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Logistical Aspects of Energy Conversion Efficiency in Marine Steam Power Plants in Off-Design Conditions

Introduction

Energy conversion efficiency is a significant issue in many aspects of economy. In transport higher fuel consumption leads to lower profitability in few ways. During long cruises each percent of higher efficiency saves significant amount of fuel, that means lower costs but also lower mass of fuel (higher capacity of the vessel) or higher range. Moreover due to increasing environment protection regulations, especially CO_2 emission, energy conversion efficiency has become a basic issue for many projects. Increasing energy conversion efficiency and reducing pollution emission ratio are main parts of the sustainable development of power engineering [1]. The great part of research in this sector refers to increasing conversion efficiency at the design point, that is at the rated load. In the maritime the rated load ratio depends on size and type of ships but usually it is reached only for short period of time.

The problem is particularly important relating to steam and gas turbines, where partial loads cause increased losses in flow sections and decrease thermodynamic efficiency (the exception is a gas turbine closed cycle). Lower energy conversion efficiency during mooring at harbor or cruise with economic speed means higher specific fuel consumption per usable energy unit and higher maintenance costs.

Therefore, investigation net efficiency and other parameters of marine steam turbine thermodynamic cycle during off-design conditions are the purpose of this paper.

Marine steam turbines

Steam turbines are currently used mostly in the special purpose ships. That because of lower economic ratio due to two stock turbocharged marine diesel engines [2, 3, 4]. Notwithstanding steam turbine can provides greater power and takes less space at the same time than diesel engine. Another advantage of turbines is that it is the only way to convert thermal energy from nuclear reactor into mechanical energy. That is why nuclear propulsion is the most often place of application steam turbines [5].

Unfortunately, nowadays nuclear marine power plants achieve the low thermodynamic efficiency because of low temperatures reached by PWR (Pressurized Water Reactor) which is the only type of reactors used on ships. Currently intensive developing High Temperature Gas Reactors (HTGR) provide an opportunity to reach high steam cycle thermal efficiency, extra safety features and decreased maintenance costs [5, 6]. This technology can brings back nuclear energy to civil transport applications.

Thermodynamic parameters of marine steam cycles are not so high as in onshore power plants. There are few reasons: rated load is achieved only for some periods of time, propulsion turbine works within variable conditions where higher pressure and temperature cause higher stresses, moreover high temperature of steam needs more expensive austenitic steel and propulsion steam turbines reach lower power then onshore power plants.

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Conditions of the analysis

Analysis has been carried out for two proposed steam turbine cycles. In both engine-rooms turbines are clutch with electric generator. This method brings in higher energy conversion loose then the gear box, but provides a constant rotational speed of turbine in variable conditions [7]. Constant rotation at design level during partial loads provides better flow efficiency of turbine. The main conditions of the analysis were the same electric generators total power taken to be 50MW, live steam and condensation parameters, and heat exchange surface in regeneration circuit sections – data gathered in Table 1. In both variants the heat source in steam generator is helium cooling High Temperature Gas Reactor (HTGR). First cycle hereinafter referred to as a "twin cycle" consists of two the same steam cycles with low and high pressure regeneration circuit. Scheme of the twin cycle is presented at Fig. 1.

