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Thermodynamic analysis of the exhaust gas heat utilization systems for ship diesel engine power plants

SUMMARY

The paper presents an example of the influence analysis of selected thermodynamic parameters on attainable output of the utilization turbogenerators for ship diesel engine power plants.

INTRODUCTION

Ship power plant design stage is one of the most important and decisive of future costs of ship's construction and exploitation. The cost of ship power plant operation is greater than 50% of the overall ship exploitation cost, 80% of which is the fuel cost. Thermal balances of the contemporary ship diesel engines indicate that a little more than 50% of the energy contained in the combusted fuel is utilized. However, in spite of the high efficiency of the engines, an important part of the energy is left unused as the so called „waste" energy. Ways of its utilization are more and more difficult due to its lower and lower exoergy. Therefore its rational utilization to improve the overall balance of ship operation costs becomes the more important problem. The need of heat energy utilization is a source of many new concepts aimed at improving the overall power plant efficiency and lowering the ship operation cost. Such solutions can be found today in the form of the so called heat utilization systems on almost all types of marine objects in service.

This paper presents a part of the problems connected with the thermodynamic analysis of the waste heat recovery systems for ship diesel engine power plants.

COMMENTS ON DESIGN PROBLEMS OF THE WASTE HEAT UTILIZATION SYSTEMS FOR SHIP DIESEL ENGINE POWER PLANTS

The waste heat utilization should be tightly connected with the energy demand of the ship.

A specific character of operation of the utilization systems, i.e. functioning only along with activity of their heat sources, should be noticed. Structural analyses of electric and heat energy consumption at different ship exploitation stages are specially useful. Fig.1 exemplifies the heating steam consumption on one of the container ships built in Szczecin Shipyard, at different design ship operation conditions. The electric energy consumption and main engine loading state on the motor ship KOPALNIA MARCEL, recorded in June 1989, are illustrated in Fig.2.

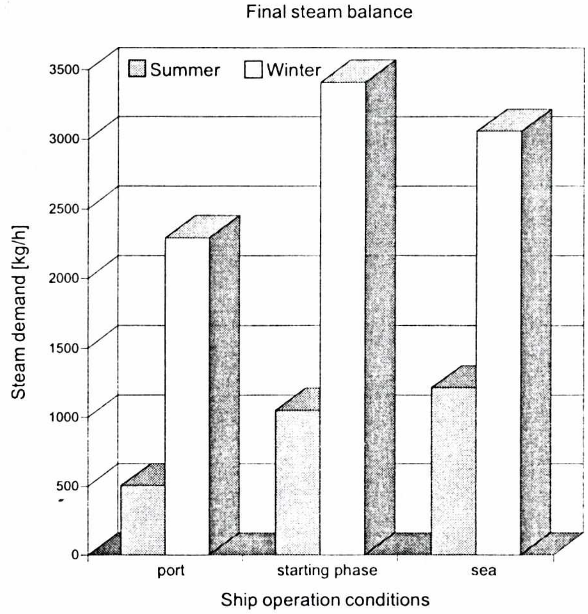

Fig. 1. Heating steam consumption on a container ship at different, design ship operation conditions

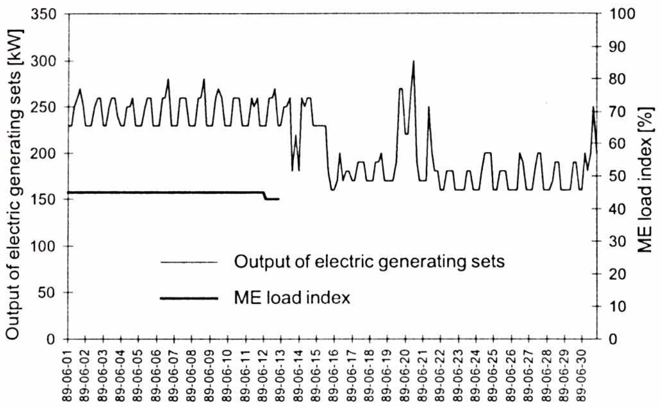

***Fig.2.** Electric energy consumption and main engine loading states on the motor ship KOPALNIA MARCEL, recorded in June 1989*

During design process special attention should be paid to the amounts and parameters of the waste heat transporting media. All kinds of balance sheets of the transferred heat energy, exoergy or temperatures are very helpful for this purpose. Selection of a concept of the waste energy utilization is usually carried out in several stages. Mathematical modelling of the investigated utilization systems is very convenient for carrying out the analyses.

