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THE APPLICATION OF THE ENTROPY ANALYSIS FOR THE EVALUATION OF THE PERFORMANCE OF THE PROCESSES WITHIN THE WASTE ENERGY RECOVERY SYSTEMS IN MARINE DIESEL POWER PLANTS

Ryszard Michalski
West Pomeranian University of Technology, Szczecin
41 Piastów Ave, 71-065 Szczecin, Poland
phone: +48 91 4494941
e-mail: ryszard.michalski@zut.edu.pl

Abstract

The paper presents a proposal of the application of the entropy analysis for the theoretical research of the processes occurring during the thermodynamic transformations taking place in the waste energy recovery systems in marine Diesel power plants. In view of the low exergy of waste energy carriers in these systems it becomes significant to make a proper selection of parameters in the individual points characterising the thermodynamic transformations of the working media. The method as presented herein consists an adaptation of the methods applied in the arrangements of shore power plants to the needs of the marine power plants. This article presents basic relations allowing to determine increments in entropy in the heating steam generation system, as well as the other basic elements forming the waste energy recovery systems in marine power plants. They constitute the basis to evaluate the performance of the individual processes and to disclose the places of occurrence of the major losses and to determine the manners to minimise same. The proposed method may contribute to the reduction of labour consumption of universally applied, traditional methods of searching the effective systems of waste energy recovery in marine Diesel power plants.

Keywords: *entropy analysis, waste energy recovery, marine power plants*

1. Introduction

The specific feature of the marine systems of waste energy recovery in Diesel power plants is the relatively low exergy of the energy carriers. This results in the fact that the degree of waste energy recovery is small, and the generally applied arrangements are mainly restricted to the recovery of the main engine exhaust gas heat to generate steam in the amount that satisfies wholly or partly the ship's heating needs. Only in few cases the available amount of waste energy allows additionally to generate mechanical power in gas or steam turbine on in both at the same time, which may be utilised to drive the generator or for the propeller drive [7]. However, in each case it is significant to properly select the parameter values in the individual circulation points, characterising the working media thermodynamic transformations. In order to make this choice in the appropriate manner it is necessary to conduct the relevant analyses whose results will enable the evaluation of the quality of the course of the individual processes and indicate the places of the major losses and the ways to minimise them.

The basis for the calculations of the waste energy recovery systems in marine Diesel power plants consists the mass and energy balance equation systems [9]. While designing the discussed systems enthalpy analysis has become generally applied. Exergetic analysis [6, 8, 9] can be used for the proper evaluation of, in particular the sources of waste energy, whereas for the evaluation of the performance quality of the processes taking place during system operation entropy analysis may be considered as the appropriate one. Such analysis is presently used not only at the design stage of new systems of shore power plants, but also to conduct the heat-flow diagnostics [5] or providing the guidelines for the modernisation directions of these power plants and evaluating the effects of their modernisation [2, 4].

The entropy analysis has not been found so far so generally useful for the designing of marine power plants. Nevertheless, it should be expected that as the solutions improving widely understood effectiveness of the marine power plants are sought, its application will turn also useful in this field. Thus this article consists an attempt to present the application of the basis of entropy analysis to the evaluation of the processes occurring in the systems and the elements forming the waste energy recovery systems in marine Diesel power plants.

The inspiration to present in this article the entropy method as a supporting tool in the complex analysis of waste energy recovery in marine Diesel power plants has been provided inter alia by the studies [2, 3, 4, 5]. The general methods of entropy increment minimisation during the processes of heat exchange and in power plants have also been referred to in [1]. Its elements have also been presented earlier by the author in [6, 8].

2. Entropy Analysis of Steam and Mechanical Energy Generation System

Considering a significant similarity of marine systems of waste energy recovery, where water and steam are working media, to the shore systems of steam turbine power plant systems, the general model consisting the basis for the entropy analysis of engine exhaust gas heat recovery in marine Diesel power plants can also be presented by use of the specification contained in [3]. The figure 1 shows general diagram of the analysed part of the system.

