Journal of POLISH CIMAC
Faculty of Ocean Engineering & Ship Technology
GDAŃSK UNIVERSITY OF TECHNOLOGY

THE APPLICATION OF THE EXERGETIC ANALYSIS IN DESIGNING OF WASTE ENERGY RECOVERY SYSTEMS IN MARINE DIESEL POWER PLANTS

Ryszard Michalski

The Szczecin University of Technology
41 Piastów Ave, 71-065 Szczecin, Poland
tel: (091) 4494941; fax: +48 91 449 44 88
e-mail : *ryszard.michalski@ps.pl*

Abstract

The efficient use of waste energy is a major element in designing the energy-saving marine power plants. The ecological aspects of the usage of this energy are of importance as well. Thus the need to perform the evaluation becomes significant – in respect of both the sources of the waste energy and the marine systems of its recovery, inter alia in terms the achievable efficiency levels. Besides the determination of the available quantity of the energy it is necessary to take into account the value characterising this energy in terms of its quality. The measure of the quality of the energy is the value of the maximum capacity of work performance referred to as the exergy. The exergetic analysis allows to determine the values of the individual jets of working media as well as, which is particularly important, allows to properly assess the proportions of losses in the individual elements of the recovery systems under investigation. Therefore it is a basis to calculate their exergetic efficiency. The article presents the balance values of the energy fluxes of the selected ship's main propulsion engines as well as, inter alia an example of the course of the changes in the specific exergy and enthalpy of the exhaust gases in the function of the load of ship's main propulsion engine. It presents also the examples of the exergetic analysis of the main propulsion engine exhaust gases recovery systems with the application of Brayton cycle, Clausius-Rankine cycle or both cycles combined.

***Keywords**: designing, marine power plants, waste energy, recovery, exergetic analysis*

1. Introduction

The basic source of the waste energy in the motor power plant are the self-ignited Diesel piston engines of the main and auxiliary (Diesel generators) propulsion systems. The exhaust gases, engine cooling water, charging air and lubricating oil are the carriers of this energy.

The physical waste energy and chemical waste energy are distinguished in relation to the operation of the marine Diesel engines. The physical waste energy occurs in the temperature form resulting from the temperature deviation of the waste energy carrier from the ambient and pressure temperature that results from the increased pressure in relation to the pressure value prevailing in the environment. The chemical waste energy is the effect of the difference in the chemical composition of the waste substance which are the exhaust gases in comparison to the generally occurring components in the environment [1. 2, 3]. In the shipping practice the physical waste energy is used. The proper evaluation of the sources of the waste energy is necessary in designing the shipboard waste energy recovery systems. This evaluation should concern not only the parameters of the waste energy carriers corresponding to the nominal engine load, but also should take into account their change resulting from the change in engine load during the ship's service life.

The quantity of energy is not a sufficient measure of its practical usability. Besides the energy quantity it is necessary to consider the value characterising the energy in terms of its quality. The choice of the measure of this usability is of relative nature. It has been assumed to apply the value of the maximum capacity for work called exergy [2].

The main task of the exergetic analysis is to detect the kind and places of occurrence of the factors increasing the imperfections of the energetic processes and another chief task is the quantity assessment of the results caused by these factors.

The exergetic balance figures allow to evaluate efficiently the values of the individual energy fluxes of working media as well as, which is of particular significance, allow to properly assess the proportion of losses in the individual elements of the system under investigation. Exergy balance consists therefore the basis for the calculation of the exergetic efficiency [2, 3, 4]. It should be noted that the differences between energy balance and exergy balance are particularly large in the examination of the processes occurring in the vicinity of ambient temperatures [4].

The efficient use of waste energy is a major element in designing the marine power plants. Thus the need to perform the evaluation becomes significant – in respect of the marine systems of waste energy recovery, inter alia in terms the achievable efficiency levels.

The ecological aspects of the usage of this energy are of importance as well. Similar like in the land power engineering the transformation of the energy carriers in a ship's power plant is related with the detrimental effects on the natural environment. It chiefly consists in the emission of the harmful exhaust gases components and the thermal contamination. In such terms every action resulting in saving of the energy, including also the use of waste energy, leads to the reduction of the harmful ecological effects.

