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THE SYSTEM COMBINED OF LOW-SPEED MARINE DIESEL ENGINE AND STEAM TURBINE IN SHIP PROPULSION APPLICATIONS

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Abstract

This paper presents a concept of a ship combined high-power system consisted of main piston engine and steam turbine subsystems, which make use of energy contained in exhaust gas from main piston engine. The combined system consisted of a piston combustion engine and an associated with it steam turbine subsystem, was considered. The system's energy optimization was performed from the thermodynamic point of view only. Any technical – economical analyses were not carried out. Numerical calculations were performed for a Wartsila and MAN Diesel & Turbo low-speed diesel engine of about 50 MW output power.

Keywords: *ship power plants, ship propulsion, combined system, Marine Diesel Engine, steam turbine*

Nomenclature

b_e	- specific fuel oil consumption	N	- power
H_i	- enthalpy drop in the turbine	p	- pressure
m	- mass flow rate	t	- temperature

Indices:

combi	- combined system	g	- exhaust gas
d	- deaerator	k	- parameters in a condenser
D	- Diesel engine	o	- live steam, calculation point
exh	- exhaust passage	ST	- Steam turbine
f	- fuel	ss	- ship living purposes
FW	- feed water		

1. Introduction

In propulsion ship systems last years there have been adopted combined systems such as gas-steam turbine systems. These systems can reach efficiency above 60% on the land. On the sea these system has been adopted on the passengers liner Millenium. But for now it is the only example of the combined system which is connected with the biggest efficiency. However these system needs more expensive fuel, such as Marine Diesel Oil. In much majority trade ships are propelled by low-speed Marine Diesel Engine, which needs relatively cheap Heave Fuel Oil. It seems that the above tendency will continue in the world's merchant navy for the next couple of years.

The Diesel engine is still most frequently use as the main engine in marine applications. On one hand it burns the cheapest fuel (heave fuel oil), on the other it has the highest efficiency of all heat engines. The exhaust gases leaving the Diesel engine contains huge energy which can be utilised in other device (engine), thus increasing the efficiency of the engine system and reducing the emission of substance to the atmosphere.

A possible solution here can be a system combined of a piston internal combustion engine and the gas and steam turbine circuit that utilises the heat contained in the exhaust gases from the Diesel engine. The leading engine in this system is the piston internal combustion engine. It seems that now, when fast container ships with transporting capacity of 8 - 12 thousand TU are entering into service, the propulsion engines require very large power, exceeding 50-80 MW. On the other hand, increasing prices of fuel and restrictive ecological limits concerning the emission of NO_x and CO_2 to the atmosphere provoke searching for new solutions which will increase the efficiency of the propulsion and reduce the emission of gases to the atmosphere.

The ship main engines will be large low-speed piston engines that burns heavy fuel oil. At the present, the efficiency of these engines nears to 45 – 50%. For such a large power output ranges, the exhaust gas which leaving the engine, contains huge amount of heat available for further utilisation.

In this article has been shown the comparison the combined systems which are composited with Low-Speed Diesel engine as the main engine and steam turbine which is powered by water steam from utilisation system exploited exhaust combustion heat with the piston system. This is considered the steam turbine with single-pressure system and two-pressure system for two Low-Speed Engine Wartsila company type RTA96C and MAN Diesel & Turbo company type K98MC.

2. Marine Diesel Low-Speed Engine

In this deliberation there has been taken to compare two Low-Speed Diesel Engine, which basic parameters has been shown in the Table 1.

Tab. 1 Basic ships parameters of Low-Speed Diesel Engine

Company		WARTSILA	MAN DIESEL & TURBO
Engine type		9RTA 96C	9K98 MC
Power	kW	46 322	48 762
Ambient air temperature	^oC	25	25
Barometric pressure	bar	1	1
Engine speed	r/min	98,5	100,4
Exhaust gases mass flow	kg/s	104,5	134,25
Exhaust gas temperature	^oC	271	232,8
Fuel		Heavy Fuel	Heavy Fuel
Calorific value of fuel oil	kJ/kg	42 700	42 700
Fuel mass flow	kg/s	2,1467	2,369

For huge power of combustion engine, in exhaust gases which drops engine, there are much amount of heat which can be utilized.

In this combined system exhaust gases from collector of exhaust Diesel engine are directed to utilisation system in which there heat gave to water steam, which feed steam turbine cycle, making additional power, Figure 1.

3. Ship combined system of Diesel engine – steam turbine

The cycle of steam turbine in the combined system has been adopted with Single-Pressure System and Two-Pressure System.

In system with the Single-Pressure System, Fig. 2, accepted only one preheater in steam system, deaerator element which is heated by touch steam stream taken from steam turbine loose. Additionally there has been accepted that steam stream for ship living purposes will be taken after superheater of steam system.

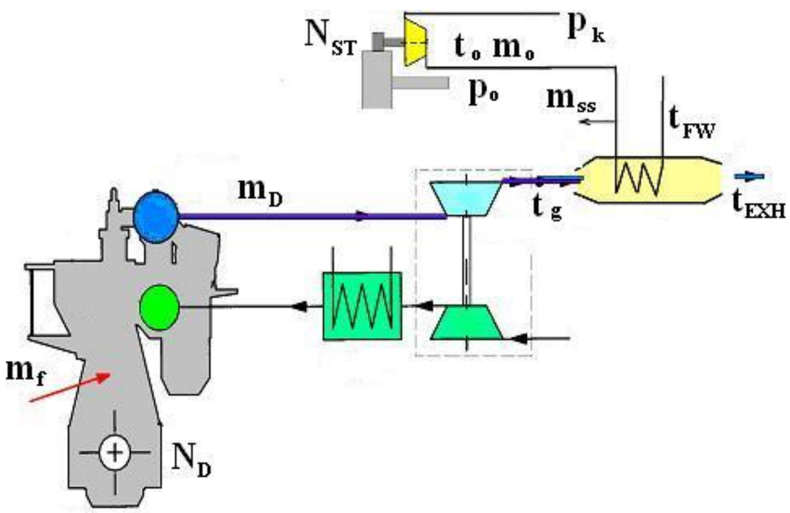


Fig. 1. Combined system with the Diesel main engine and the steam turbine

In system with the Two-Pressure System, Fig. 3, received two steam pressure in boiler drum, however in low pressure boiler drum saturated steam (x=1) reinforce steam turbine and steam stream is taken for ship living purposes. There has been also accepted only one regenerative preheater, deaerator element which is heated by steam stream from turbine loose.

