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ANALYSIS OF POSSIBILITY AND PURPOSEFULNESS OF APPLICATION OF WASTE-HEAT BOILERS TO TRAILING SUCTION HOPPER DREDGERS

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Abstract

This paper presents an analysis of possibility and purposefulness of application of waste-heat boilers to trailing suction hopper dredgers. Using results of own operational research on dredgers this author determined thermal power demand for six hypothetical trailing suction hopper dredgers of various size, at accounting for a type of power system and kind of fuel combusted by dredger's power plant. By means of basic indices of economical analysis it was determined under which conditions the application of waste-heat boilers to suction hopper dredgers is economically justified.

Key words: *Trailing suction hopper dredgers, ship power plants, waste-heat boilers*

1. Introduction

Waste-heat boilers (exhaust boilers) are commonly used on transport ships. Practically, they can be found on all types of transport ships of both small and large size. It results from general use of heavy oil and a greater thermal power demand connected with it. On most types of transport ships is used a system of auxiliary boilers consisted of a waste-heat boiler covering thermal power demand during ship voyage and an oil combusting boiler which operates during manoeuvres, port stopovers and anchoring. On ships of a large thermal power demand (e.g. tankers) the oil combusting boiler operates also during voyage supporting this way the waste-heat unit.

However there are types of ships on which the application of waste-heat boilers is not so common as compared with transport ships. It obviously results from not so common use of heavy oil as well as from their operational characteristics. Among them, dredgers can be numbered for instance. The most characteristic type of dredgers is suction hopper one. Not yet long ago the waste-heat boilers have been rarely applied to such dredgers, only to large ones. In present, the trend has been changing for a dozen or so years. The waste-heat boilers are used on smaller and smaller dredgers. This paper is an attempt to show in which situation the application of waste-heat boilers to such dredgers would be economically justified.

2. Characteristics of trailing suction hopper dredgers and their power systems

The suction hopper dredgers are characterized by hydraulical loosening the soil which is transferred to soil hopper by using special pumps, dredge ones capable of forcing through a soil-water mixture. The suction hopper dredgers are as a rule fitted with their own propulsion systems which ensure moving the dredger during operation. The demanded high maneuverability is usually provided by a two-propeller propulsion system and bow thrusters as well. The propulsion system makes transporting the spoil to a given dump place, possible. Emptying the hopper is realized by the so - called silting up (pumping the spoil through a pipeline to land) or gravitationally (by opening hopper bottom flaps or valves).

Such dredgers are built in a wide size range. The basic parameter which characterizes dredger's size is soil hopper capacity contained within the range of 300÷33 000 m^3. The total power of installed diesel engines reaches 1000÷38000 kW.

The power systems of suction hopper dredgers can be very different. Their basic type is a system in which two (usually) main engines provide propulsion to the dredger and drive to all mechanical and electrical power consumers. The electric generating sets (usually two in number) operate sporadically and cover electric power demand practically only during main engine standstill. The type of power system has several variants differing to each other by a way of driving the main mechanical power consumers [4].

There are also power systems characterized by a much greater number of diesel engines. The most extreme example can be systems in which every main mechanical power consumer is driven by a separate diesel engine and the electric power demand from the side of auxiliary consumers is covered by electric generating sets only. In this case the number of diesel engines reaches even ten. As showed below, the application of waste-heat boilers is affected by a type of power system installed on suction hopper dredgers.

3. Determination of thermal power demand

In order to calculate thermal power demand which takes place on suction hopper dredgers the use was made of the results of the author's operational investigations on dredgers [2,7,8] as well as a design method based on them [9].