2. The Evaluation of the Sources of the Waste Energy in the Diesel Power Plants

It is necessary to know the share in % of the waste energy and the effective mechanical energy in the total energy of the burnt fuel, expressed in terms of energy balance in order to perform the evaluation of the amount of waste energy and the effective mechanical energy.

In order to evaluate the amounts of waste energy the thermal balance values of the engines are determined. The complement of the information on this energy form is the knowledge of the temperature and pressure of its carriers.

Analysing the balance structure it can be preliminarily concluded which factors are to be used in the first place and which may be regarded as the additional sources, less applicable in practice. While designing the waste energy recovery systems it should be borne in mind that the suitability of a given waste energy source is proven, besides the thermodynamic parameters, also by the physical and chemical parameters of the energy transferring medium.

Table 1 shows the balances of the energy fluxes of the MAN and Wärtsilä main propulsion low-speed Diesel engines corresponding to the maximum continuous rating value, MCR. These balances have been achieved on the basis of the catalogue data of the engines [7, 8]. The table shows the maximum and minimum figures of the share in % of the waste power and waste heat flux contained in various carriers.

Table 1. Balances of the energy fluxes of some selected marine main propulsion engines, %

Manufacturer	**MAN**		**Wärtsilä**	
Energy flux, %	max	min	max	min
Engine output	50.8	47.1	50.9	48.5
Exhaust gases	24.6	21.5	25.5	23.7
Charging air cooling water	19.5	16.5	16.3	15.6
Lubricating oil	6.3	3.8	6.0	4.5
Cylinder cooling water	9.1	6.5	10.5	7.7
Radiation	0.9	0.5	0.6	0.5

Table 2 shows on the other hand the characteristic temperature ranges of the waste energy carriers of MAN and Wärtsilä main propulsion low-speed Diesel engines corresponding to the maximum continuous rating value [7, 8].

Table 2. Waste energy carrier temperatures of some selected main propulsion engines

Manufacturer	**MAN**		**Wärtsilä**	
Temperature, K	max	min	max	Min
Exhaust gases	528.15	508.15	548.15	535.15
Charging air cooling water	331.15	318.15	331.15	329.15
Lubricating oil	324.55	323.35	347.85	334.55
Cylinder cooling water	353.15	353.15	363.15	363.15

The presented data allow to conclude that the efficiently used heat consists 47.1÷50.9% of the energy contained in the burnt fuel. The heat transferred in the exhaust gases consists 21.5÷25.5%, in charging air cooling water – 15.6÷19.5%, in cylinder cooling water – 6.5÷10.5%, and the heat contained in the lubricating oil – 3.8÷6.3% accordingly. It should be noted that the relatively high value of the heat fluxes does not always correspond to the high temperature of the heat carriers. Such is the case for instance in respect of heat contained in charging air cooling water.

The evaluation of the sources of the waste energy performed on the basis of the engine heat balance does not provide the explicit and clear information on its quality, although given in connection with the information on the energy carrier temperatures. The application of the exergetic analysis for the evaluation of the quality of the waste energy however allows to put the sources of the waste energy in the right order in terms of their quality.

An important component of the exhaust gases exergy, besides its temperature part, is its pressure part. Information on this exergy part is significant for the designing of the recovery systems with Diesel turbines.

The specific exergy of the exhaust gases, covering the temperature and pressure parts, can be determined by the equation:

$$b_s^{wl} = c_p\left(T_s^{wl} - T_o\right) - T_o c_p \ln\frac{T_s^{wl}}{T_o} + RT_o \ln\frac{p_s^{wl}}{p_o}, \tag{1}$$

where:

b_s^{wl} – specific exergy of the exhaust gases, kJ/kg,

c_p – mean specific heat capacity under constant pressure, kJ/kgK,

T_s^{wl} – exhaust gas temperature before turbine, K,

T_o – ambient temperature, K,

R – exhaust gas constant, kJ/kgK,

p_s^{wl} – exhaust gas pressure before gas turbine, Pa,

p_o – ambient pressure, Pa.

Figure 1 shows the engine exhaust gases exergy and specific enthalpy values with the assumed ambient temperature T_0=298 K, ambient pressure p_0=100 kPa and exhaust gas pressure p=200 kPa. In the Figure 1 the physical specific temperature and pressure exergy is marked as “bs”, the physical specific temperature exergy is marked as “bsT”, and the specific enthalpy as “isT”.

