DEVELOPMENT OF MAIN MARINE BOILERS' STRUCTURES

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ABSTRACT

Based on the literature sources, the paper presents an analysis of the structural solutions for marine main boilers aimed at their efficiency improvement. Particular attention has been paid to the utilization of waste heat from exhaust gas exiting the boilers. Using the technical documentation and the operational test results, the characteristic values and technical parameters have been determined: the parameters and volume of generated steam, efficiency and performance subject to the fuel type, unit fuel consumption.

Keywords: *marine main boilers, construction, technical parameters, waste heat recovery*

INTRODUCTION

Steamship propulsion system was developed in the middle of 19^{th} century. Initially, piston steam engines were used as main and auxiliary engines. They were fed with saturated steam while in the 20^{th} century, steam superheated up to 250 ^{0}C and of the pressure up to 2MPa, was used. For the purpose of generating the said steam, flame tube-smoke tube boilers were installed. They characterize with large dimensions and weight due to a large water capacity and low efficiency in the range from 70% to 75%. As a breakthrough, the use of steam turbines as propelling devices for the main and auxiliary engines is considered. This situation took place at the turn of the 19th and 20th centuries. Among the factors affecting the efficiency and performance of the steam turbine are the parameters of the steam fed. Along with the steam pressure and superheat temperature increase, the steam turbine performance is higher. Generating steam of high parameters required to create a new design of main boilers. As a result, water tube boilers were developed and they have been used up-to-day. They are equipped with steam-water drums and water drums. Due to that, for the first time, a directed circulation of water and wet steam was employed. It significantly improved the heat exchange process. Along with the development of metallurgy, the materials used thereby characterize with increased resistance to high temperatures, which enables to obtain higher superheat temperature. New-structured boilers are characterized with the efficiency in the range of 82-84% [4].

Changing parameters of steam generated in main boilers, from the last 70 years, are shown in Figure 1. As it may be noticed on the figure, the highest increase of working pressure and temperature of the steam occurred in the years 1950-1960. During this decade the steam pressure increased from 3 to 6 MPa, and the temperature of superheated steam from 400 ^{0}C to 500 ^{0}C. The intention to increase the marine steam turbine power systems resulted in further improvement of generated steam parameters.

In the mid-1990s, the steam pressure generated in marine boilers increased to

6 -7 MPa, and the superheating temperature to 525 ^{0}C. The experimental marine steam turbine power systems are equipped with steam boilers producing steam at a pressure of 10-12 MPa and a superheat temperature of 560 ^{0}C.

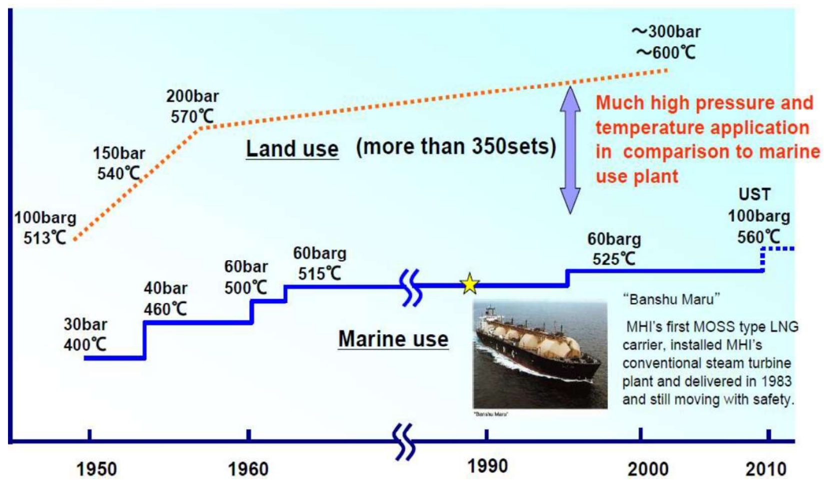

Fig.1. Evolution of steam operating parameters in marine and land use [3], [6].