The method for determining the distribution parameters of the operational loading of auxiliary thermal power consumers deals with determining the total thermal power of each of the three thermal power groups $(N_{CE}^{nom})_j$, values of nominal power usage coefficients of thermal power consumers in each of the three groups of consumers $(\varepsilon_{CE})_j^{śr}$, and then the distribution parameters of thermal power demand from the side of all consumers. The above mentioned groups of thermal power consumers are the following:

- auxiliary power plant devices (e.g. heaters of fuel oil, lubricating oil and water, heating coils of fuel oil return tanks);
- shipboard devices (e.g. heaters of air conditioning units, accommodation heating) ;
- heating units of hull tanks (e.g. coils in heavy oil storage, settling and daily tanks).

The total nominal power of *j-th* group of thermal power consumers, $(N_{CE}^{nom})_j$, was determined under assumption on their linear dependence on a given design parameter (or function of parameters), A_j , of dredgers , which characterizes a given group of consumers or is logically associated with it :

$$(N_{CE}^{nom})_j = a_j + b_j \cdot A_j \tag{1}$$

where: a_j, b_j - constans

In Tab.1 the correlation formulae (1) for three groups of thermal power consumers on trailing suction hopper dredgers, are presented.

The operational nominal power usage coefficients for particular groups of thermal power consumers, $(\varepsilon_{CE})_j$, were determined as ratio of the operational demand on thermal power from the side of *j-th* group of consumers in a considered operational state, $(N_{CE}^{ekspl})_j$, and the nominal power of *j-th* group of consumers, $(N_{CE}^{nom})_j$:

$$(\varepsilon_{CE})_j = \frac{(N_{CE}^{ekspl})_j}{(N_{CE}^{nom})_j} \tag{2}$$

In Tab. 2 are presented the averaged (mean) values of the coefficients $(\varepsilon_{CE})_j^{av}$ and their standard deviations (σ_{CE}^j), determined on the basis of thermal balances of eight dredgers. The values were determined for winter conditions.

Tab. 1

The linear regression equations which determine the total power of groups of particular thermal power consumers

Thermal power consumers groups	**Relations**	**Statistical evaluation**				
		σ $[kW]$	R	F	F_{kr}	m
Auxiliary power plant equipment	$(N_{CE}^{nom})_1 = 0{,}0763 \cdot N_{DE} + 67{,}81$	188,5	0,814	11,78	5,99	8
Shipboard devices	$(N_{CE}^{nom})_2 = 17{,}647 \cdot Z + 106{,}55$	188,9	0,754	7,91	5,99	8
Heating units of hull tanks	$(N_{CE}^{nom})_3 = 0{,}49 \cdot V_{ST} + 75{,}58$	102,7	0,918	32,29	5,99	8

where:

N_{DE} - total installed diesel engine power, kW

V_{ST} - storage tank volume, m^3

Z - crew, persons

Tab. 2

The averaged (mean) values of the coefficients $(\varepsilon_{CE})_j^{av}$ and their standard deviations $(\sigma_{CE})_j$

Thermal power consumers groups	$(\varepsilon_{CE})_j^{av}$	$(\sigma_{CE})_j$
Auxiliary power plant equipment	0,42	0,11
Shipboard devices	0,53	0,12
Heating units of hull tanks	0,57	0,19

The distribution parameters of thermal power demand during realization of dredging work are determined by the relations:

$$\left.\begin{aligned} N_{CE}^{av} &= \sum_{j=1}^{n} (N_{CE}^{nom})_j \cdot (\varepsilon_{CE})_j^{av} \\ \sigma_{CE} &= \sqrt{\sum_{j=1}^{n} (\sigma_{CE})_j^2 \cdot (N_{CE}^{nom})_j^2} \end{aligned}\right\} \quad (3)$$

For calculations of thermal power demand six hypothetical dredgers of various size, whose parameters are given in Tab. 3, were selected. The parameters were determined by using technical parameters of dredgers, contained in the data base DRAGA [3].