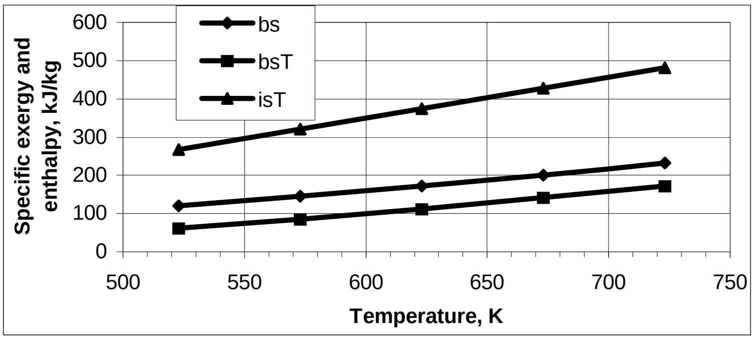

Fig 1. Specific exergy and enthalpy values of the engine exhaust gases in the function of the temperature

The figure above shows that although the exhaust gas specific enthalpy is relatively high its exergy is low. The knowledge of exergy allows to assess properly the quality of waste energy.

A significant issue in designing the waste energy recovery systems is the evaluation of the parameters of exhaust gases corresponding to engine partial loads. The available quantity of waste energy contained in exhaust gases in such conditions decreases due to their decreasing flux despite some increase in their specific exergy. At that time the total heat demand on a ship in general decreases insignificantly.

Figure 2 shows the changes of the temperatures of exhaust gases before turbocharger (before TC), after turbocharger (after TC) and the mean exhaust gas temperature after cylinders (after cyl.) in the function of 7S60 MC-C engine load according to the characteristics of the screw.

On the other hand figure 3 shows the changes of the specific exergy and enthalpy of the exhaust gases after turbocharger in the function of the load of the engine under investigation. The physical specific temperature exergy has been marked as "b(T)", and the specific enthalpy as "iT". The values of the presented parameters have been obtained pursuant to the measurements conducted on engine test bed in the H Cegielski Mechanical Works in Poznań.

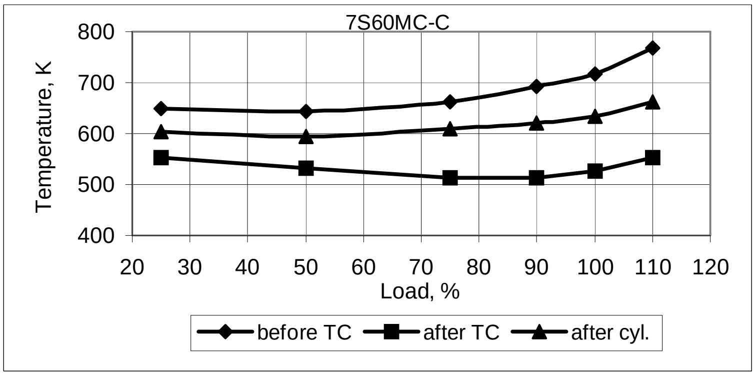

Fig 2. The change of the exhaust gases temperature of 7S60MC-C engine

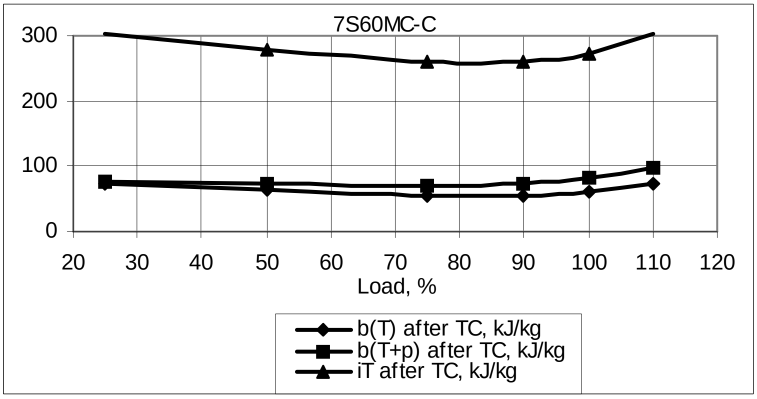

Fig 3. The change of the specific exergy (b) and enthalpy (iT) of the exhaust gases of 7S60MC-C engine

The physical exergy flux transferred by cylinder cooling water can be determined from the relation:

$$\dot{B}_w = b_e W_d N_e \alpha_w \left(1-\frac{T_o}{T_w}\right)\cdot\frac{0{,}01}{3600}, \tag{2}$$

where*:*

$\dot{B}_w$ – physical exergy flux, kW,

b_e – specific fuel consumption, kg/kWh,

W_d – fuel lower calorific value, kJ/kg,

N_e – effective power, kW,

α_w – proportional share of heat transferred by cylinder cooling water, %,

T_0 – ambient temperature, K,

T_w – engine cooling water temperature, K.