CALCULATION MODEL OF THE WASTE HEAT UTILIZATION SYSTEMS

Multivariant thermal calculations were based on a model of the single- and dual-pressure, waste-heat utilization systems, formed in compliance with the proposals of Senior Thermal Engineering Company [1]. The systems are presented in Fig.3 and 4 respectively.

The calculation model was elaborated (in accordance with the concept of CADES software [2]) in the form of a set of the mutually coupled calculation algorithms which simulate operation of particular elements of the heat utilization system. Program environment of the model is based on the Microsoft EXCEL calculation sheet in order to make operations of data input and output visualization as easy as possible.

The modelled utilization system was, to a large extent, simplified in order to get more distinct imaging of the thermodynamic processes running in the system, and to make analyzing the results easier. The calculations start from the outlet of the supply water heater (by charging- air cooling water) and stop at the utilization turbogenerator. The following devices were neglected in the calculations : the deaerator and supply water mixing heaters at the inlet to the LP evaporation section and the economiser (ECO).

The following five basic parameters of the system can be calculated by means of the software in question :

- power of the utilization turbogenerator (TPU)
- minimum differences between temperatures of the exhaust gas and working medium in the utilization boiler (KU), and
- mass flow intensities of heating and superheated steam.

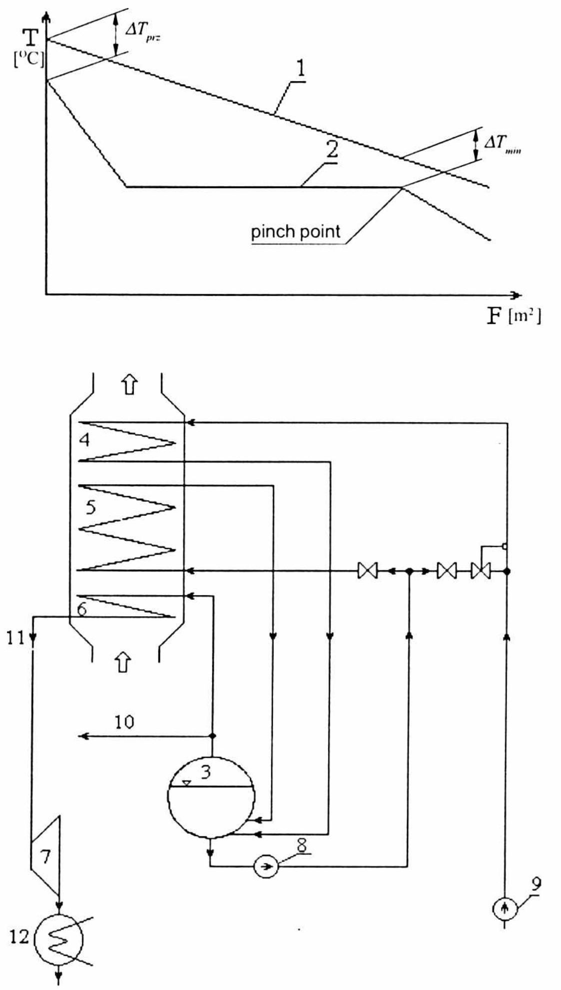

***Fig.3.** Temperature distribution and schematic diagram of the single pressure system with utilization turbogenerator : 1 - exhaust gas, 2- working medium, 3- steam drum, 4- economiser, 5- steam generator, 6- superheater, 7- utilization turbogenerator, 8- circulation pump, 9- feed pump, 10- steam input for heating purposes, 11- superheated steam, 12- condenser*