Tab. 3

Selected technical parameters of six analyzed suction hopper dredgers

Size of dredger	V_{HP}	V_{ST}	N_{ME}		N_{AE}		Z
	m^3	m^3	kW		kW		$os.$
Dredger 1500	1500	350	2300[1)]	1800[2)]	240[1)]	2000[2)]	12
Dredger 2500	2500	440	3700[1)]	2400[2)]	700[1)]	3200[2)]	14
Dredger 4000	4000	600	5500[1)]	3000[2)]	750[1)]	3800[2)]	18
Dredger 6500	6500	750	9000[1)]	5000[2)]	1400[1)]	6600[2)]	20
Dredger 9000	9000	850	11000[1)]	9000[2)]	1800[1)]	7600[2)]	24
Dredger 12000	12000	950	12000[1)]	10000[2)]	2300[1)]	10000[2)]	32

where:

V_{HP} - hopper volume, m^3

N_{ME} - total main engine power, kW

N_{AE} - total auxiliary engine power, kW

1) – the solution of the power system in which main engines cover whole power demand from the side of main and auxiliary consumers , but auxiliary engines cover the demand only during standstill of main engines;

2) – the solution of the power system in which main engines cover power demand from the side of main screw propellers, but the remaining demand is covered by various auxiliary engines.

The calculated thermal power demand for six hypothetical dredgers (in winter conditions) is presented in Tab. 4 and Fig. 1. For the analysis the two above described extremely different types of power system as well as two kinds of fuel: MDF DMC light oil, and HFO180 heavy oil, were selected. In Fig. 1 the mean demand values and their standard deviations are presented (distinguished by whiskers).

While comparing the data given in Tab.4 and Fig.1, can be observed a very great difference in thermal power demand depending on a kind of used fuel oil. When heavy oil is used the thermal power demand is threefold higher on average. While comparing the suction hopper dredgers with other ships of a similar power plant output the smaller thermal power demand can be observed (at the same kind of fuel oil).This is probably caused by a smaller capacity of spare fuel tanks. The capacity results from an assumed ship operation autonomy. The transport ships are characterized by the autonomy of about 60÷90 days, deep-sea fishing trawlers –of even 100÷110 days, whereas the suction hopper dredgers - of about 20÷30 days only.

In the case of the application of light oil, thermal power demand is so low that the use of steam boilers or oil heaters is often unjustified. Then the solutions are applied in which the entire thermal power demand covered by means of electric devices or electric heaters is supported by water boilers (one combustion boiler as a rule) which serve for accommodation heating.

The use of heavy oil requires to choose another heating medium (water vapour or heating oil) as well as to think a system of auxiliary boilers (number and type of boilers) over.

When analyzing calculation results of thermal power demand on suction hopper dredgers it is necessary to observe the following facts : 1^0 - the calculations were conducted for winter conditions , 2^0 – the values of the coefficients $(\varepsilon_{CE})_j$ determined on the basis of available thermal balances are probably a little too high. Like in the case of electrical power balances a correction factor (called in various ways, e.g. general coincidence factor) should be introduced. For electrical power balances its values are usually assumed to be within the range of 0,7 ÷ 0,8 , [5,6].

Tab. 4

Calculation results of distribution parameters of thermal power demand on six analyzed trailing suction hopper dredgers

Size of dredger	**Heavy fuel**				**Diesel oil**	
	Type power system-1		Type power system-2		Type power system-1 and 2	
	$N_{CE}^{śr}$	σ_{CE}	$N_{CE}^{śr}$	σ_{CE}	$N_{CE}^{śr}$	σ_{CE}
Dredger 1500	419,3	67,0	459,7	72,1	168,7	38,2
Dredger 2500	522,7	82,6	561,1	88,4	187,4	42,4
Dredger 4000	664,1	105,4	681,6	108,1	224,8	50,9
Dredger 6500	857,4	138,1	895,8	145,2	243,6	55,1
Dredger 9000	999,6	161,1	1121,2	185,1	280,9	63,6
Dredger 12000	1150,4	182,4	1332,8	218,4	355,8	80,6