When compared with the land steam boilers used by the energy industry, the parameters of the steam generated by marine boilers (Fig.1.) are much lower. It is mainly due to the fact that the marine boilers operate in unstable conditions (storms, vibrations). Other reasons for that situation may be considered as often changes to the requirement for steam, a limited number of boiler operators, reduced velocity of natural circulation along with increasing pressure, rising boilers' weight accompanied by increasing pressure, a higher purchase cost of materials used to construct a boiler along with an increase of superheat temperature. Steam turbine power systems were widely used between 1960 and 2005 on high load capacity ships with a large demand for power (tankers, passengers' ships, LNG ships). The power at those ships, in the range from 20 to 50 MW, might have been generated only by steam turbines as there were no internal combustion engines of that power.

The development of the diesel engines, an increase of their power, engagement of dual-fuel engines has resulted in a lower number of ships being equipped with a steam propulsion system. Currently, orders for only 10% of the constructed LNG tankers include the requirement of having steam propulsion system installed [1]. The main reason for such a situation is a low performance of the steam systems which equals from 36% to 38% and which is significantly lower than the efficiency of the modern combustion systems. The latter one's performance is higher than 50%. The intention to improve the efficiency resulted in the development of experimental steam turbine power systems e.g. Ultra Steam Turbine (UST) Plant. The parameters of the plant are presented in Figure 1. Apart from improving the steam parameters, inter-stage steam superheating and carnotization of the power cycle, new structures of boilers were implemented. Due to the said structures, natural circulation velocity increased along with waste heat utilization. The system performance increased up to 40 % [3].

Based on the literature sources, vessel technical documentation, operational test results, the author has presented in the paper an analysis of the structural solutions for marine main boilers and their technical and operational parameters. The discussion below refers to the main boilers produced by Mitsubishi, Kawasaki, Greens Power, Combustion Engineering.

NATURAL CIRCULATION

Providing natural circulation of the highest possible velocity is one of the major tasks of steam boilers' designers. An increase in the water flow rate results in an increased convective heat transfer coefficient but, simultaneously, increases the flow resistance in water tubes, which should be taken into consideration during the selection of boiler tubes' diameter.

A scheme showing the natural circulation in a water-tube boiler presents Figure 2.

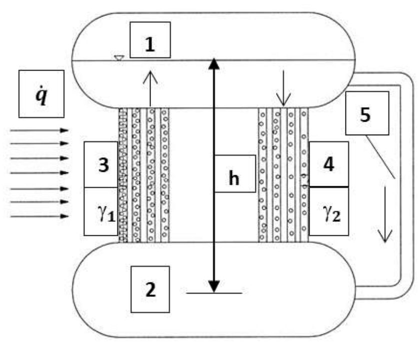

Fig.2. Natural circulation in a steam boiler.

1-steam-water drum, 2-water drum, 3-riser tubes, 4-downcomer tubes, 5-downcomer water tube, γ_1,γ_2-wet steam specific weight, h-distance between drums, q-heat flux.

Source: Authors' elaboration.

The figure above presents a system where a steam-water drum (1) and a water drum (2) are connected by boiler tubes (3 and 4). When heating the boiler tubes with a heat flux (q), the heat will be more intensively exchanged on tubes 3 where wet steam is generated. The steam is of higher dryness degree than the wet steam generated in tubes 4. Due to differences in the wet steam specific weight, hydraulic pressure occurs and triggers the natural circulation in the boiler. The wet steam will flow up the tubes 3, while in tubes 4 water, and then wet steam, flows downwards. Therefore, tubes 3 are called riser tubes and tubes 4 are named downcomer tubes.

The hydraulic pressure affecting the natural circulation velocity may be determined using formula 1 [7]:

$$H = h(\gamma_2 - \gamma_1) \quad [N/m^2] \qquad (1)$$

H – hydraulic pressure [N/m^2]
h – distance between drums [m]
γ_1 – minimum value of wet steam specific weight [kg/m^3]
γ_2 - maximum value of wet steam specific weight [kg/m^3]

The hydraulic pressure depends on the distance (h) between the drums and the difference between the specific weights (γ_1 and γ_2) of wet steam in riser tubes and downcomer tubes. At every volume of generated steam, the maximum circulation velocity is obtained when γ_2 is of the maximum value, which means that there is water in the tubes. This is a result of using downcomer tubes 5 (Fig. 2.) connecting steam-water drum and a water drum, which have no contact with exhaust gas. The downcomer water tubes' diameter in modern boilers is up to 300mm [5], [7]. Given increased flow resistance in downcomer tubes caused by countercurrent flow of steam bubbles, the diameter of downcomer tubes used in the boilers is greater compared to riser tubes.