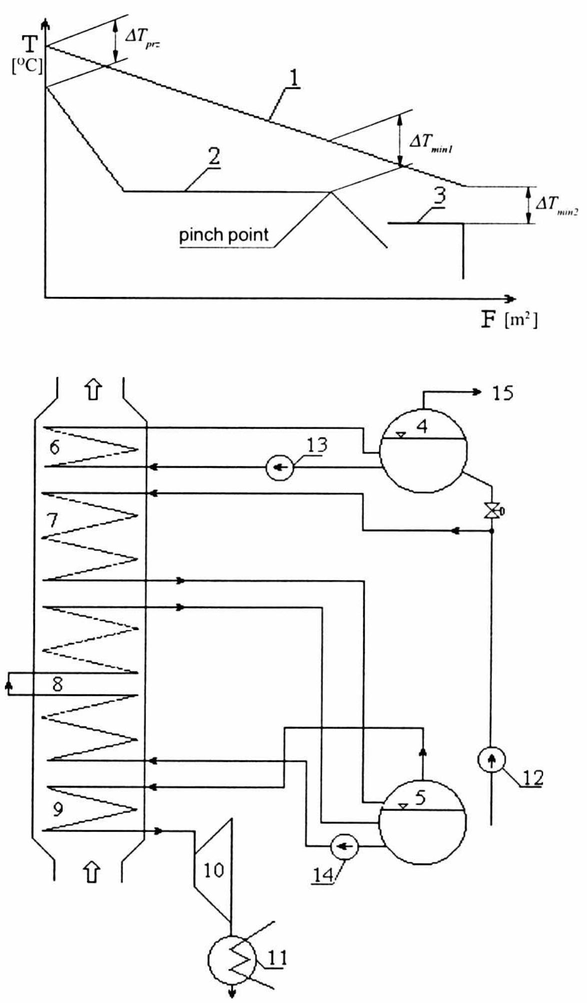

***Fig.4.** Temperature distribution and schematic diagram of the double pressure system with utilization turbogenerator : 1 - exhaust gas, 2- HP stage working medium, 3- LP stage working medium, 4- LP steam drum, 5- HP steam drum, 6- LP steam generator, 7- HP economiser, 8- HP steam generator, 9- superheater, 10- utilization turbogenerator, 11- condenser, 12- feed pump, 13- LP circulation pump, 14- HP circulation pump, 15- steam input for heating purposes*

Graphic analysis of calculation results is possible due to the applied calculation sheet, in the form of function diagrams of the selected input parameters.

The model consists of six elements :

- ***Three-way distributor***. Available mass flow intensities of heating and superheated steam are calculated in it on the basis of the heat balance, for assumed parameters of the media.
- ***LP steam generator***. It makes it possible to calculate the exhaust gas temperatures at outlet from the steamer, minimum temperature difference and heating steam enthalpy.
- ***Economiser***. Exhaust gas temperatures at outlet from the ECO as well as supply water temperatures and enthalpies are calculated in it.
- ***HP steam generator***. It makes it possible to calculate the exhaust gas temperatures at outlet from the steamer, temperatures and enthalpies of the produced saturated steam, and minimum difference between exhaust gas and steam-water mixture temperatures.
- ***Superheater***. Exhaust gas temperature at the outlet from the superheater and enthalpy of the produced superheated steam are calculated in it.
- ***Utilization turbogenerator***. This is the model for calculating the isentropic and real enthalpy drop, turbogenerator power and steam temperature at the end of the expansion process.

The model operates in a fully interactive way. It means that all the calculations are performed automatically just after modification of any input data. Moreover it is possible to use the inherent mechanisms of the EXCEL calulation sheet (Solver and Result Search options) in order to find solution of any problem connected with input and output data relationships.