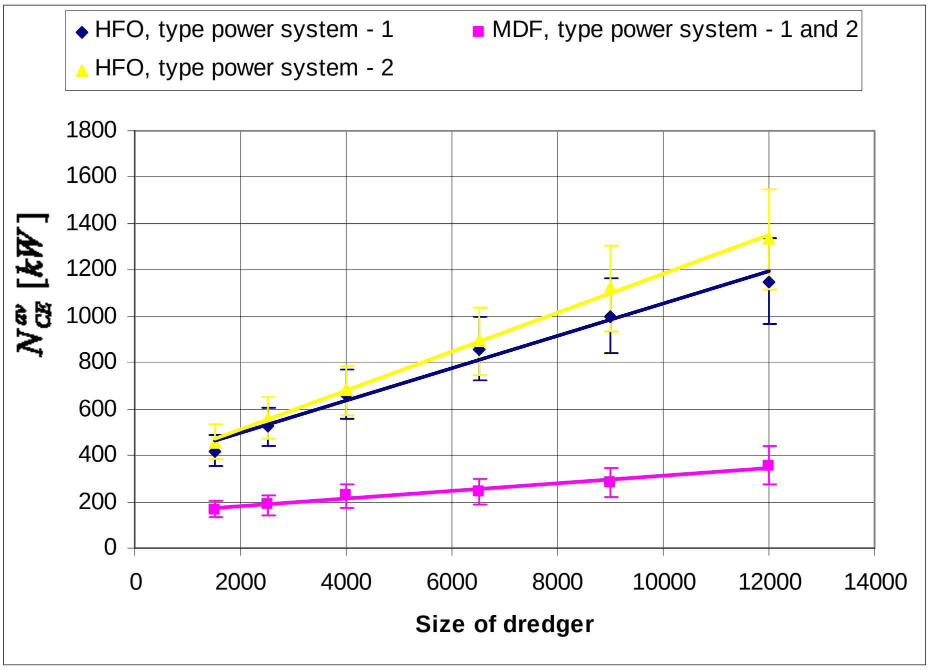

Fig.1. Thermal power demand taking place on six analyzed suction hopper dredgers

4. Possibility of thermal power production by waste-heat boilers during dredging

The thermal power of waste-heat boiler, N_{EB}, is determined by the relation:

$$N_{EB} = m_s \cdot c_s \cdot (t_{s1} - t_{s2}) \cdot \eta_{EB} \tag{4}$$

where:

m_s - mass flow of exhaust gases from the engine,

c_s - specific heat of exhaust gas,

η_{EB} - waste-heat boiler efficiency,

t_{s1}, t_{s2} - exhaust gas temperature (at the inlet and outlet of the exhaust boiler).

A random character of main engine loading makes that the real effectiveness characteristics of waste-heat boilers interacting with the engines, are of similar character. In calculating a thermal power amount which can be produced by waste-heat boiler the method given in [1] may be useful. In this case to know the characteristics of waste-heat boiler in function of main engine loading, $\overline{Q}_{EB} = f(\overline{N}_{ME})$, is necessary. The characteristics can be determined by means of Eq. (4) at simultaneous knowledge of the relation between operational parameters of the engine and its loading. In general case the characteristics can be approximated by the relation as follows:

$$\overline{Q}_{EB} = a_0 + a_1 \cdot \overline{N}_{ME} + a_2 \cdot \overline{N}_{ME}^2 \tag{5}$$

where:

a_0, a_1, a_2 - constans,

If the main engine loading distribution is described by the density function $f(\overline{N}_{SG})$ then the mean (average) thermal power of waste-heat boiler can be determined by using the following relation:

$$N_{EB}^{av} = N_{EB}^{nom}[a_0 + a_1 \cdot \overline{N}_{ME}^{av} + a_2(\overline{N}_{ME}^{av} + \overline{\sigma}_{ME}^2)^2 \tag{6}$$

and standard deviation:

$$\sigma_{EB} = \frac{\sigma_{SG}}{N_{ME}^{av}} \cdot N_{EB}^{av} \tag{7}$$

In Tab.5 are presented the calculation results dealing with the thermal power distribution parameters of the waste-heat boilers on six analyzed dredgers under dredging work. Operation of suction hopper dredger is characterized by a working cycle consisted of: loading the spoil, transporting it, discharging it , and sailing back free of the load. The operations greatly differ to each other as far as the operational loading of main engines is concerned. The operations are appropriately distinguished in Tab. 5.