The performed analyzes and numerical simulations have shown that for marine boilers, effective heat exchange associated with natural circulation occurs for working pressure below7 MPa [5], [7]. Hence, for a majority of main boilers, the working pressure values are in the range from 6 to 7 MPa.

In experimental marine steam turbine power systems, higher working pressure was employed and it equaled from 10 to 12 MPa. The natural circulation performance was provided by a larger distance between the drums. It resulted in increased boilers' height and in the need to extend the boilers' room and its proper location in the hull. A second method that may be applied is removing the water drum and replacing it with a manifold. A scheme of a boiler with a water manifold is presented in Figure 3.

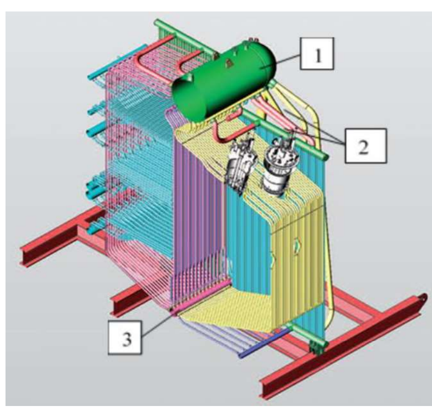

Fig.3. Greens Power boiler, ESD IV [8].
1– water–steam drum; 2 – downcomer water tubes; 3 – water collector

A water collector (3) organizes and directs natural circulation in opposition to the up-to-date used water drum, where wet steam is transported by downcomer tubes to a large volume room. It disturbs the flow and results in higher flow resistance.

WASTE HEAT UTILIZATION

In the case of marine boilers, we should consider waste heat in the exhaust gas and radiant heat. If there is no waste heat recovery system installed, the exhaust gas temperature after the boiler shall equal from 340 to 400 ^{0}C, and exhaust loss shall be 15% -18% [5], [7].

In the modern solutions for marine main boilers, waste heat in the exhaust gas is used to heat water feeding the boiler and/or the air used for the combustion process. The heat exchange surface and the heating temperature are established so that the temperature of exhaust gas discharged from the boiler (depending on the Sulphur content in the liquid fuel) equaled from 130 ^{0}C to 160 ^{0}C [7]. Certain boilers' designs include using radiant heat for the purpose of heating the air. The air absorbs the heat from the boiler shell when flowing through special chambers.

Examples of options for waste heat recovery in marine main boilers are shown in Figure 4.

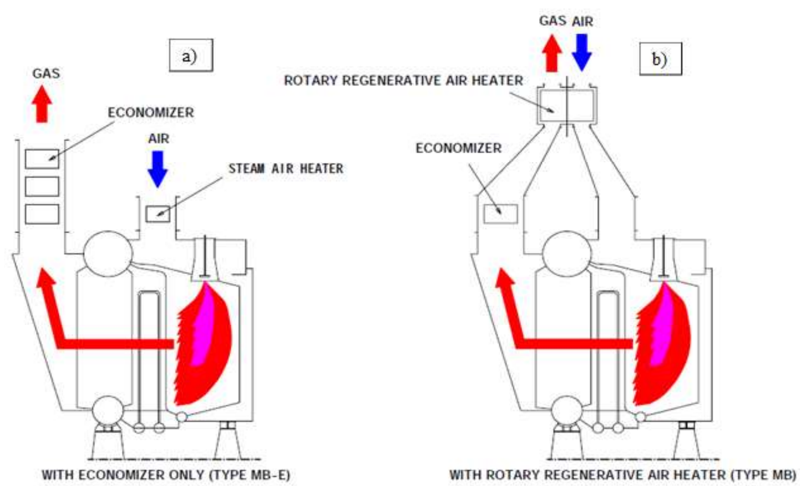

Fig.4. Options of waste heat utilization for MB boiler of Mitsubishi: a) multistage water heater b) water and air heater. [3], [6]

