Analysis of the Operational Reliability of the Rotary Cup Burner of a Marine Boiler

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Abstract: - One of the steps in predicting the reliability of a system includes determining the failure rate of the system's components. The latter is obtained on the basis of the data available to the manufacturer, experience in using similar systems, using statistical methods and technical literature. In practice, the starting point in the process of foreseeing the reliability of any technical system is the assumption of constant failure rates. The system components' failure rates which are determined in this way represent the so-called nominal values. This value is commonly modified by taking into account operation loads and environment conditions under which the observed system component is supposed to operate. In most cases the quantitative values of these two factors result from the engineering assessment that is based on the data available to the manufacturer or the user and takes into account the inevitable effect of a number of subjective factors. Predicting the reliability is a process of determining numerical values which show the probability that the machinery or the engine will meet the previously set requirements. The basic objective of reliability prediction is to ensure timely maintenance. This paper discusses the predicting the operational reliability of the rotary cup burner in the marine steam boiler.

Key-Words: - Marine boiler, rotary cup burner, reliability and failure.

1 Introduction

There are four sources of data for predicting the reliability of a system in the stage of development:

- manufacturer;
- experience in using similar systems;
- adequate statistical methods;
- technical literature.

The system as a whole is the starting point when gathering the information necessary for reliability forecasting. If the data referring to a system are not available, it is necessary to decompose the system to the levels for which the data are available. It is neither necessary nor recommended to go any further, even in the event of stopping at the first level that is lower than the system level. However, it is sometimes necessary to reach the most elementary components of the system as it is at this level that the needed data can be gathered. When predicting the operational reliability of a marine steam boiler rotary cup burner, according to [9], it is necessary to:

- define the rotary cup burner as a system;
- define faults;
- define operational and maintenance conditions;
- set the algorithms for calculating the reliability;
- determine the failure rates for separate components of the rotary cup burner;
- modify the fault indexes for the burner components;
- calculate the reliability of the rotary cup burner.

When defining the rotary cup burner as a system, it is necessary to determine its components and their relationships. The components represent the subsystems of the rotary cup burner.
A fault is defined as an occurrence of conditions that impede the rotary cup burner's operation. The operational conditions determine the rotary cup burner's working conditions.
The maintenance conditions affecting the reliability of the rotary cup burner must be known before reliability prediction. The block diagram of reliability presents the functional connection of the system or the blocks within the system. The rotary cup burner's reliability is obtained by introducing the values of the failure rates of the system components into the algorithm for calculating the reliability in a defined period of time.

2 Considering the assumption about the constant failure rate

The above mentioned procedure for predicting the reliability does not assume that the failure rate has to be constant. It is known that the failure rate for most electronic components is constant, i.e. not dependent on time. Although the failure rates for other components depend on time, it has been found out that these changes are small, considering the long period of operation of these components.

In both cases a minor error is made by introducing the assumption about the constant failure rate. If the failure rates of components are independent of time, then the reliability of a system comprising such components could be calculated by applying the exponential distribution, according to [9], therefore:

$$R_g = e^{-\lambda_g t} \quad (1)$$

where R_g is the reliability of the system – the rotary cup burner, and λ_g is the failure rate of the system – the rotary cup burner. In the case of sequence configuration, λ_g is calculated from the form:

$$\lambda_g = \sum_{i=1}^{n} \lambda_i \quad (2)$$

where λ_i is the failure rate of the i component of the system – the rotary cup burner. It should be noticed that, in this case, the mean time between failure of the system – the rotary cup burner M_g can be calculated from:

$$M_g = \frac{1}{\lambda_g} \quad (3)$$

Even in the event of major changes in failure rates dependent on time, minor mistakes result from using the so-called stable failure rate in foreseeing the reliability of a system over a certain period of time, provided that the period of time corresponds to the period of time for which the value of the stable failure rate has been determined.

This is in line with the renewal theory, since the application of preventive maintenance to the components having a growing failure rate accelerates the renewal process and helps achieve the so-called state of balance faster. In this case it can be assumed that the system fails according to the law of the exponential distribution, according to [9].

2.1 Using the χ^2 distribution for establishing the confidence limit in the exponential distribution

Quite often there are no available data on any failures for some of the system components but we do know the time that component was in service. If we assume that the exponential distribution can be applied to the given component, it is possible to establish the lower confidence limit of the failure rate, both for the situation where there was no failure and for the situation where there was one or more failures, according to [2].

The lower confidence limit for the mean time between failures $\hat{\theta}$, for the confidence interval *1 –* α, is given by the time:

$$\hat{\theta} \geq \frac{2t_r}{\chi_\alpha^2, 2r+2} \quad (4)$$

where:

t_r – total time of operation of the system (rotary cup burner);

r – number of failures of the system (rotary cup burner);

$\chi_\alpha^2, 2r+2$ - random changeable value belonging to the χ^2 distribution.

In this case the upper value of the failure rate $\hat{\chi}$, for the confidence interval 1- α, is calculated from the equation:

$$\hat{\chi} = \frac{\chi_\alpha^2, 2r+2}{2t_r} \quad (5)$$

For a given value of the confidence interval 1-α and the known number of failures r, the value of $\chi_\alpha^2, 2r+2$ can be determined, according to Table 1, according to [5].

On the basis of the available data from the engine log and the technical references supplied by the manufacturer, it is necessary to predict the operational reliability of the rotary cup burner. In addition, it should be ascertained whether the predicted operational reliability meets the previously set requirements and then, on the basis of the gathered findings, we should be able to conclude whether it is necessary to take adequate measures for increasing the reliability.