For the calculations, Wartsila medium-speed engines (and the mean values of the constants: $a_0 = 0{,}23$, $a_1 = 0{,}77$, $a_2 = 0$ as well), were selected. The distribution parameters of the operational engine loading during conducting the operations included in the scope of dredging work, were determined on the basis of the author's operational investigations [2,7,8].

For all the kinds and size of the dredgers fitted with the 1st type power system the predicted values of mean thermal power of waste-heat boilers are greater than the thermal power demand calculated for them (Tab.4). In the case of the 2nd type power system the mean thermal power values of waste-heat boilers exceed the thermal power demand only during sailing. The application of waste-heat boilers to suction hopper dredgers is justified only when the boilers are capable of covering thermal power demand for the entire duration time of the state of dredging. The conclusion drawn from the analysis of the data given in Tab. 4 and 5 is unambiguous:

- in the case of the dredgers fitted with the 2nd type power system, application of waste-heat boilers is not justified because during loading and discharging operations amount of thermal power produced by them is too small. This results from a low value of main engines loading which occurs during loading and discharging the soil.

Tab. 5

The thermal power distribution parameters of the waste-heat boilers installed on six analyzed trailing suction hopper dredgers

Size of dredger	Type of power system	Sailing		Loading the spoil		Discharging the spoil	
		N_{ME}^{av}	σ_{ME}	N_{ME}^{av}	σ_{ME}	N_{ME}^{av}	σ_{ME}
		kW	kW	kW	kW	kW	kW
Dredger 1500	1	457,3	114,3	555,4	83,4	450,1	81,1
	2	405,9	81,2	228,0	27,4	207,7	29,1
Dredger 2500	1	785,5	196,3	947,2	142,1	752,3	135,6
	2	561,6	112,3	310,8	37,3	283,7	39,7
Dredger 4000	1	1291,5	284,2	1453,2	188,7	1176,3	188,5
	2	735,8	147,2	405,5	48,7	363,1	50,8
Dredger 6500	1	2202,9	444,5	2405,1	288,6	1960,1	274,4
	2	1280,2	256,0	710,4	85,3	610,7	85,5
Dredger 9000	1	2940,1	588,2	3100,4	372,6	2548,3	356,8
	2	2410,6	482,1	1267,1	152,1	1088,1	152,5
Dredger 12000	1	3148,6	629,7	3323,7	398,8	2798,2	391,7
	2	2845,4	569,1	1420,7	170,5	1221,3	171,0

5. Economical assessment

For economical analyses, economical effectiveness indices are commonly used to measure quality of analyzed variants of a given design solution. The following indices are usually applied: the Average Annual Costs ***AAC***, the Net Present Value ***NPV*** and the Recoupment Period Time ***RPT***. In this paper only the ***RPT*** index was used. It is defined as follows [10]:

$$RPT = \begin{cases} \dfrac{\log(1 + \frac{q-1}{q} \cdot \frac{\Delta C_{UE}}{\Delta K_{P,O}})}{\log q} & dla \quad q \neq 1 \\ \dfrac{\Delta C_{UE}}{\Delta K_{P,O}} & dla \quad q = 1 \end{cases} \tag{8}$$

$$q = \frac{1+s}{1+r} \quad (9)$$

where:

ΔC_{UE} - difference between price of a considered boiler system variant and that of the cheapest variant assumed basic, [€];

ΔK_P - difference between yearly fuel cost for the power system variant assumed basic and that for a considered power system variant, [€/year] ;

r - yearly rate of discount, [%/100];
s - rate of inflation (yearly increase of fuel and lubricating oil price),[%/100].