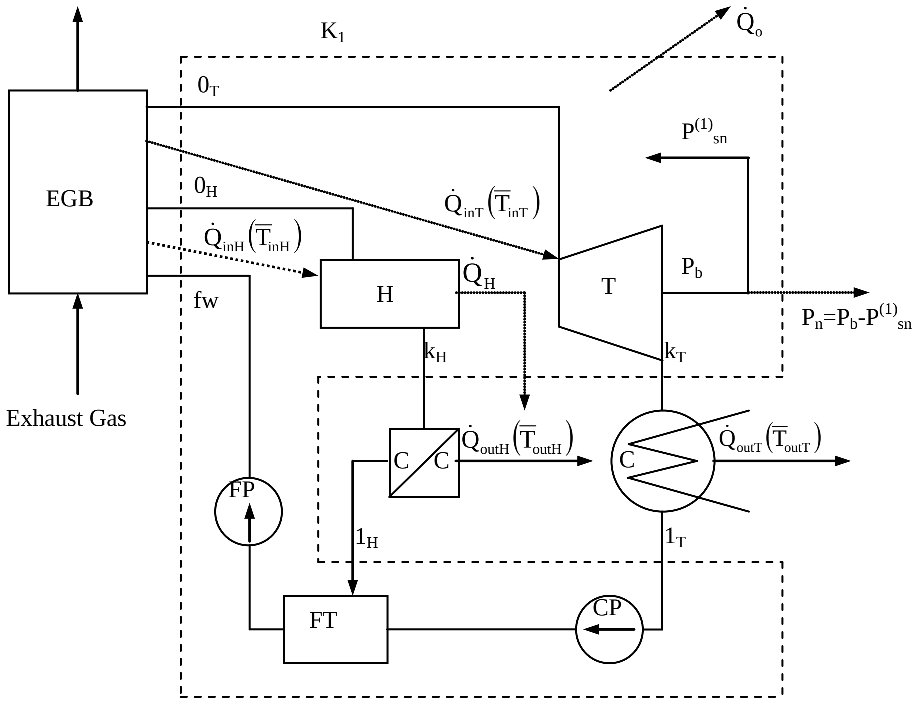

Fig 1. General diagram of the system of heat recovery of marine Diesel power plant engine exhaust gases

This part under discussion has been separated by means of cover sheet K_1, marked in the figure with the interrupted line. The diagram shows: EGB – exhaust gas boiler; H – heaters; CC – condensate cooler behind the heaters; T – waste heat turbine; C – condenser of turbine outlet steam; FT – feed tank (hotwell); CP – condensate pump; FP – feed pump.

Outside the cover sheet there are: waste heat boiler, condensate cooler and steam condenser. Processes taking place in these elements can be a subject of separate analysis which basis have been referred to in the further part of this paper.

By use of denominations applied in the figure 1 the energy balance within the cover sheet can be presented by means of the equation:

$$\dot{Q}_{inH} + \dot{Q}_{inT} - \dot{Q}_{outH} - \dot{Q}_{outT} - \dot{Q}_{o} = \dot{Q}_{H} + P^{(b)} - P^{(1)}_{sn} = \dot{Q}_{H} + P_{n} \tag{1}$$

where:

$\dot{Q}_{inH}$ - heat flux supplied to the marine heating system within cover sheet,

$\dot{Q}_{inT}$ - heat flux supplied to the turbocharger within cover sheet,

$\dot{Q}_{outH}$ - heat flux carried out of ship's heating system by the condensate cooler,

$\dot{Q}_{outT}$ - heat flux carried out from the turbine by the condenser,

$\dot{Q}_{o}$ - heat flux exchanged by the system with the environment (heat losses to the environment,

$\dot{Q}_{H}$ - usable heat flux transferred to shipboard heaters,

$P^{(b)}$ - (gross) power of generator driving turbine,

$P^{(1)}_{sn}$ - own needs of the processes taking place within cover sheet,

P_{n} - (net) power of turbocharger.