In those both cases in steam turbine cycle there has been taken steam turbine type: condensation, which condenser is cool down by sea water.

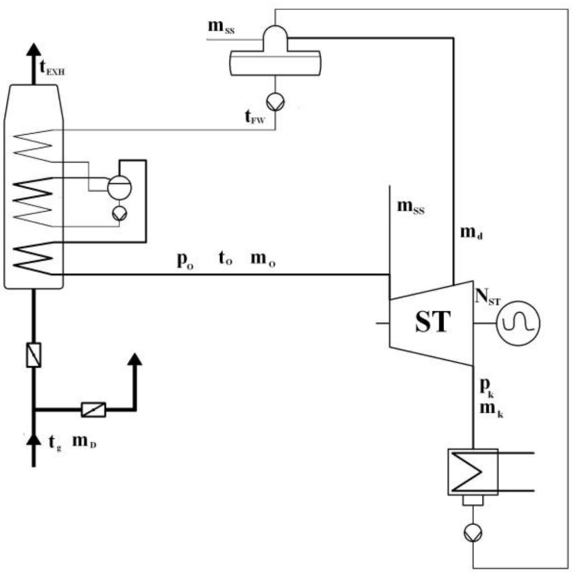


Fig. 2. Flow Diagram of the Single-Pressure System of Steam Turbine

In this calculation there has been accepted that temperature of live steam in steam turbine system will be lower about 10^{o}C than temperature of exhaust combustion from the combined system [3]. The pressure in condenser is the same in both taken engines. To calculation connected with steam stream for ship living purposes accepted for both engines the same value and the same return temperature of water stream for ship living purposes with heat box. Deaerator is boiling type (blend) in which the condensate stream from condenser is heated by steam stream loose from turbine to taken water temperature, reinforce steam system.

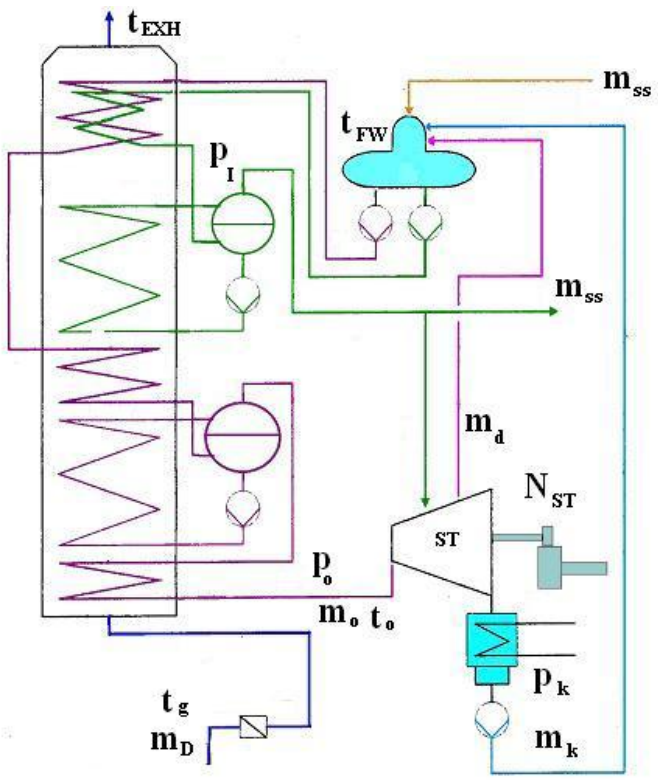


Fig. 3. Flow Diagram for a Two – Pressure System of Steam Turbine

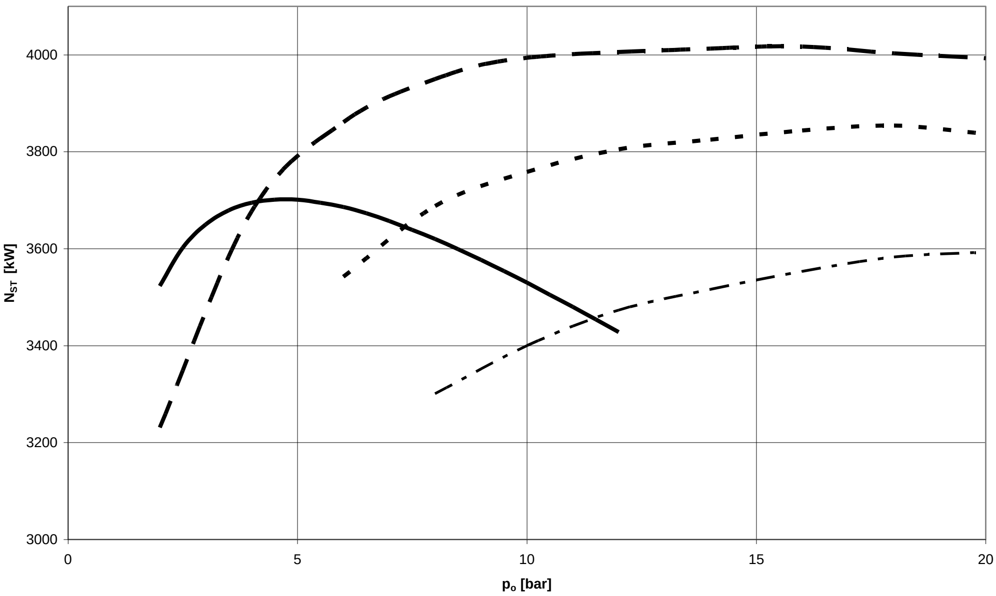
4. Comparison of calculation combined cycle for low-speed combined system