In Tab.6 are collected differences in investment cost between the solutions composed of two-waste-heat boilers and one combustion boiler and the solution of only one combustion boiler. In Tab. 7 are presented differences in operational cost, limited to those in combusted fuel cost, as well as the calculated index ***RPT.*** Three fractions of dredging operation time related to calendar year time were assumed: 30%, 50% and 60%. To simplify, the values $r = s = 5\%$ were assumed.

Tab. 6

Differences in investment cost of two considered variants of waste-heat boiler systems on suction hopper dredgers

Size of dredger	ΔC_{UE}
	euro
Dredger 1500	160.000
Dredger 2500	180.000
Dredger 4000	220.000
Dredger 6500	250.000
Dredger 9000	280.000
Dredger 12000	300.000

The fraction of duration time of the dredging mode in one calendar year can be very different. For the dredgers of Polish and foreign owners, on which comprehensive operational investigations were carried out in the years 2000÷2006 the dredging duration time values related to calendar year time are contained within the interval of 0,16 ÷ 0,68, with the mean value equal to 0,4 (the data were determined on the basis of records in ship's log-books) And, the smaller values concerned smaller dredgers and the greater ones – larger dredgers.

In economical analyses of design solutions of ships the RPT index value equal to 2 ÷ 3 year is usually deemed satisfactory [10,11].

Taking into account the above given information and analyzing the data contained in Tab. 7 one can conclude that the application of waste-heat boilers to suction hopper dredgers may be economically justified for the dredgers having hopper capacity of about 6500 m^3 and larger. In certain cases the application of waste-heat boilers may be considered also to smaller dredgers.

Tab. 7

*Differences in operational cost of two considered variants of waste-heat boiler systems, as well as calculated values of the **RPT** index for six analyzed suction hopper dredgers*

Size of dredger	The fraction of duration time of the dredging mode in one calendar year					
	30%		50%		60%	
	ΔK_P	RPT	ΔK_P	RPT	ΔK_P	RPT
	euro/rok	lata	euro/rok	lata	euro/rok	lata
Dredger 1500	21.800	7,3	36.300	4,4	43.600	3,7
Dredger 2500	27.500	6,5	45.800	3,9	55.000	3,3
Dredger 4000	34.700	6,3	57.900	3,8	69.500	3,1
Dredger 6500	44.600	5,6	74.400	3,4	89.300	2,8
Dredger 9000	52.000	5,4	86.500	3,2	104.000	2,7
Dredger 12000	60.000	4,9	99.500	2,8	119.400	2,3

6. Recapitulation and conclusions

On the basis of the performed analysis the following remarks and conclusions may be offered:

1. Quantity of thermal power demand on suction hopper dredgers depends first of all on a kind of combusted fuel. In the case of heavy oil application the demand increases threefold on average;
2. Thermal power demand on suction hopper dredgers is smaller than that on typical cargo ships or fish factory trawlers of a similar main engine output. This results from their lower operational autonomy and hence smaller fuel reserves;
3. Possibility of covering the thermal power demand only by waste-heat boilers depends on a type of power system used on a given dredger. The most favorable from this point of view is decidedly the commonly applied system in which main engines cover the whole power demand from the side of main and auxiliary consumers, and auxiliary engines cover the demand only during standstill of main engines. Other types of power system are not capable of covering the thermal power demand themselves because of a low value of loading the main engines during operations of loading and discharging the soil;
4. The performed economical analysis demonstrated that the application of waste-heat boilers may be economically justified already to the dredgers of 4000 m^3 hopper capacity. It depends on a predicted yearly working time: the longer the time the shorter investment recumbent period;
5. The application of heavy oil is very often associated with the use of waste-heat boilers. On the basis of the data collected in the DRAGA data base it can be stated that about 90% of suction hopper dredgers combusting heavy oil is fitted with waste-heat boilers.

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