The engine charging air cooling water physical exergy flux or the lubricating oil exergy fluxes can be determined in the similar manner.

The exhaust gases from main and auxiliary engines have high exergy level. Cylinder and charging air cooling water has significantly lower exergy level thus its applicability is indeed limited. Also the lubricating oils are characterised by low exergy and can only consist a supplementary source of the waste energy to be used in the recovery systems.

In the designing practice mainly the energy contained in main engine exhaust gases and cylinder cooling water whereas that contained in engine charging air is used less frequently and that in lubricating oil only from time to time.

3. The Exergetic Analysis of the Shipboard Systems of Waste Energy Recovery

In order to conduct the analysis of the arrangements of the waste energy recovery systems it is necessary to use a set of, among others, mathematical models concerning the thermodynamic changes occurring in their elements. These allow to analyse the processes occurring both in themselves as well as in any recovery systems – the simplest ones, single-pressure, producing saturated steam for heating purposes and multi-pressure type – used for the production of heating steam and superheated steam to supply turbo-generator and those using waste energy contained in cylinder cooling water, in engine charging air and lubricating oil. The description of the appropriate calculation models has been provided among others in paper [4]. The method of determination of the exergetic efficiency of the waste heat boilers, exergetic efficiency of the systems including the waste heat turbo-generator and the exergetic efficiency of the system producing electric power and steam for heating purposes has been presented inter alia in [5].

In the self-ignition engines the parameters of the exhaust gases leaving turbocharger are far from the ambient parameters. The heat contained therein can be used in steam turbine running according to Clausius-Rankine cycle. The progress in the increase of the charging turbocharger efficiency provides a possibility of using a part of the exhaust gases in a separate gas turbine supporting the ship's propeller propulsion system, referred to as reverse turbine, or in turbine driving the generator. Thus a problem appears to make a choice of the arrangement of the engine exhaust gas waste energy recovery system. This can involve among others the use of Brayton cycle with the waste gas turbine and Clausius-Rankine cycle with waste steam turbine. The results of the analysis of this type can be found in [9]. The author of this article has expanded the investigation scope by incorporating the complex systems where Brayton cycle has been combined with Clausius-Rankine cycle. The more comprehensive results of the investigations are contained in [6]. The said cycles are being offered nowadays among others by MAN [10] and Wärtsilä [11].

The exergetic analysis performed for the cycles is of theoretical nature. It does not include inter alia the turbine internal efficiency values or energy consumption for own needs of both systems. On the other hand it takes into account the necessity to keep the temperatures difference in the waste heat boiler bigger than zero which is the condition for heat transfer to take place. It is of particular importance to keep at the same time the minimum temperature difference between the exhaust gases and the steam-water mixture – pinch point (ΔT_{min}).

The calculations of the unitary work of the Brayton turbo-gas cycle have been carried out according to the following model.

The specific exergy of exhaust gases before turbine b_s^{wl} has been determined according to equation (1). In the further course of this article the symbols adopted for this equation have been maintained too.

The temperature of the exhaust gases after turbine T_s^{wy} is determined by the equation:

$$T_s^{wy} = T_s^{wl} \left(\frac{p_s^{wl}}{p_o} \right)^{\frac{\kappa - 1}{\kappa}} \text{, K,} \tag{3}$$

where $\kappa = \frac{c_p}{c_p - R}$ - isentropic curve exponent in the exhaust gas expansion process in turbine.