The calculation of combined cycle with low-speed combined engine and steam turbine with Single-Pressure system and Two-Pressure system is effected for two types of engine Wartsila company 9RTA96C and Man Diesel & Turbo company 9K98MC, as in Table 1.

The calculation is effected for two values of feeding water temperature, the same for two types of system. In this calculations there has been searching the maximum power of steam turbine in pressure function of live steam p_o. The maximum power of steam turbine system also asserts the biggest efficiency of combined cycle.

On Figure 4 is shown progress of steam turbine power in the case of pressure of live steam to constant temperature of reinforce water and for cycle with Single-Pressure system or Two-Pressure system without steam stream collection on ship living purposes. From diagrams appears that Two-Pressure system for both engine provide the maximum power of steam turbine in the case of properly taken pressure of low pressure boiler drum. The extension of pressure of low pressure boiler drum decreases the power of steam turbine. In both cases the maximum steam turbine power of Single-Pressure system is lower than the maximum power of Two-Pressure system. However the optimum pressure of live steam for Single-Pressure system is lower than pressure of live steam for Two-Pressure system.

a)



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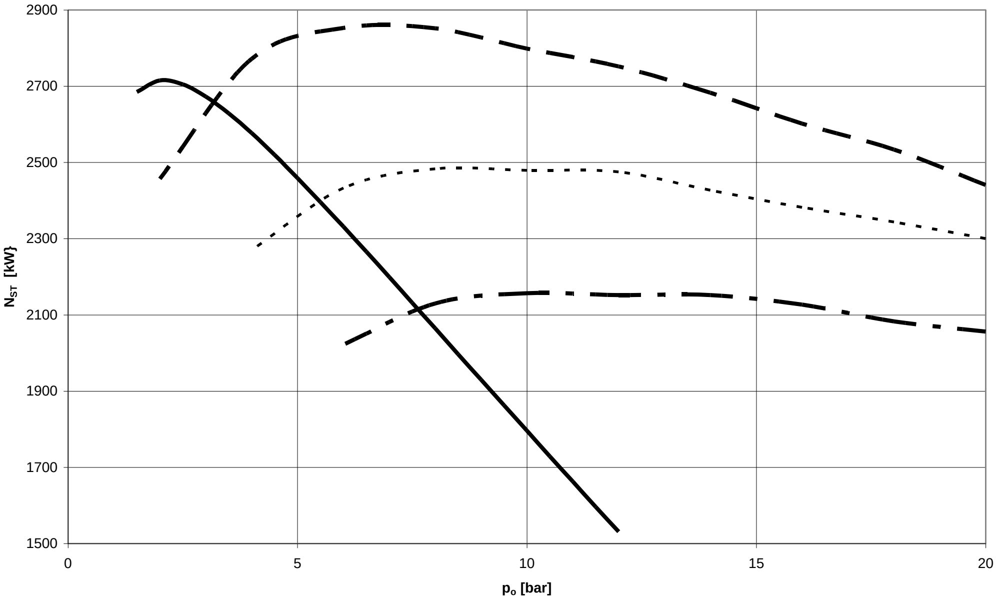
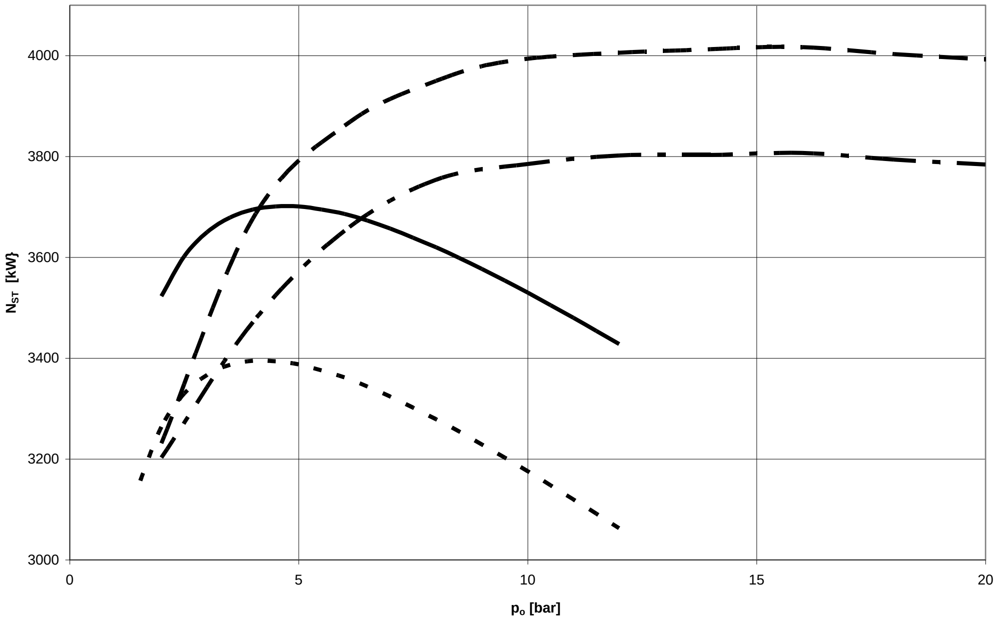