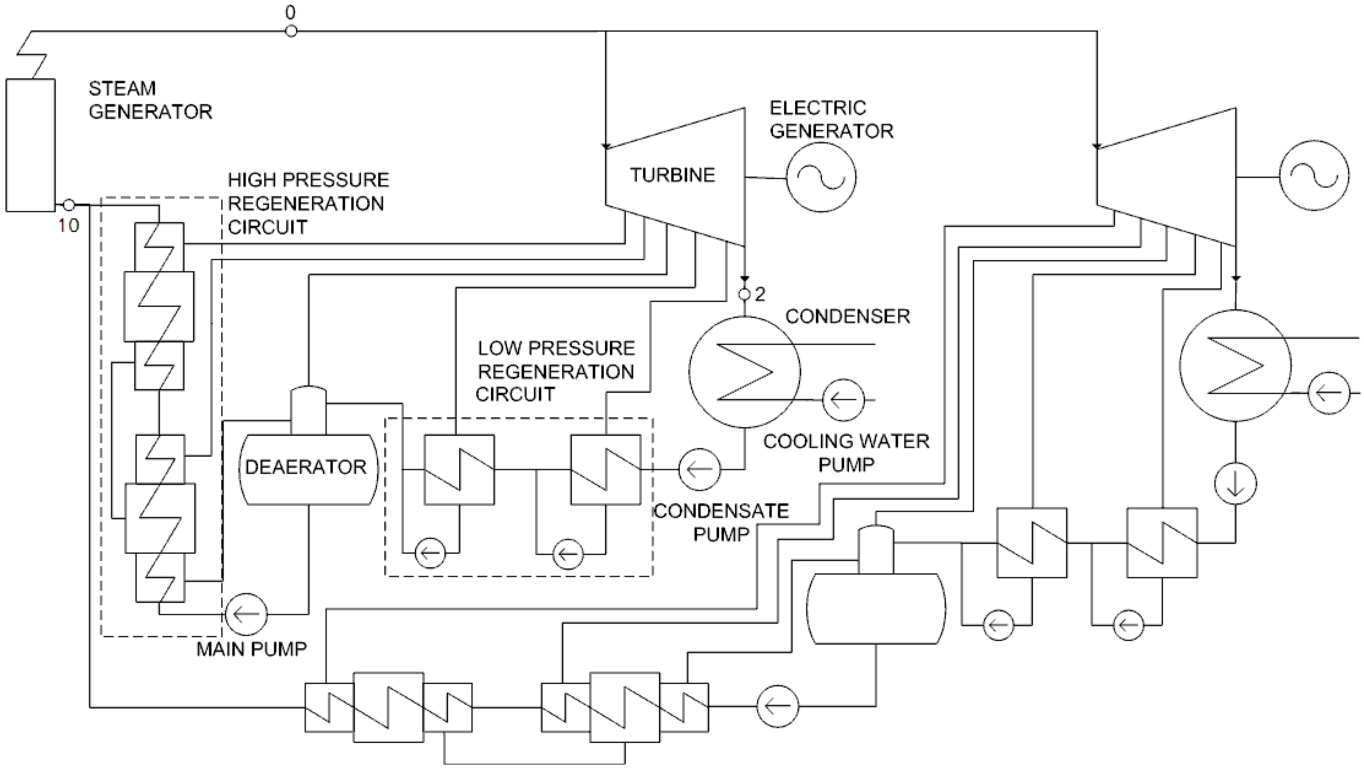

Fig. 1.The twin cycle thermodynamic scheme

Second cycle consists of high and low pressure steam turbine, high and low pressure regeneration circuit and steam generator with steam reheat section. Thermodynamic scheme of steam cycle with reheat is presented at Fig. 2.