The sum of entropy generated within cover sheet can be determined as:

$$\dot{m}_{0H}(s_{fw} - s_{0H}) + \dot{m}_{0T}(s_{fw} - s_{0T}) - \dot{m}_{kH}(s_{1H} - s_{kH}) - \dot{m}_{kT}(s_{1T} - s_{kT}) + \dot{S}_{o} = \dot{S}_{gen} \tag{2}$$

where:

$\dot{m}_{0H}, \dot{m}_{kH}$ - working medium fluxes at the heater inlet/outlet, respectively,

$\dot{m}_{0T}, \dot{m}_{kT}$ - working medium fluxes at the turbine inlet/outlet, respectively,

s_{fw} - specific entropy of boiler supply water,

s_{0H}, s_{0T} - specific entropy of working medium at inlet/outlet of heaters and turbine, respectively,

s_{kH}, s_{kT} - specific entropy of working medium at the outlet of heaters and turbine,

s_{1H}, s_{1T} - specific entropy of working medium at the outlet of heating steam condensate cooler and condenser, respectively,

$\dot{S}_{o}$ - increase of entropy fluxes related with the $\dot{Q}_{o}$ loss,

$\dot{S}_{gen}$ - the sum of entropy generated in the processes taking place within cover sheet.

It should be noted that:

$$\dot{Q}_{inH} = \dot{m}_{0H}(h_{0H} - h_{fw}), \quad (3), \qquad \dot{Q}_{inT} = \dot{m}_{0T}(h_{0T} - h_{fw}), \quad (4)$$

$$\dot{Q}_{outH} = \dot{m}_{0H}(h_{kH} - h_{1H}), \quad (5), \qquad \dot{Q}_{outT} = \dot{m}_{0T}(h_{kT} - h_{1T}). \quad (6)$$

The average entropy temperatures for the heat flux flows in the individual system elements are defined as:

$$\overline{T}_{inH} = \frac{h_{0H} - h_{fw}}{s_{0H} - s_{fw}}, \qquad (7) \qquad \overline{T}_{inT} = \frac{h_{0T} - h_{fw}}{s_{0T} - s_{fw}}, \qquad (8)$$

$$\overline{T}_{outH} = \frac{h_{kH} - h_{1H}}{s_{kH} - s_{1H}}, \qquad (9) \qquad \overline{T}_{outT} = \frac{h_{kT} - h_{1T}}{s_{kT} - s_{1T}}, \qquad (10)$$

where:

h_{0H}, h_{0T} - specific enthalpy values of working media at the inlet to heaters and turbine, respectively,

h_{kH}, h_{kT} - specific enthalpy values of working media at the outlet of the heaters and turbine, respectively,

h_{1H}, h_{1T} - specific enthalpy values of working media at the outlet from heating steam condensate cooler and turbine steam condenser, respectively,

h_{fw} - specific enthalpy of boiler supply water.

By the application of the equations (2)÷(10) the sum of the generated entropy fluxes in the processes taking place within the cover sheet can be determined as:

$$\dot{S}_{gen} = -\frac{\dot{Q}_{inH}}{\overline{T}_{inH}} + \frac{\dot{Q}_{outH}}{\overline{T}_{outH}} - \frac{\dot{Q}_{inT}}{\overline{T}_{inT}} + \frac{\dot{Q}_{outT}}{\overline{T}_{outT}} + \dot{S}_o . \qquad (11)$$

While eliminating by equation (1) $\dot{Q}_{outT}$ from the equation (11), the sum of entropy fluxes in the discussed processes can also be expressed by the equation:

$$\dot{S}_{gen} = -\frac{\dot{Q}_{inH}}{\overline{T}_{inH}} + \frac{\dot{Q}_{outH}}{\overline{T}_{outH}} - \frac{\dot{Q}_{inT}}{\overline{T}_{inT}} + \frac{\dot{Q}_{inH} + \dot{Q}_{inT} - \dot{Q}_o - \dot{Q}_{outH} - \dot{Q}_H - P_n}{\overline{T}_{outT}} + \dot{S}_o \qquad (12)$$

From the equation (12) it results that the total entropy flux generated in the analysed system of heat recovery depends not only on the value of heat fluxes but on average entropy temperatures within the process of heat flow in the individual system elements. This property should be considered during the system designing, inter alia while adopting the adequate values of working media parameters in the individual equipment. However it should be noted that the minimising of entropy flux increments results directly in the reduction of the system operating costs, nevertheless it is related with the increase of the investment outlays. Although it is already a cliché to state that the decision-making processes while designing marine power plants should be supported by a complex multicriteria analysis, it is still worthwhile to emphasise this necessity.