$m_{ss} = 0$ $t_{FW} = 100^oC$

Fig. 4. The power of steam turbine in function of live steam pressure for constant feed water temperature in steam turbine cycle with Single-Pressure and Two-Pressure system (without steam flow of ship living purposes)
a) Wartsila engine 9RTA96C b) MAN Diesel & Turbo engine 9K98MC
______ - single-pressure
two-pressure - - - - - p_I = 2 bar . . . . . . - p_I = 4 bar _ . _ . _ - p_I = 6 bar

a)



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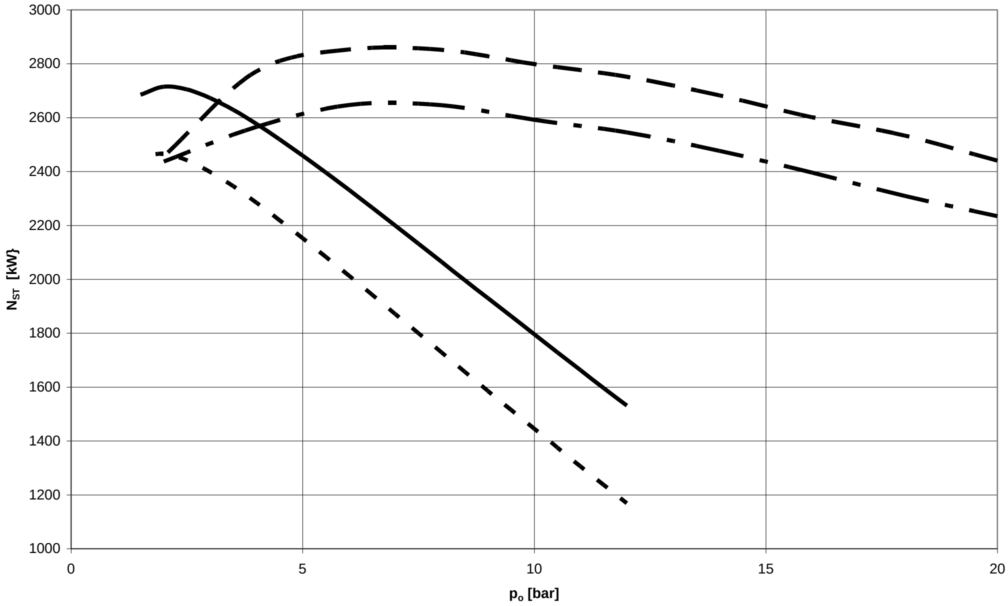


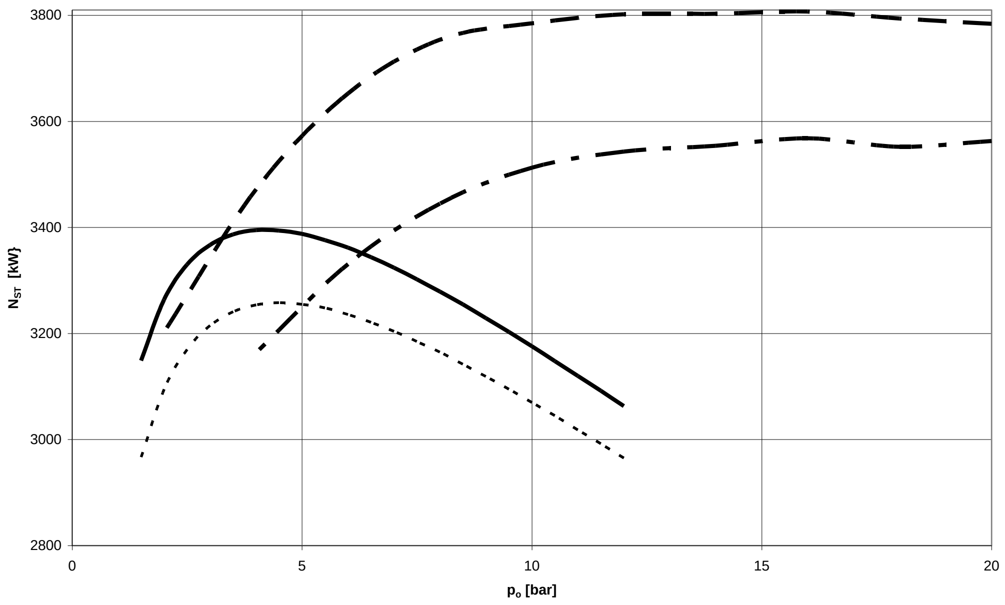
t_{FW}= 100 ^{o}C

Fig. 5. The power of steam turbine in function of live steam pressure for constant feed water temperature
a) Wartsila engine 9RTA96C b) MAN Diesel & Turbo engine 9K98MC
m_{ss} = 0 ______ Single-Pressure System - - - - - Two-Pressure System
m_{ss} = 2000 kg/h . . . . Single-Pressure System _ . _ . _ Two-Pressure System

On Figure 5 shows progresses of steam turbine power in function of live steam pressure in the case without taking flow steam on ship living purposes and for flow m_{ss} = 2000 kg/h. For both engines the power of steam turbine is lower in the case taking steam m_{ss} to cycle without taking this steam. In the same time for both engines in case of taking steam stream on ship living purposes the optimum pressure of live steam in Single-Pressure and Two-Pressure system for the maximum power of steam turbine is lower the in the case without taking steam m_{ss}. For Two-Pressure system the pressure in low pressure boiler drum is the same for both cases.