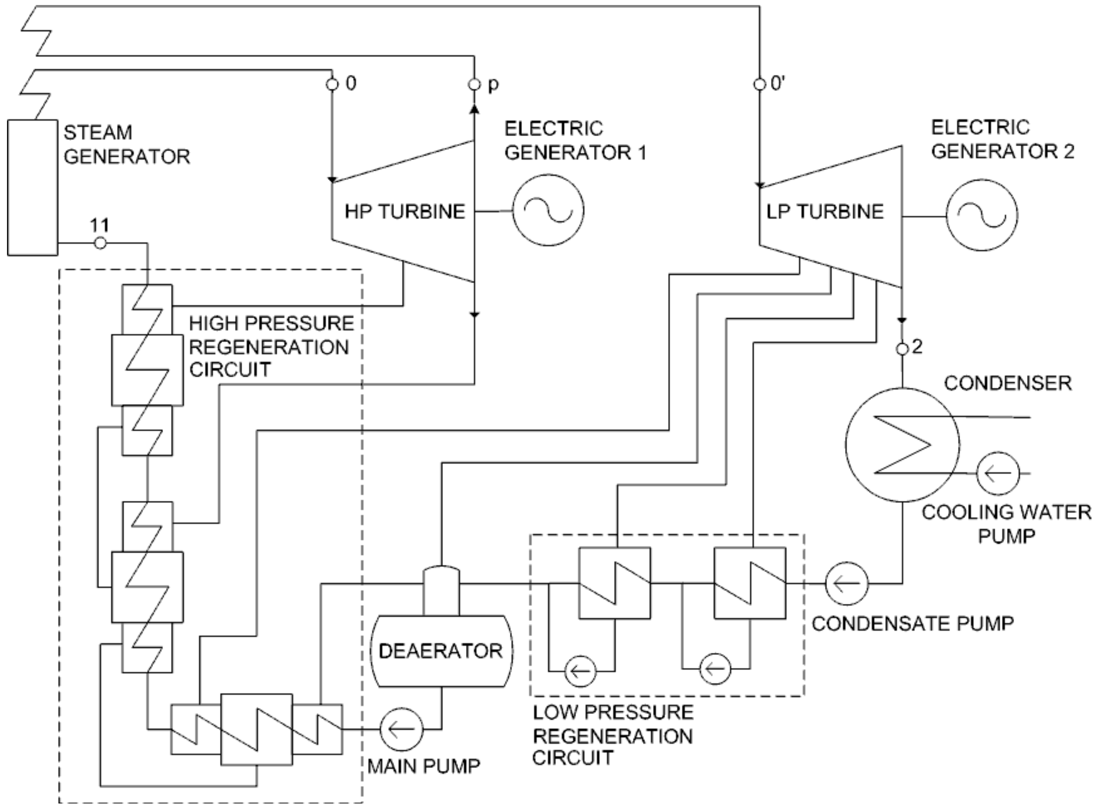

Fig. 2. Steam cycle with reheat thermodynamic scheme

The main difference between proposed cycles is power distribution ratio. In the twin cycle it is possible to achieve the same efficiency during rated and half load. However the maximum cycle efficiency is lower than in cycle with steam reheat section. Main thermodynamic parameters of proposed cycles are presented in table 1.

Table 1. Steam parameters in characteristic pints of proposed thermodynamic cycles

Parameter	Symbol	Unit	Cycle with reheat	Twin cycle
Live steam temperature	t_o	°C	535	535
Live steam pressure	p_0	bar	100	100
Reheated steam temperature	$t_{o'}$	°C	535	-
Reheated steam pressure	$p_{o'}$	bar	18	-
Condenser pressure	p_2	bar	0.05	0.05
Total number of regeneration heat exchangers	-	-	5	8

The twin cycle have three regeneration heat exchanger more than the steam cycle with reheat but because of adequate parameters of heat exchange the heat exchange surface is nearly the same and is about 3000 m^2. Similar power and dimension of proposed marine engine-rooms is helpful in precise comparing of thermodynamic cycles.

Additional advantage of marine engine-room with two main turbines is possibility of achieve some partial power in accident situations. The twin cycle can give half of his nominal power simply using cut-off valve of damaged turbine lope. During that secondary turbine can work in normal conditions. In cycle with reheat it is also possible to run only one turbine. In this case reducing and cooling station is necessary to reach proper steam parameters. Reducing and cooling station is a kind of live steam regulation valve with water injection.

Mathematical model

Steam parameters in characteristic points of thermodynamic cycles in partial loads conditions were calculated using Stodola's cone law also known as Ellipse Law [7]. The equal describe permeability of turbine:

$$\frac{m_i}{m_{i\,0}} = \frac{p_i}{p_{i\,0}} \sqrt{\frac{t_{i\,0}}{t_i}} \sqrt{\frac{1-\left(\frac{p_{i+1}}{p_1}\right)^2}{1-\left(\frac{p_{i+1\,0}}{p_{1\,0}}\right)^2}} \tag{1}$$

where:

m – mass flow rate,

p – pressure,

t – temperature,

i – *i*-number steam bleed,

0 – rated conditions.