SELECTED EXAMPLES OF THE DUAL-PRESSURE HEAT UTILIZATION SYSTEM CALCULATIONS

The utilization systems which use the waste heat from the following three main engines were analyzed :

I MAN B&W 4S50MC engine of 5720 kW output, 235°C exhaust gas temperature and 14.33 kg/s exhaust gas flow rate
II SULZER 6RTA52U engine of 9360 kW output, 275°C exhaust gas temperature and 20.28 kg/s exhaust gas flow rate
III SULZER 6RTA62U engine of 13320 kW output, 275°C exhaust gas temperature and 28.86 kg/s exhaust gas flow rate.

Series of utilization system characteristics were elaborated on the basis of the model calulations in accordance with the following relationships :

- electric power of TPU **in function** of heating energy demand
- electric power of TPU **in function** of minimum temperature differences in utilization boiler (KU)
- electric power of TPU **in function** of difference of exhaust gas and superheated steam temperature
- electric power of TPU **in function** of pressure of steam from TPU in condenser
- electric power of TPU **in function** of exhaust gas temperature at outlet from KU
- steam pressure **in function** of heating energy demand
- steam pressure **in function** of minimum temperature differences in KU

All the above specified characteristics were prepared at the following values of input parameters (unless any of them was the argument of an investigated relationship) :

- the heating energy demand $Q = 300$ kW
- the minimum temperature difference inside KU, $\Delta T_{min} = 5°C$
- the temperature difference of exhaust gas and superheated steam $\Delta T_{prz} = 15°C$
- the pressure of steam from TPU inside condenser 0.005 MPa
- the exhaust gas temperature at outlet from KU 150°C.

The results of selected calculations obtained for the system co-operating with SULZER 6RTA52U engine are illustrated in Fig.5÷11.

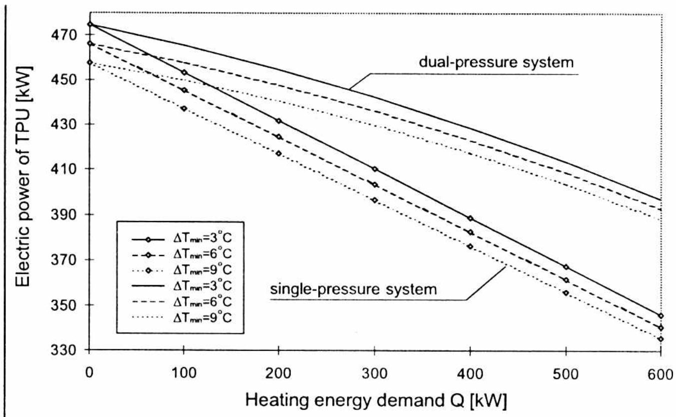

Fig.5. Comparison of the turbogenerator (TPU) electric output available from the single- and dual-pressure system in function of heating energy demand

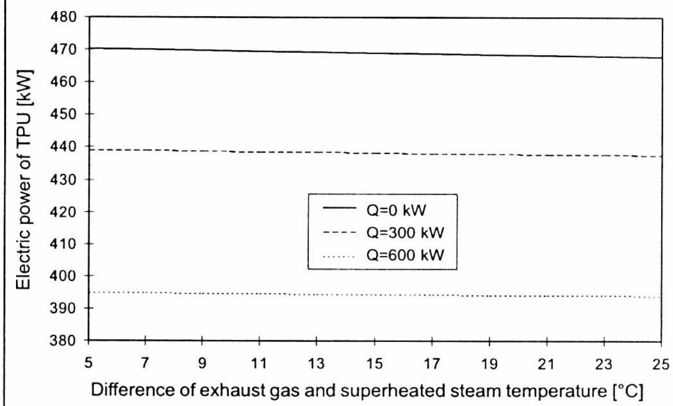

Fig.6. Electric power of TPU in function of the difference of exhaust gas and superheated steam temperatures