Diagrams in Figure 6 show dependence of steam turbine power for two feed water temperatures.

a)



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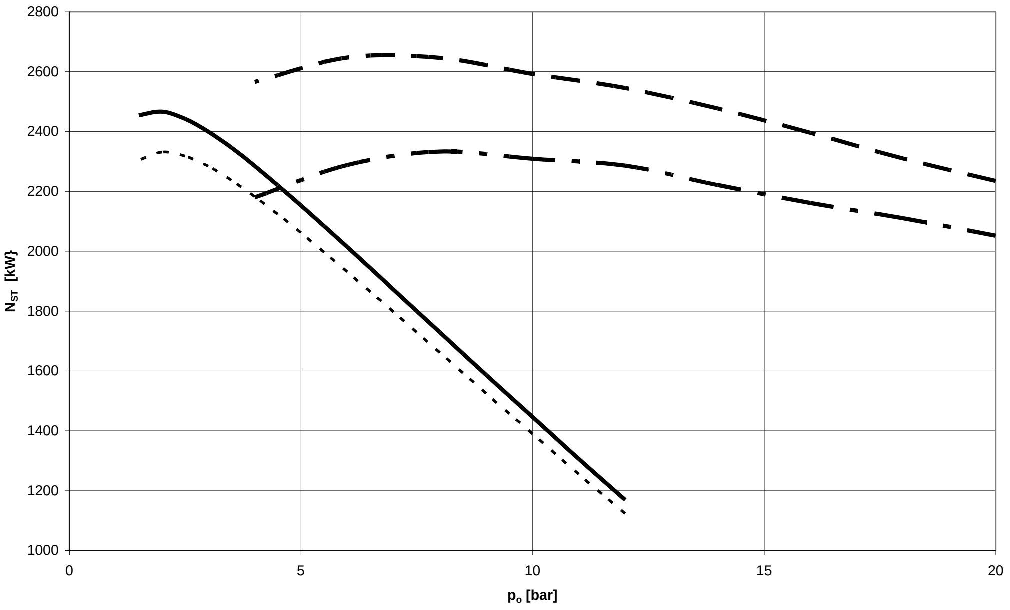


m_{ss} = 2000 kg/h

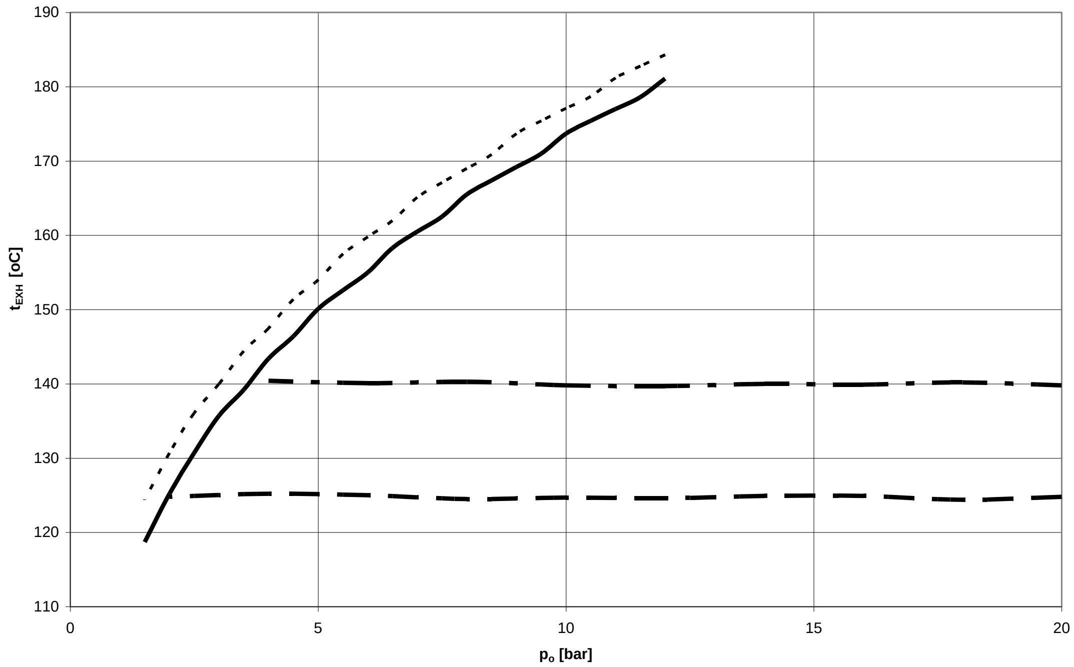
Fig. 6. The power of steam turbine in function of live steam pressure for constant steam flow in ship living purposes and for constant feed water temperature

a) Wartsila engine 9RTA96C b) MAN Diesel & Turbo engine 9K98MC

$t_{FW} = 100^oC$ ______ Single-Pressure System - - - - - Two-Pressure System

$t_{FW} = 120^oC$ . . . . Single-Pressure System _ . _ . _ Two-Pressure System

a)