Steam pressures between turbine stages are increasing and decreasing at the same time during momentum regulation process, so the expression (1) can be simplified on each turbine stage except last one where p_{i+1} is the condensation pressure p_2

$$\frac{1-\left(\frac{p_{i+1}}{p_1}\right)^2}{1-\left(\frac{p_{i+1\,0}}{p_{1\,0}}\right)^2} \approx 1 \tag{2}$$

Then, the equation (1) becomes

$$\frac{\dot{m}_i}{\dot{m}_{i\,0}} \approx \frac{p_i}{p_{i\,0}} \sqrt{\frac{t_{i\,0}}{t_i}} \tag{3}$$

Further calculations require an iterations methods to reach the result. The first approximation implies that change of mass flow rate in each turbine stage is the same as mass flow change on turbine inlet:

$$\frac{\dot{m}'_i}{\dot{m}_{i\,0}} = \frac{\dot{m}}{\dot{m}_0} \tag{4}$$

On this step pressures in all steam bleeds are changing evenly to mass flow on turbine outflow

$$\frac{p'_i}{p_{i\,0}} = \frac{p'}{p_0} = \frac{\dot{m}}{\dot{m}_0} \sqrt{\frac{t_1}{t_{1\,0}}} \tag{5}$$

When p'_i pressure in every steam bleed is known for set turbine load, more accurate thermodynamic calculation of whole cycle can be evaluate. This method possesses the fast convergence and needs only few iterations to reach the precision results.

The electric net efficiency of the twin cycle define equal:

$$\eta_{net} = \frac{N_{net}}{\dot{Q}_{SG}} = \frac{N_G - N_{OC}}{2\dot{m}_0(i_1 - i_{10})} \tag{6}$$

and of the cycle with steam reheat equal:

$$\eta_{net} = \frac{N_{net}}{\dot{Q}_{SG}} = \frac{N_G - N_{OC}}{\dot{m}_0(i_0 - i_{11}) + \dot{m}_{0'}\left(i_{0'} - i_p\right)} \tag{7}$$

where:

N_{net} – Net total electric power,

$\dot{Q}_{SG}$ – Steam Generator thermal energy flow rate,

N_G – Electric Generators total power,

N_{OC} – Own Compunction power in thermodynamic cycle,

$\dot{m}_0$ – Steam mass flow rate in rated conditions in defined points of thermodynamic cycle,

i – entropy in defined points of thermodynamic cycle.

The calculation and diagrams were carried out using equations mentioned above and additional assumptions listed in [6]. There are some mathematical models of steam cycles in literature [2, 3, 4], but they are much more simplified and not including partial loads conditions.

Results of the analysis

Using mathematical model, which has partly been described in previous paragraph, characteristics of chosen parameters in variable conditions for proposed thermodynamic models of marine main propulsion system were carried out. Results of calculated electric generators efficiency η_G, cycle net electric efficiency η_{netto}, average mechanical efficiency of high and low pressure turbine η_T and live steam mass flow rate m_x/m_0 as a function of load variations for cycle with steam reheat are presented on Fig. 3. Electric net efficiency is a proper parameter for comparison of different thermodynamic cycles that contain the electric generators, because it defines thermal energy to usable electric energy conversion efficiency.