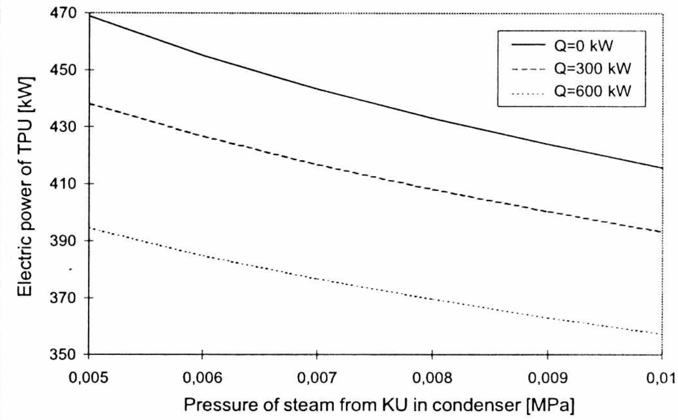

Fig.7. Electric power of TPU in function of the pressure of steam from KU in condenser

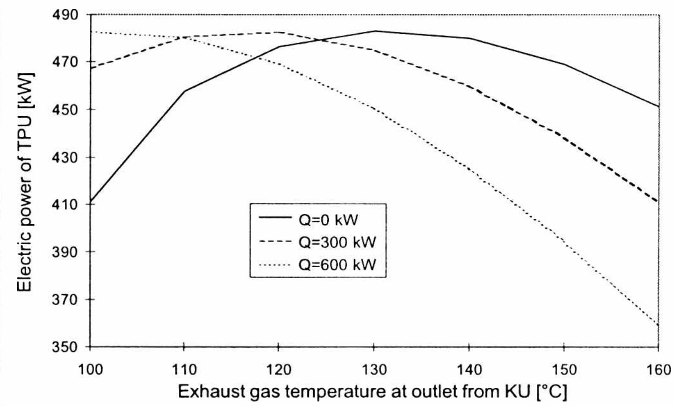

Fig.8. Electric power of TPU in function of the exhaust gas temperature at outlet from KU (at the assumed temperature differences of exhaust gas and steam in KU, $\Delta T_{min1} = \Delta T_{min2} = 5$ °C)

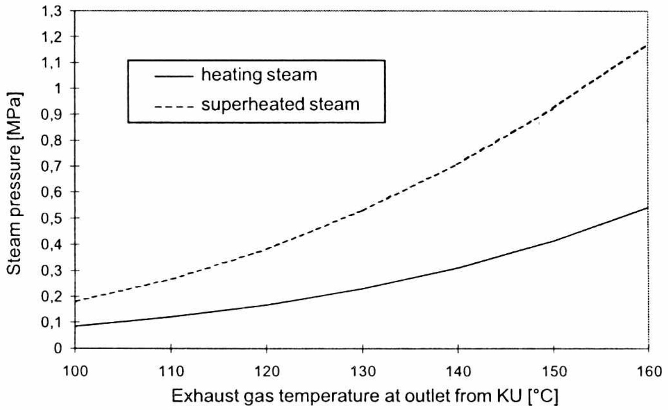

***Fig. 9.** Produced steam pressure in function of the exhaust gas temperature at outlet from KU (at the assumed temperature differences of exhaust gas and steam in KU, $\Delta T_{min1} = \Delta T_{min2} = 5$ °C)*