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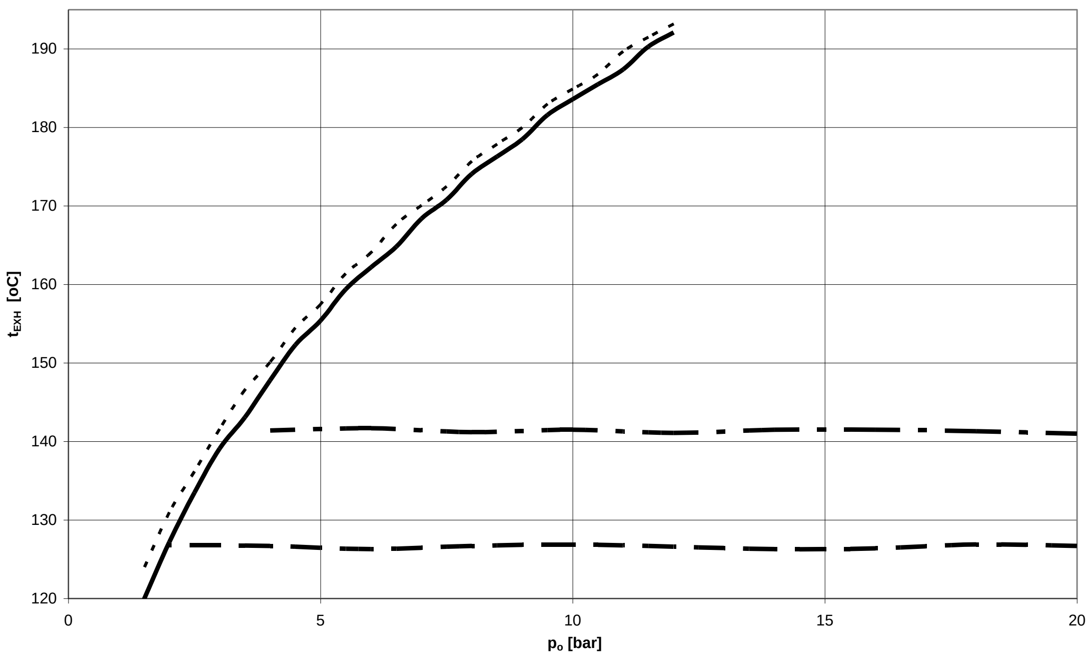
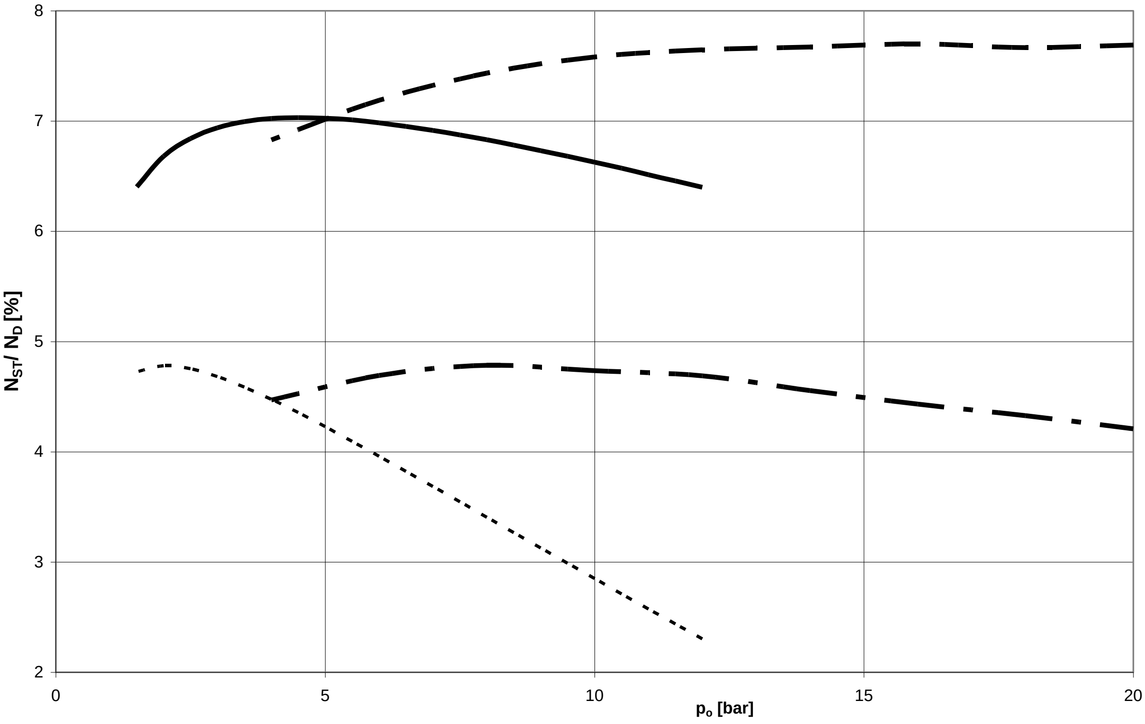


Fig. 7. Changes of exhaust gases temperatures from utilisation system of combined system for m_{ss} = 2000 kg/h
a) Wartsila engine 9RTA96C b) MAN Diesel & Turbo engine 9K98MC
t_{FW} = 100°C ______ Single-Pressure System - - - - - Two-Pressure System
t_{FW} = 120°C . . . . Single-Pressure System _ . _ . _ Two-Pressure System

The temperatures of exhaust gases in utilisation system of combined system for both cases of engine is the same for Single-Pressure and Two-Pressure system no mater of than it takes steam on ship living purposes or not, Figure 7. For higher feed water temperature, with increase of live steam pressure the exhaust gases temperature for Two-Pressure system is constant. But in case of Single-Pressure system the exhaust temperature for both engines is fast growing.