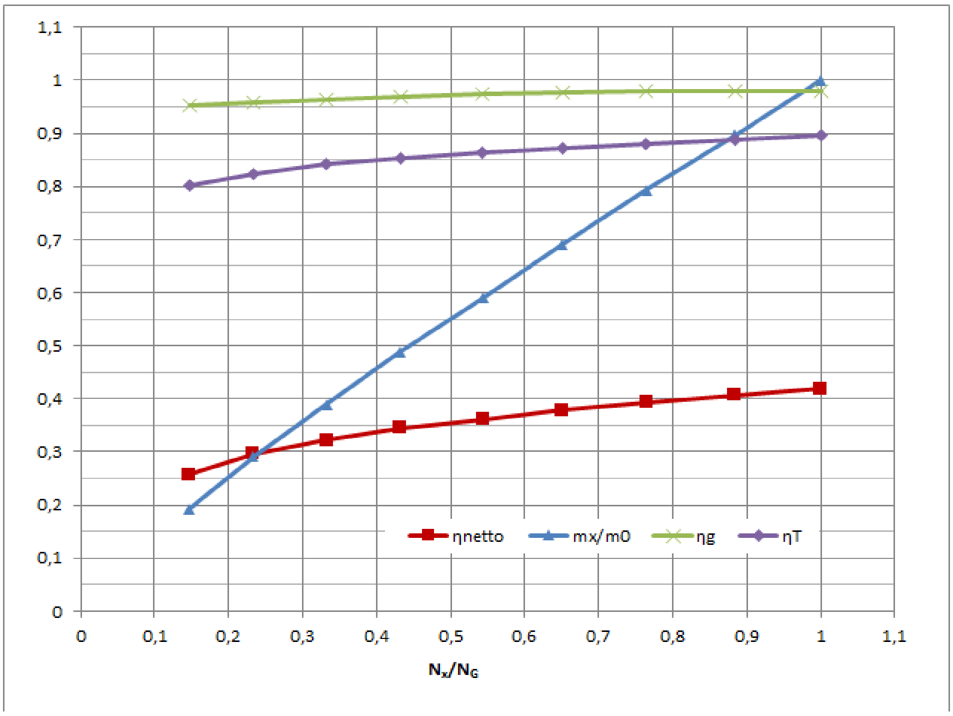

Fig. 3. Characteristic of: electric generators efficiency η_G, electric net efficiency η_{netto}, turbines average mechanical efficiency η_T and live steam mass flow rate m_x/m_0 as a function load variations N_x/N_G for cycle with steam reheat.

Next, calculations results for the twin cycle are presented on fig. 4. Additional parameter added to the chart is the live steam average pressure on turbine inlet p_x/p_0 as a function of load variations. For cycle with steam reheat this parameter practically covers the live steam mass flow curve, from that reason it has been omitted on chart at Fig. 3.

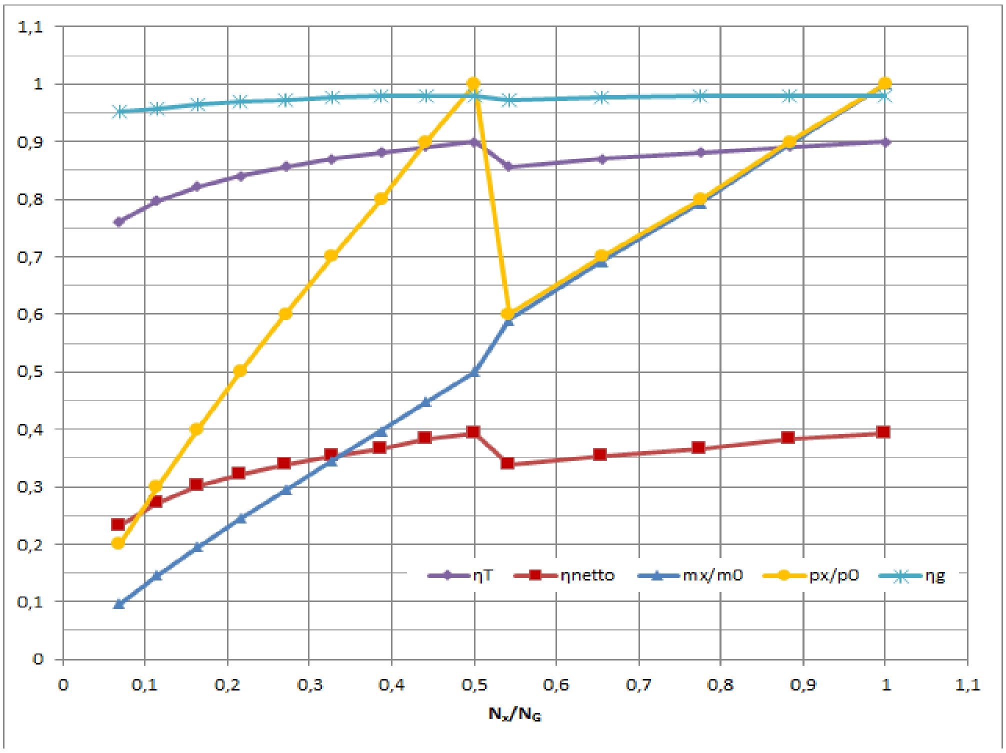

Fig. 4. Characteristic of: electric generators efficiency η_G, electric net efficiency η_{netto}, turbines average mechanical efficiency $\eta_{T,}$ and live steam mass flow rate m_x/m_0 as a function load variations N_x/N_G for cycle with steam reheat.