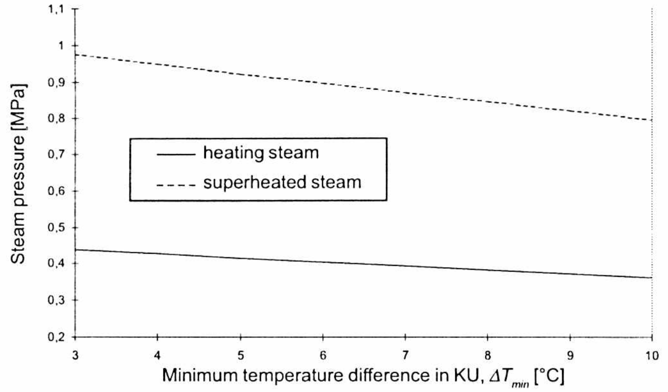

***Fig. 10.** Produced steam pressure in function of the minimum temperature difference in KU*

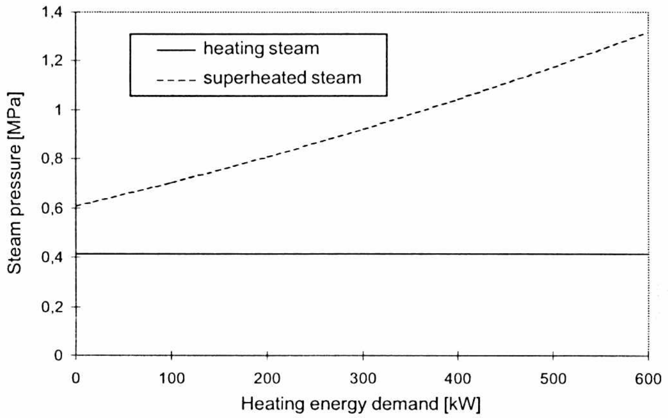

***Fig. 11.** Produced steam pressure in function of heating energy demand*

Fig.5 shows TPU electric output values in function of the heating steam amount obtained from the double-pressure system. Analogous TPU output values of the single-pressure system are depicted in the figure for comparison. The remaining figures concern the double-pressure systems. The system connected to the 6RTA52U main engine was taken into account in all the cases.

In Fig. 6 the relationship of TPU electric output versus the temperature difference of exhaust gas and superheated steam is presented. Fig.7 shows the influence of vapour pressure in condenser on available TPU output, and Fig.8 illustrates the influence of exhaust gas temperature at outlet from the utilization boiler on available electric output at the assumed constant values of the minimum temperature difference (ΔT_{min}). Fig. 9÷11 present the relationships of the produced steam pressure versus : the exhaust gas temperature at outlet from the utilization boiler, minimum difference of temperature in the utilization boiler and heating energy demand for ship's general purposes, respectively.

CONCLUSIONS

Application of an appropriate utilization system on the ship can provide several other advantages apart from increasing the overall efficency of its power plant. It is possible to eliminate the strong sources of noise connected with generating sets operation by using an utilization turbogenerator instead of the sets.Lowering the maintenance labour demand is also possible due to substitution of many different energy sources (electric, heat, mechanic) by the integrated system of waste heat utilization.

The performed calculations make it possible to draw the following detailed conclusions :

- The maximum output of the utilization turbogenerator depends to a very small degree on the assumed temperature difference of the exhaust gas and produced superheated steam. A superfluous increase of the heat exchange surface area of the steam superheater is rather unprofitable. Especially as it works at the highest temperatures of media and requires better materials for its construction.

- The pressure increase in the condenser from 0.005 to 0.01 MPa can lower the TPU output by 12% in the considered case. It means that it is necessary to assume the pressures in the condenser as low as possible with taking into consideration limiting temperatures of condenser cooling water and avoiding an excessive increase of the condenser surface area.

- Lowering the temperature of the exhaust gas from the utilization boiler at the assumed constant ΔT_{min} values improves the utilization system's effectivness at the beginning. But the point exists at which the TPU output reaches its maximum. The reason is that the pressure of the produced steam decreases along with the decreasing exhaust gas temperature. Although the boiler surface area increases which improves its efficency but specific enthalpy values of steam would decrease and in consequence the steam enthalpy drop in the turbine would commence decreasing.

- The pressures of the produced steam should be so selected as to obtain real values of the minimum temperature difference ΔT_{min} of the exhaust gas and steam in the utilization boiler (Fig. 9÷11).

NOMENCLATURE

ECO	-	economiser
F	-	heat exchange surface of the utilization boiler
HP	-	high pressure
KU	-	utilization boiler
LP	-	low pressure
ME	-	main engine
Q	-	heating energy demand
T	-	temperature
TPU	-	turbogenerator
ΔT_{min}	-	minimum temperature difference in the utilization boiler
ΔT_{prz}	-	temperature difference of exhaust gas and superheated steam

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