By using the equation (12) the power of water heat turbocharger possible to achieve can be determined with the assumed circulation parameters:

$$P_n = \dot{Q}_{inT}\left(1 - \frac{\overline{T}_{outT}}{\overline{T}_{inT}}\right) - \dot{Q}_H - \dot{Q}_o - \overline{T}_{outT}\left(\dot{S}_{gen} - \dot{S}_o\right) - \dot{Q}_{outH}\left(1 - \frac{\overline{T}_{outT}}{\overline{T}_{outH}}\right) - \frac{\dot{Q}_{inH}\overline{T}_{outT}}{\overline{T}_{inH}} \qquad (13)$$

The equation (13) allows to determine the actual achievable power output of waste heat turbocharger. Its first part shows maximum achievable value of this power output under assumption that the entire heat flux would be used for the production of mechanical energy and that no heat losses to the environment occur, whereas the processes taking place are not accompanied by entropy increase. By use of the above models it is relatively simple to determine the optimum parameters of working media in the individual points of transformations.

3. Entropic Analysis of Selected Equipment of Steam and Mechanical Energy Generation System

While analysing the processes taking place in marine waste heat boilers there should be distinguished three functional types of heat exchange section. These are, in case of the most complex and extended system, supply water exhaust gas heater, separating sections (high and low-pressure) and steam heater. The processes of heat exchange between heating exhaust gases and the media receiving heat are accompanied by working media entropy increase. It originates both from the heat flow process itself as well as from the pressure losses due to friction. The latter however are much smaller in comparison with the former ones. Thus they will be omitted here.

The entropy increase in waste heat boiler is equal to the sum of entropy increments of all bodies participating in the transformation:

$$\sum \Delta S = \Delta S_{hm} + \Delta S_{eg} \tag{14}$$

where:

ΔS_{hm} - entropy increase of the heated medium (water and steam),

ΔS_{eg} - exhaust gas entropy increase.

The increase of exhaust gas entropy flux is calculated under assumption of its constant specific heat capacity:

$$\Delta \dot{S}_{eg} = \int_{T_0}^{T_1} \frac{d\dot{Q}}{T} = \dot{m}_{eg} c_{peg} \int_{T_0}^{T_1} \frac{dT}{T} = \dot{m}_{eg} c_{peg} \ln \frac{T_1}{T_0}, \tag{15}$$

where:

T_0, T_1 - exhaust gas temperature in the beginning and end of the process,

c_{peg} - average specific heat capacity of exhaust gases,

$\dot{m}_{eg}$ - exhaust gas mass flux.

The increase of entropy flux of water (steam-water mixture or overheated steam) should be calculated as the difference of specific entropy values at the outlet and inlet from the section under consideration “i” of the waste heat boiler:

$$\Delta \dot{S}_{wi} = \dot{m}_{wi} \left(s_{1wi} - s_{0wi} \right), \tag{16}$$

where:

$\dot{m}_w$ - water mass flux,

s_{1wi}, s_{0wi} - specific entropy value of the working medium at the outlet and inlet of the section under consideration.

The study [9] presents the results of exergetic analysis of the processes occurring in the marine waste heat boiler. Its completion required the determination of entropy increments in its individual sections. By use of the results of this analysis it can be stated that the biggest losses do take place in the evaporating section. These are related inter alia with the water properties, and more specifically with the relatively large value of evaporation specific enthalpy with the moderate pressure values of steam. Its reduction takes place along with the increase of stem in boiler, however, it leads to the reduction of the degree of the heat utilisation of the engine exhaust gases. Therefore it is of major importance while designing marine engine exhaust gas heat recovery systems to adopt the appropriate steam pressure.

By use of denominations in figure 2, the increase of entropy flux in steam separator can be determined as [9]:

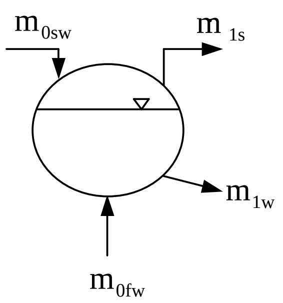

Fig 2. General diagram of steam separator

$$\Delta\dot{S} = \dot{m}_{1s}\left[x_1 s_{1s} + (1-x_1)s_{1w}\right] + \dot{m}_{1w}s_{1w} - \dot{m}_{0fw}s_{0fw} - \dot{m}_{0sw}\left[\frac{s_{0s}}{k_c} + s_{0w}\left(1-\frac{1}{k_c}\right)\right], \qquad (17)$$

where:

$\dot{m}_{1s}, \dot{m}_{1w}$ - steam and water mass fluxes at the separator outlet,

$\dot{m}_{0fw}, \dot{m}_{0sw}$ - mass fluxes of feed water and steam-water mixture at the separator inlet,

s_{1s}, s_{1w} - specific entropy of steam and water at the separator outlet,

s_{0s}, s_{0w}, s_{0fw} - specific entropy of steam, boiling water and feed water at separator inlet,

x_1 - steam dryness degree at separator outlet,

k_c - number of circulations in boiler.

The adoption of the appropriate value of the number of circulations in boiler should be particularly emphasised. Adoption of too big value of this parameter results in the straight manner in the increase of the losses. On the other hand, too small value may lead to intensive sedimentation of boiler scale in boiler evaporating section.

The entropy increments in the surface heat exchangers can be calculated in the similar mode as in case of waste heat boiler. The simple method is reading of the relevant entropy values from the available tables or charts. It is also possible to assume constant specific heat capacity of a medium and calculating the entropy increase as:

$$\Delta\dot{S} = \dot{m}c_p \ln\frac{T_1}{T_0}, \qquad (18)$$

where:

$\dot{m}$ - medium mass flux,

c_p - medium specific heat capacity of medium,

T_1, T_0 - medium temperature at the exchanger outlet and inlet, respectively.

Mixing-type heater, summing T-pipe and hotwell are the elements where, similar as in steam separator, the entropy increments are chiefly caused by the process of mixing of working media. Entropy increase in these elements can be determined on the basis of the readings taken from the appropriate entropy tables or charts of the individual media "i" at the inlet and outlet of the recovery system element under consideration. The entropy increase flux is determined by:

$$\Delta\dot{S} = s_1 \sum_1^n \dot{m}_{0i} - \sum_1^n \dot{m}_{0i} s_{0i} , \tag{19}$$

where:

$\dot{m}_{0i}$ - mass flux of i-medium at the inlet,

s_{0i} - specific entropy of i-medium at the inlet,

s_1 - specific entropy of the mixture at the outlet,

n - number of media fluxes at the inlet.

The increase of entropy flux in throttle valve can be determined as:

$$\Delta\dot{S} = \dot{m}(s_1 - s_0), \tag{20}$$

where:

$\dot{m}$ - medium mass flux,

s_1, s_0 - medium specific entropy values at the outlet and inlet.

In the effect of friction in the steam turbine the expansion process is not isentropic. In the result the actual expansion work is less than isentropic expansion work and the process itself is a source of irrecoverable exergy losses.

The entropy value can be taken from the diagram of i-s for steam or calculate them basing on the appropriate relations as functions of eg pressure and temperature of steam in the relevant points of process taking place in the turbine.

The liquid specific entropy increase in pump can be expressed by formula [9]:

$$\Delta s = v(p_1 - p_0)\frac{1}{\overline{T}}\left(\frac{1}{\eta_i} - 1\right), \tag{21}$$

where:

v - liquid specific volume,

p_1, p_0 - pressure at delivery and suction side,

$\overline{T}$ - averaged liquid temperature,

η_i - pump internal efficiency.

Conclusions

Although the enthalpy method allows to determine the effectiveness of energy transformation in the designed installation, it does not allow to determine clearly the places where energy losses occur or size of these losses.

The restriction of energy losses is of particular importance while designing the waste energy recovery systems in view of small exergy of this energy sources.

The entropy method allows to determine the energy losses in the individual processes and locations of the performance of the thermodynamic transformations which in consequence allows to take actions aiming at their reduction.

The entropy method can consist the supplement to enthalpy method which is generally applied in designing marine power plants, including the designing of waste energy recovery in marine Diesel power plants.

While designing the systems of recovery of waste energy in marine Diesel power plants it should be taken into consideration that the reduction of losses is accompanied in general by the increase of investment outlays related with the execution of energy-saving arrangement. Thus it is important to conduct a complex, multicriteria evaluation of the solutions possible to implement, including not only thermodynamic and technical aspects but also inter alia ecological and widely understood economic aspects.

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