Moreover main parameters of thermodynamic cycles under rated load have been presented in Table 2. As a result of heat loss omissions in steam generator in mathematical model, steam generator thermal power is identical as required nuclear reactor thermal power.

Table 2. Chosen parameters of proposed thermodynamic cycles in rated conditions with the same gross electric generators total power – 50 MWe

Parameter	Symbol	Unit	Cycle with reheat	Twin cycle
Steam Generator thermal power	$\dot{Q}_{SG}$	MWt	112,40	120,41
Electric net power	N_{net}	MWe	47,21	46,96
Live steam mass flow rate	m_0	kg s^{-1}	38,31	44,67
Reheated steam mass flow rate	$m_{0'}$	kg s^{-1}	33,14	-
Heat exchange surface	F_w	m^2	2981	3022
Electric net efficiency	η_{net}	-	0,42	0,39

Analysis of data form Table 2 and charts from Fig. 3 and Fig. 4 brings the conclusion than application of steam reheat between high and low pressure steam turbine increase total net electric efficiency of turbine cycle of about 3 percent points (pp) due to cycle without steam reheat section. However the twin cycle is more efficiency under half load. The efficiency is higher for about 4pp. The proposed turbine cycles have quite the same dimensions and mass thanks to the same number of turbines and heat exchange surfaces.

Conclusion

The efficiency of energy conversion from source an available to useful form is one of the most significant issue about power engineering and it has influence on each sector of economy. There are some limitations of thermodynamic cycles efficiency that can be never exceeded, however, increasing energy conversion efficiency is one of the main aims of power engineering. On the other hand higher efficiency is not always valuable from the economic point of view because it often means more complicated systems, machines made of more expensive material, sometimes purest fuel is needed or in different physical state. That is the reason why the main condition in power engineering is profitability and payback time. Different approach is imposed by sustainable development. Here the main condition is environment protection and to save fossil fuels reserves so that next generations could live on the same or better standard of living.

Performed calculations leads to conclusion that design of energy conversion system which is optimally matched to maintenance conditions as well as in power engineering also in transport sector leads to higher energy conversion efficiency without higher investing costs. In logistic the issue is especially important for ships using economic speed for most of the cruises or have long mooring at harbors with passengers onboard like in case of ferries or cruise ships.

Abstract

The paper presents logistical aspects of energy conversion efficiency in off-design conditions. The main part of the article is based on results of thermodynamic calculation for large propulsion steam turbine under partial loads. Calculations are made on extended mathematical model of two proposed steam turbine thermodynamic cycles using Stodola's cone law. The conclusion based on calculation results contains importance of off-design calculations on energy conversion efficiency in aspects of transport and logistics profitability and sustainable development postulates.

Keywords: steam turbine, steam cycle, marine power plant, nuclear propulsion, off-design conditions, partial load

ANALIZA EFEKTYWNOŚCI KONWERSJI ENERGII W OKRĘTOWYCH SIŁOWNIACH TURBOPAROWYCH W ZMIENNYCH WARUNKACH RUCHU

Streszczenie

W artykule przedstawiono wyniki analizy sprawności konwersji energii w turbinowych siłowniach parowych przy obciążeniach częściowych pod kątem wpływu na sektor transportu i logistyki. W pracy opisano fragment modelu matematycznego pozwalającego wyznaczyć parametry obiegu turbiny parowej przy obciążeniach częściowych. Obliczenia zostały przeprowadzone dla dwóch proponowanych obiegów termodynamicznych używając m.in. równania przelotności turbiny Stodoli. Wnioski oparte na wynikach obliczeń ukazują znaczenie zagadnienia sprawności konwersji energii w transporcie morskim w odniesieniu do rentowności i idei zrównoważonej konwersji energii.

Słowa kluczowe: siłownia turboparowa, turbina parowej, obieg termodynamiczny, transport morski

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