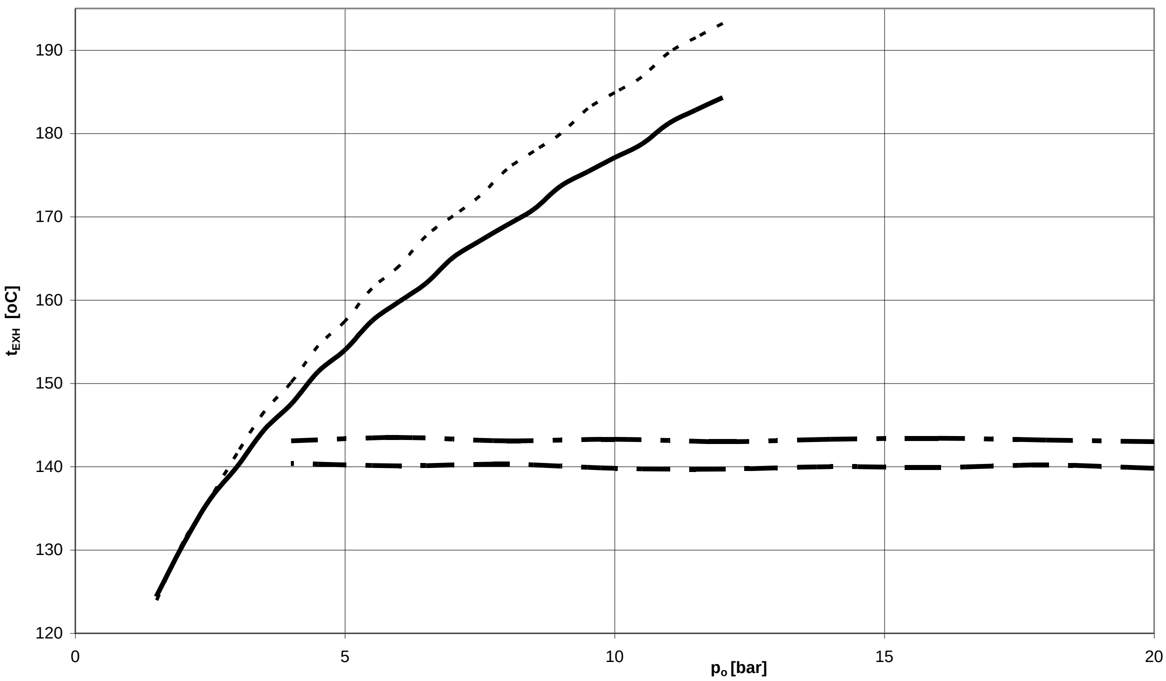


m_{ss} = 2000 kg/h t_{FW} = 120°C

Fig. 8. Reference of steam turbine power in function of fresh steam pressure of Single-Pressure and Two-Pressure system

Engine 9RTA96C ______ Single-Pressure system - - - - - Two-Pressure system

Engine 9K98MC . . . . Single-Pressure system _ . _ . _ Two-Pressure system



m_{ss} = 2000 kg/h t_{FW} = 120°C

Fig. 9. Exhaust gases temperature of utilisation system in function of live steam pressure of Single-Pressure and Two-Pressure system

Engine 9RTA96C ______ Single-Pressure system - - - - - Two-Pressure system

Engine 9K98MC . . . . Single-Pressure system _ . _ . _ Two-Pressure system

In Figure 8 shows reference power of steam turbine in the proportion to Diesel engine power in function of live steam pressure. Alike for Wartsila company engine and for MAN Diesel & Turbo company engine the power of steam turbine from Two-Pressure system is higher in the proportion to Single-Pressure system. The relative power of steam turbine with Wartsila engine is higher about 46-61% than the relative power of steam turbine in MAN Diesel & Turbo engine.
The capability of temperature progress of exhaust gases from utilisation system is similar, Figure 9. For Wartsila engine the exhaust gases temperature for Single-Pressure system and Two-Pressure system are lower.

5. The parameters of steam turbine cycle for combined system

From thermodynamic calculations of steam turbine cycle for combined system there has been appointed the parameters of steam turbine for engine company: Wartsila and MAN Diesel & Turbo. It has been searching the maximum power of steam turbine for two values of feed water temperature 100 ^oC and 120 ^oC, however the calculations has been done for cycle without taking the steam flow on ship living purposes and for taking flow m_{ss} = 2000 kg/h.
In Table 2 there has been shown calculations value of combined cycle for maximum power of steam turbine in accepted steam flow on ship living purposes.

Engine 9RTA96C company Wartsila

The maximum power of steam turbine with Single-Pressure system is smaller than power of steam turbine with Two-Pressure system about 7,3 % for t_{FW} = 120^oC and about 12 % for feed water temperature equal 100 ^oC. The power of steam turbine for higher feed water is smaller beside calculation for t_{FW} = 120^oC properly about 5,5 % for Single-Pressure system and 9,2 % for Two-Pressure system. The live steam pressure for Two-Pressure system is higher than for Single-Pressure system. For higher feed water temperature the live steam pressure is going high and is almost 3 times higher for Two-Pressure system than for Single-Pressure system. The live steam flow for Single-Pressure system is higher about 24-30 % in the proportion to Two-Pressure system, conversely is with decrease of enthalpy in steam turbine, properly is growing about 23-26 % in Two-Pressure system. The temperature of exhaust gases for Single-Pressure system is higher than for Two-Pressure system, but with the grown of t_{FW} the temperature of exhaust gases is also going up. The flow of heating steam in Two-Single system m_d is higher about 12-23 % in the proportion for Single-Pressure system, which is cause by bigger flow of condenser in the condenser of Two-Pressure system (higher about 5-18 %). The calculations show steam turbine in combine system with Two-Pressure system cause the acceleration of propulsion system efficiency, decreasing specific fuel oil consumption for about 5,7-6,2 % in the proportion for classic efficiency system with low-speed Diesel engine.