In the case of MB boilers of Mitsubishi, two methods of exhaust gas waste heat utilization have been proposed. The first method (Fig. 4a) includes using total available waste heat to heat water feeding the boiler in a multistage water heater. For the purpose of heating the air, a heat exchanger fed with saturated steam of the pressure from 0.6 to 2.0 MPa was assembled. [3], [6]. The second method (Fig. 4b) consists in dividing the waste heat for the purpose of heating both the water feeding the boiler and the air needed in the combustion process

DISCUSSION

The collected data and the performed analysis constituted the grounds for drawing up Table 1. It includes the basic technical and operational parameters of selected marine main boilers.

Table1 Basic technical parameters of selected marine main boilers [3], [6], [8], [9], [10]

Producer	Boiler type	Steaming rate range	Steam parameters		Temp. of air to be combusted	Feed water temp.	Boiler performance
			Pressure	Temp.			
		D [t/h]	p [MPa]	t [°C]	t_p [°C]	t_w [°C]	η [%]
Mitsubishi	MB	23-75	6,15	515	150	210	90,0
	MB-E	15-70	6,15	515	120	138	88,5
	MBR	40-70	10	560	120	138	88,5
Kawasaki	UM	47-143	6,1	525	155	205	90,0
	UME	47-143	6,1	525	130	145	88,5
	UFR	50-140	10,3	525	130	195	90,2
	UTR-II	35-100	12	565	133	229	90,2
Greens Power	ESDI V	36-65	6,2	515	165	180	91,3
Combustion Engineering	V2M8	30-85	6,2	515	290	183	89,4
	V2M9	60-140	6,6	515	200	190	90,0

The variation range for the main boilers' performance, at the minimum volume of generated steam, equals from 88.5% to 91.3%. The highest performance at the level of 91.3% is reached by ESD IV boiler despite the low use of waste heat. The reason for this state of affairs is replacing the water drum with a water distribution system (Fig. 3) which resulted in improved performance of the natural circulation and hence better heat exchange. Boilers of higher steam working pressure (10-12 MPa) and of the superheated steam temperature equaled to 560 ^{0}C and 565 ^{0}C, achieve high efficiency of 90%, except for the MBR boiler. Its performance at the working pressure of 10 MPa equals to 88.5%. This is a result of secondary steam superheating in MBR boiler in an additional heater equipped with a combustion chamber with its own burner. That means that an suitable amount of fuel is combusted in order to obtain the temperature of steam re-superheated equaled to the temperature of primary steam one (560 ^{0}C). Due to exhaust gas waste heat, it is possible to heat water feeding the boiler to the temperature from 138 ^{0}C to 229 ^{0}C and the air to the temperature from 120 ^{0}C to 290 ^{0}C. It should be noted that the waste heat volume, that is available, is used to heat two media namely water and air. It means that it is necessary to select the medium that would reach the higher heating temperature. For example, at the maximum heating temperature of 290 ^{0}C, the temperature of feeding water equals to 183 ^{0}C, while at the maximum water temperature of 229 ^{0}C, the air temperature shall reach 133 ^{0}C.

The relation between the applied method and the exhaust gas temperature after the boiler and the exhaust loss value is presented in Table 2.

Table 2. Relation between the applied method and the exhaust gas temperature after the boiler and the exhaust loss [2,4,5,7]

Use of waste heat	Exhaust gas temp. after boiler	Exhaust loss
	t_s [^{0}C]	S_w [%]
No use	340-400	15-18
Heating water	200-230	10-12
Heating water and air	130-160	5-6

During the analysis of data included in Table 2, it may be noted that along with increased use of exhaust gas waste heat, the exhaust gas temperature is decreasing after the boiler. It contributes to the drop in the value of the highest boiler loss, namely exhaust loss. When compared with boilers where no waste heat was used, the loss value is 3 times lower.

As the analysis and tests proved [2], [4], [7], if the temperature of water feeding the boiler increases by 10 K, at constant fuel consumption, the generated steam volume will increase by 2%-2.5%.