The specific exergy of the exhaust gases after turbine b_s^{wl} is determined from the relation:

$$b_s^{wy} = c_p \left(T_s^{wy} - T_o \right) - T_o c_p \, ln \frac{T_s^{wy}}{T_o} \text{, kJ/kg.} \tag{4}$$

The unitary theoretical work l_t of the cycle is equal to:

$$l_t = b_s^{wl} - b_s^{wy} \text{, kJ/kg.} \tag{5}$$

The exergetic efficiency of the cycle η_b is determined by the relation:

$$\eta_b = \frac{l_t}{b_s^{wl}} . \tag{6}$$

The calculations of the Clausius-Rankine steam cycle have been performed by the use of the Util1 software [4]. In the cycle calculations the constant steam pressure in condenser has been assumed equal to 0.007 MPa, also there has been assumed the constant value of the temperature difference of exhaust gases and steam in steam heater, equal to 15 K and the exhaust gas temperature after the waste heat boiler, equal to 443 K. The calculations have been conducted for $\Delta T_{min.}$=15 K. In this situation among others the pressure of the steam generated has been changed.

The results obtained have been presented in figures 4 and 5 where Brayton cycle has been marked with B and the Clausius-Rankine cycle with C-R.

Figure 4 shows the achievable recoverable unitary work values in Brayton and Clausius-Rankine cycles as well as unitary work achieved additionally in Clausius-Rankine cycle obtained owing to the use of heat of the exhaust gas of gas turbine (in figure 4 it is marked as “dop. ob. C-R”) and the joint work of Brayton cycle together with the combined Clausius-Rankine cycle. It is significant that once a certain temperature is exceeded, the unitary work of the additional Clausius-Rankine cycle is larger than the work achieved in the basic Brayton cycle. As shown in figure 4, the unitary work increases in case of both cycles together with the growing temperature of the exhaust gases. At the same time there is an area where Brayton cycle is more useful and another where the Clausius-Rankine cycle is the better arrangement. This corresponds also to the conclusions presented in [9].

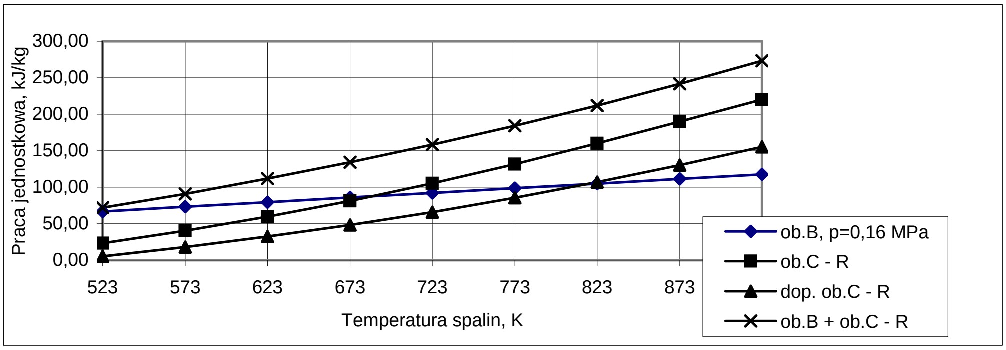

Fig. 4. Possible work to obtain due to the consideing cycles versus exhaust gas temperature after diesel engines

Figure 5 shows the course of efficiency of Brayton and Clausius-Rankine cycles in the function of exhaust gas temperature under assumption of the constant value of the exhaust gas pressure (p=0,16 MPa).

The efficiency values defined by equation (6) increase together with the temperature increase in case of Clausius-Rankine cycle and decrease in Brayton cycle. In the latter case it results from the fact of simultaneous increase of temperature of exhaust gas leaving the gas turbine which is characteristic for the expansion process in turbine. The degree of exhaust gas energy recovery in Brayton cycle increases together with the exhaust gas pressure increase and decreases for the Clausius-Rankine cycle. In every case the efficiencies of both cycles combined increase.

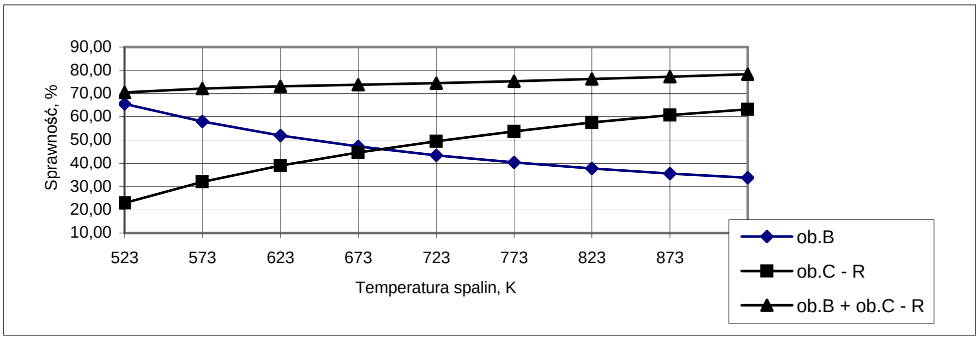

Fig. 5. The efficiency of the considering cycles versus exhaust gas temperature after diesel engines