Engine 9K98MC company MAN Diesel & Turbo

In combined system with engine company MAN Diesel & Turbo the maximum power of steam turbine is obtained for Two-Pressure system, but there is noticed that it is high dependence from feed water temperature. For feed water temperature 120 ^oC the maximum power of steam turbine is comparable for both system. With decrease of feed water temperature to 100 ^oC, the maximum power of steam turbine with Two-Pressure system is higher about 7% than the power of turbine with Single-Pressure system. The optimum of live steam pressure, is similar to combined system with engine company Warsila, which is also higher for Two-Pressure system (about 4 times more) in the compare to Single-Pressure system. The flow of live steam and the stream of heating steam in the deaerator is bigger for Two-Pressure system, properly about 28-38 % and 7,9-9,6 % in the compare for Single-Pressure system. The stream of condenser is smaller in Single-Pressure system. The temperature of exhaust gases from system for t_{FW} = 100^oC is almost exactly for both system, but for t_{FW} = 120°C the temperature of exhaust gases is higher about 10°C for Two-Pressure system than for the temperature for Single-Pressure system. The decrease of enthalpy in both cases in steam turbine is higher for Two-Pressure system beside of feed water temperature, for t_{FW} = 100°C is about 24,5 %, and for 120°C about 30% in the proportion for Single-Pressure system. The delve studies show that for combined circulation with higher of feed water temperature for Single-Pressure system is comparable with Two-Pressure system in the case of steam turbine power, but for the feed water temperature is smaller (100 °C) the increase of steam turbine in Two-Pressure system is not so big in comparable to Single-Pressure system. Therefore it appears that for this engine in combined system in relative to comparative low temperature of exhaust gases from Diesel engine, the system of steam turbine should be feed from Single-Pressure system (invest cost are lower). For this case the efficiency of combined system is higher than for classic system, and also there is lower specific fuel oil consumption - about 4,8-5,1 % for t_{FW} = 100°C and about 4,6 % for t_{FW} = 120°C in the compare to classic Diesel engine.

Tab. 2. The calculations of combined cycle for the maximum power of steam turbine

		9RTA96C Watrsila		9K98MC MAN Diesel & Turbo	
N_D	kW	46332		48762	
t_g	°C	271		232,8	
be_D	g/kWh	166,8		174,9	
η_D	%	50,55		48,2	
		Waste Heat Boiler		Waste Heat Boiler	
		Single-Pressure	Two-Pressure	Single-Pressure	Two-Pressure
m_{ss}	kg/h	2000			
t_{FW}	°C	**100**			
t_o	°C	261		222,8	
p_o	bar	3	10	2	6
p_I	bar		2		2
m_o	kg/h	18811	14296	19332	14016
m_d	kg/h	2144	2634	2204	2417
m_k	kg/h	16666	18811	17128	17882
t_{EXH}	oC	136,8	125,3	127,2	126,3
N_{ST}	kW	2765	3085	2466	2647
N_{combi}/N_D	%	105,97	106,66	105,06	105,43
η_{combi}	%	53,56	53,91	50,64	50,82
$\Delta\eta/\eta_D$	%	5,97	6,66	5,06	5,43
be_{combi}	kg/kWh	157,41	156,39	166,5	165,9
$\Delta be/be_D$	%	-5,63	-6,24	-4,81	-5,15
H_i	kJ/kg	580,8	714,4	508	632,3
t_{FW}	°C	**120**			
t_o	°C	261		222,8	
p_o	bar	3	12	2	8
p_I	bar		3		3
m_o	kg/h	18811	13168	19332	12083
m_d	kg/h	2690	3010	2687	2900
m_k	kg/h	16121	16930	16644	15466
t_{EXH}	°C	141,7	141,6	131	141,2
N_{ST}	kW	2621	2823	2331	2333
N_{combi}/N_D	%	105,66	106,1	104,8	104,8
η_{combi}	%	53,40	53,63	50,51	50,51
$\Delta\eta/\eta_D$	%	5,66	6,09	4,78	4,78
be_{combi}	kg/kWh	157,9	157,2	166,9	166,9
$\Delta be/be_D$	%	-5,35	-5,74	-4,56	-4,56
H_i	kJ/kg	580,8	733,2	508	663,2

6. Final conclusions

From the compare of combined system Diesel engine with steam turbine for two types of low-speed engine appears:

- achieved powers of steam turbine for both engine increase the total power of system from 4,8 to 6,4 % for engine 9K98MC company MAN Diesel & Turbo and 5,7-6,7 % engine 9RTA96C company Wartsila. The powers of steam turbine for engine company Wartsila is higher than for combined system with engine company MAN Diesel & Turbo. It appears that from higher heat energy tight in exhaust gases of Wartsila engine (the temperature of exhaust gases is high about 38 ^{o}C),
- combined systems with engine company Wartsila have bigger efficiency,
- for engine 9RTA96C it appears that it is more profitable to use Two-Pressure system in combined system, whereas in engine 9K98MC using Two-Pressure system do not radically increase the power of steam turbine. What more, on that content of sulphur in fuel, producers advice higher temperature of feed water, for example MAN Diesel & Turbo advices temperature of feed water no lower than 120 ^{o}C [3, 4].

It is possible to adopt combined cycle Marine Diesel Engine as major engine and steam turbine which uses heat inside exhaust gases of Diesel engine. Those systems can have thermodynamic efficiencies compare to circulations of combined gas turbines, whose are connected with steam turbines. Adopted combined system in case of variant and load of major engine can help increasing of power system from 4,8 to 6,7 % in the compare to conventional system for the same fuel flow. Therefore combined system decreases individual fuel expenditure about 4,6-6,24 % in the proportion to conventional system. The efficiency of combined system is growing in the proportion to conventional system similar to system power, i.e. from 4,8 to 6,7 % achieve efficiency values of system about 50,5-53,9 % of maximum power.

Adoption of combined system not only gives thermodynamic advantages – increase of efficiency and economic – lower fuel consumption for the same power of propulsion system, but also ecologic advantages.

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