If feeding water is heated in an atmospheric degasser and the air is removed, it should be noted that its temperature, before an internal combustion heater, equals to 100 ^{0}C. Hence, heating water in that heat exchanger up to the maximum applicable temperature of 229 ^{0}C (Table 1), shall result in an increased volume of generated saturated steam by ca. 25%. In contrast, the increase of 100 K of the air temperature, required for the combustion process, results in an increase of the combustion temperature by 70 K. This causes that the amount of heat absorbed in the boiler is higher [7]. A steam boiler performance is also affected by the type of used fuel.

The varied efficiency of a selected boiler, fed with liquid and gas fuel, is shown in Figure 4.

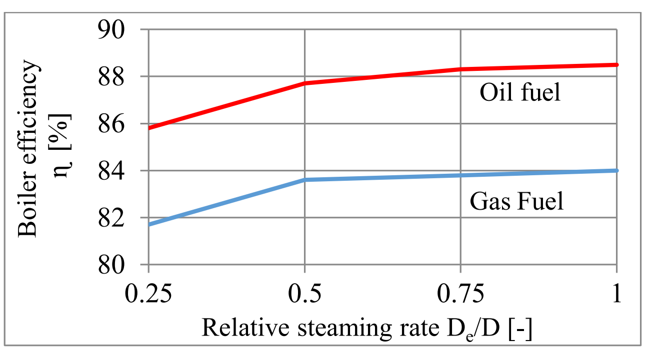

Fig.4. MB-E boiler efficiency in relation to the type of fuel and generated steam volume. Source: Authors' elaboration.

Analyzing the course of the curves in Fig. 4, it can be stated that the efficiency of the boiler depends to a large extent on the type of fuel. In the case of using gas as a fuel, the efficiency of the boiler is lower by about 4.5% in the whole range of the analyzed relative steaming rate, compared to the efficiency of the boiler fueled with liquid fuel. This situation is caused by different values of air required for the combustion process and the excess air ratio supplied to the boiler's combustion chamber. In order to calculate combustion processes and heat exchange in the boiler, the heating value of the liquid fuel is assumed to be equal to WO = 43 MJ / kg and in terms of gas WG = 55 MJ / kg [5], [7]. Analysis of stoichiometric combustion processes, after taking into account the calorific values of both fuels, showed that the theoretical amount of air required is about 40% higher than in the case of combusting liquid fuel. In addition, the recommended air-fuel ratio is 0.1 higher for gas combustion. That means a further increase in the actual amount of air supplied to the combustion chamber of a gas-fired boiler. Taking into account the heat balance of the combustion process, it should be stated that the increasing amount of air supplied, that does not participate in the combustion process, reduces the combustion temperature, and thus the amount of heat available for the heat exchange processes in the boiler also decreases. Literature sources show that a change in the value of the air-fuel ratio by 0.1 affects the combustion temperature by 100 K [5], [7].

CONCLUSION

Modern marine boilers should be considered as highly efficient power plants (88.5%-91.3%) in a wide range of generated steam volume (25%-100%). Such high efficiency was achieved due to the recovery of heat contained in the exhaust gas;

The advantage of boilers is the possibility of feeding them with liquid fuel and gas in any proportions. The gas supply system is characterized by a simple construction and low gas parameters (pressure 0.3-4,0 MPa and temperature 40 ^{0}C [3,6]). Therefore, steam turbine power systems are used mainly on LNG vessels, where gas for feeding boilers is supplied directly from cargo tanks. Modern dual-fuel combustion engines also enable gas combustion. However, for high-power low-speed engines, much higher parameters are required (pressure equaled from 200 MPa to 250 MPa and temperature of 40 ^{0}C). It is also necessary to construct an additional gas fuel system with cryogenic liquid gas tanks, pumps, heat exchangers and compressors;

It has been proved that gas-fired boilers operate with a 4.5% lower efficiency, which will affect the efficiency of the steam turbine power system. The advantages of gas as a fuel include: the use of naturally evaporated gas, the lack of post-catalytic products used in the process of processing of crude oil causing high-temperature corrosion, higher combustion quality resulting in reduced loss of incomplete combustion. Therefore, less sludge accumulates on the heat exchange surface and the volume of emitted harmful exhaust components is reduced;

Further boiler structure development will be directed to and focused on improving the efficiency of natural circulation and heat exchange efficiency.

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