
Heat recovery for three DE at 72% load	THR_3	8528	kW

RESULTS AND DISCUSSION

The settings of the control parameters in the automatic temperature control system before and after optimization as well as both thermal efficiencies are shown in Table 5.

Although it is theoretically possible to adjust parameters in such way that there will be no heat loss at all (if $\Delta t_{WHR} = \Delta t_{ECW}$) it is obvious that such recovery cannot be achieved in practice. Due to that reason, the parameters are to be selected on highest possible level allowed by manufacturer with maximum savings.

Table 5: Automatic temperature control settings (HT cooling water) and thermal efficiencies before and after optimization

HT cooling water temperature	***Before optimization***	***After optimization***
t_1	72 °C	75 °C
t_3	93 °C	95 °C
t_4	92 °C	94 °C
t_5	81 °C	77°C
η_{WHR}	0,52	0,85
THR_3	5256 kW	8528 kW

The difference obtained in reused power is:

$$\Delta THR = THR_{3,b} - THR_{3,a} = 8528 - 5256 = 3272\ \mathrm{kW} \quad (5)$$

The recovered heat as useful power can be presented through savings in **daily cruising fuel consumption** (*FCd*) when running one of engines with **specific fuel consumption** (*SFOC*) of 200 g/kWh as:

$$FC_d = \frac{\Delta THR \cdot 24 \cdot SFOC}{1 \cdot 10^6} = \frac{3272 \cdot 24 \cdot 200}{1 \cdot 10^6} = 15.71\ \mathrm{t} \quad (6)$$

Considering global average bunker price [7] for *Intermedial Fuel Oil 380 (IFO 380)* that is 463.50 USD/t **daily savings** on cruising will be 7282 USD (or approximately 2.6 mil USD/year) which is quite significant for any company.

CONCLUSION

Taking into consideration development of environmental legislation as well as capital and operational expenses for ship owners to comply with it is obvious thatenergy efficiency of the ship becomes more important.

Traditionally, the Chief Engineer on board will keep the settings of the automatic temperature control system of the diesel generator HT/LT water cooling system at the same values (or as close as possible to the minimum deviation) as it was set during the trial run or at the values transmitted during the “Chief Engineers’ handover protocol”.

This papershows that significant savings might be achieved through optimization of parameters in automatic temperature control of diesel engines HT/LT cooling water system. Different settings are resulting with different thermal efficiencies. Consequently, recovered heat reduce fuel consumption and increases energy and costs efficiency.

However, it is to be noted that before attempting of any parameter adjustment, the mechanical and physical condition of all elements included into system (engine, coolers, pumps, regulation valves, …) must be carefully examined as well as operational condition in sailing area.

Further research will be focused on cruising speed optimization respecting diesel electric propulsion.

REFERENCES

1. http://www.imo.org/en/KnowledgeCentre/IndexofIMOResolutions/Marine-Environment-Protection-Committee-(MEPC)/Documents/MEPC.203(62).pdf, 22/05/2019
2. OCIMF. (2011). GHG Emissions- Mitigating Measures for Oil Tankers. London: OCIMF Oil Companies International Maine Forum, available at: https://www.ocimf.org/media/8922/GHG%20Emission-Mitigating%20Measures%20for%20Oil%20Tankers%20Part%20A%20Review%20of%20Reduction%20Potential%20FINAL.pdf , 22/05/2019
3. Energy saving – course, ABB, Helsinki 29/08/2013 – personal records

4. Technical documentation of the ‘Voyager’ class cruising ship– personal records
5. Technical parameter records from the ‘Voyager’ class cruising ship –personal records
6. Wartsila 46F Product Guide, June 2016
7. https://shipandbunker.com/prices , 17/09/2019

Paper submitted: 12.02.2020.
Paper accepted: 13.05.2020.