Conclusions

The basis of the evaluation of the waste energy resources in marine Diesel power plants is their exergy whereas the basis for the evaluation of the possibility and manner of waste energy recovery is their exergetic analysis. While designing the waste energy recovery system the number and the parameters of the carriers of this energy should be of particular concern. All kinds of listing and specifications of the amounts of energy transferred, temperatures of its carriers, specific exergy or specific heat capacity are particularly useful.

The application of exergetic analysis in connection with energetic analysis allows to qualify and put in the right order the sources of waste energy in terms of their quality.

There is a possibility of large variety of the applications of the marine systems of waste energy recovery. The individual arrangement of a waste energy recovery system should depend on the appropriate kind of energy and its amount needed to keep the operation of the ship's engine room and ship herself, prevailing ambient conditions during the ship's service, planned main engine distribution loads and main engine type.

The exergetic analysis allows to evaluate the quality of the processes occurring in the waste energy recovery systems. It also allows to indicate the least effective processes thus facilitating the optimising of the designed systems.

At the same time a due attention should be paid to the specific nature of the operation of these systems which are operative only while their heat sources are active.

The final evaluation of the variants of the energy recovery arrangement in the motor ship's power plant is possible upon due consideration of the thermodynamic criteria as well as technical, service and economic criteria.

LITERATURE

[1] Szargut, J. i inni, *Przemysłowa energia odpadowa. Zasady wykorzystania. Urządzenia, [Industrial Waste Energy. The Principles of Recovery. Equipment]*, WNT, Warszawa 1993.

[2] Szargut, J., *Analiza termodynamiczna i ekonomiczna w energetyce przemysłowej [Thermodynamic and Economic Analysis in Industrial Power Engineering]*, WNT, Warszawa 1983.

[3] Szargut, J., Ziębik, A., *Podstawy energetyki cieplnej [The Basics of Heat Power Engineering]*, Wydawnictwo Naukowe PWN S.A., Warszawa 1998.

[4] Michalski, R., *Przykład zastosowania analizy egzergetycznej do badania procesów utylizacji ciepła odpadowego w siłowniach motorowych [An Example of the Application of the Exergetic Analysis for the Investigation of the Recovery Processes of the Waste Heat in Motor Ships Power Plants]*, XX Sympozjum Siłowni Okrętowych, Wyd. Uczeln. AMW w Gdyni, Gdynia 1998.

[5] Michalski, R., *Ocena termodynamiczna okrętowych systemów utylizacji energii odpadowej spalin [Thermodynamic Evaluation of the Exhaust Gas Waste Energy Marine Recovery Systems]*, Zeszyty Naukowe Wyższej Szkoły Morskiej w Szczecinie, Nr 66, ss. 287-299, Szczecin 2002.

[6] Michalski, R., *Porównawcza analiza termodynamiczna obiegu Braytona i Clausiusa-Rankine'a w okrętowych systemach utylizacji energii odpadowej spalin [A Comparative Thermodnamic Analysis of Brayton and Clausius-Rankine Cycles in the Exhaust Gas Waste Energy Recovery Marine Systems]*, XXII Sympozjum Siłowni Okrętowych, Szczecin 2001.

[7] ME Project Guide, MAN-B&W, 1998-2000.

[8] Engine Selection and Project Manual, Wärtsilä, 1997-2008.

[9] Woodward, J. B., *Evaluation of Brayton and Rankine alternatives for Diesel waste heat exploitation*, Journal of Engineering for Gas Turbine and Power; Vol. 116, January 1994.

[10] Thermo Efficiency System (TES) for Reduction of Fuel Consumption and CO_2 Emission, MAN B&W Diesel, Reg. No. 39 66 13 14, P.9161-00, Jul. 05.

[11] Schmid, H., *Less Emissions Trough Waste Heat Recovery*. Green Ship Technology Conference, London, 28/29 April 2004, Wärtsilä Corporation, April 2004.