Table 1.
Probability values for the χ^2distribution.

v	χ^2 0.50	χ^2 0.30	χ^2 0.25	χ^2 0.20	χ^2 0.10	χ^2 0.05	χ^2 0.025	χ^2 0.01	χ^2 0.005	v
1	0.455	1.074	1.323	1.642	2.706	3.841	5.024	6.635	7.879	1
2	1.386	2.408	2.773	3.219	4.605	5.991	7.378	9.210	10.597	2
3	2.366	3.665	4.108	4.642	6.251	7.815	9.348	11.345	12.838	3
4	3.357	4.878	5.385	5.989	7.779	9.488	11.143	13.277	14.860	4
5	4.351	6.064	6.626	7.289	9.236	11.070	12.832	15.086	16.750	5
6	5.348	7.231	7.841	8.558	10.645	12.592	14.449	16.812	18.548	6
7	6.346	8.383	9.037	9.803	12.017	14.067	16.013	18.475	20.278	7
8	7.344	9.524	10.219	11.030	13.362	15.507	17.535	20.090	21.955	8
9	8.343	10.656	11.389	12.242	14.684	16.919	19.023	21.666	23.589	9
10	9.342	11.781	12.549	13.442	15.987	18.307	20.483	23.209	25.188	10
11	10.341	12.899	13.701	14.631	17.275	19.675	21.920	24.725	26.757	11
12	11.340	14.011	14.845	15.812	18.549	21.026	23.337	26.217	28.300	12
13	12.340	15.119	15.984	16.985	19.812	22.362	24.736	27.688	29.819	13
14	13.339	16.222	17.117	18.151	21.064	23.685	26.119	29.141	31.319	14
15	14.339	17.322	18.245	19.311	22.307	24.996	27.488	30.578	32.801	15
16	15.338	18.418	19.369	20.465	23.542	26.296	28.845	32.000	34.267	16
17	16.338	19.511	20.489	21.615	24.769	27.587	30.191	33.409	35.718	17
18	17.338	20.601	21.605	22.760	25.989	28.869	31.526	34.805	37.156	18
19	18.338	21.689	22.718	22.900	27.204	30.144	32.852	36.191	38.582	19
20	19.337	22.775	23.828	25.038	28.412	31.410	34.170	37.566	39.997	20

The basic requirement that is set for the rotary cup burner's reliability refers to the number of operation hours during the ship's time in port. It is required that the rotary cup burner operates 600 hours before overhaul with reliability no less than 0.75. Twenty rotary cup burners are used for examination of reliability.

2.2 Block diagram of the rotary cup burner type of a marine boiler

If the level of complexity of the rotary cup burner's components is determined, the components may be presented as the separate blocks of the subsystem, as shown in Fig.1, according to [9].

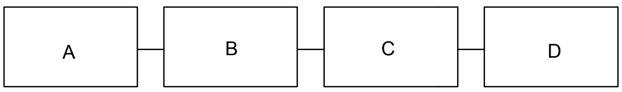

Fig. 1. Block diagram of the rotary cup burner type of a marine boiler

Where:
A - rotary cup atomizer;
B - light oil igniter;
C - oil compound regulator;
D - combustion air fan.

The rotary cup burner components are serially interdependent. Given the requirement that the rotary cup burner should be able to operate 600 hours before overhaul at the reliability value of 0.75, the failure rate can be calculated according to the equation (1):

$$\lambda_g = -\frac{\ln R_g}{t} = -\frac{\ln 0.75}{600} = 47.95 \cdot 10^{-5} \textit{ failures / hour}$$

Where:

R_g – reliability of the rotary cup burner;
λ_g – failure rate of the rotary cup burner;
t - required time of reliable operation of the rotary cup burner.

The mean time between failure, according to (3) is:

$$M_g = \frac{1}{\lambda_g} = \frac{1}{47.95 \cdot 10^{-5}} = 2085.5 \; hours$$

2.3 Determining the failure rate for the basic subsystems

2.3.1 Rotary cup atomizer of a marine boiler

The rotary cup atomizer of a marine boiler consists of 15 basic parts shown in Fig.2, according to [9]. Each basic part may be composed of a number of elements.

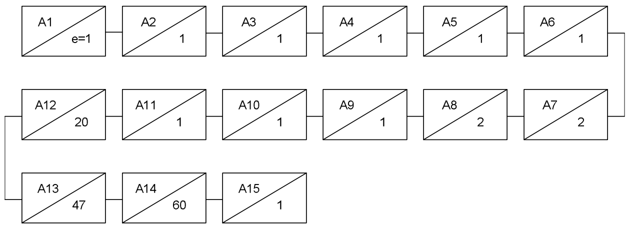

Fig. 2 Block diagram of the rotary cup atomizer of a marine boiler

Where:
e - number of elements;
A_1 – system for directing the primary air;
A_2 - rotary cup;
A_3 - shaft;
A_4 - primary air fan;
A_5 - electromotor;
A_6 - poly- V belt;
A_7 - strap-wheels;
A_8 - ball bearings;
A_9 - primary air regulation damper;
A_{10}- safety cover;
A_{11}- seal;
A_{12}- studs;
A_{13}- nuts;
A_{14}- shims;
A_{15}- fuel line.

The rotary cup atomizer of a marine boiler subsystem experienced failures of the basic part A_2 after 100 hours of operation, the part A_6 failed after 530 hours, whereas the part A_{11} failed after 586 hours of operation.

The total number of the rotary cup atomizer of a marine boiler elements is 141, which makes 2820 elements in 20 burners.

The failure rate function λ_g is equal to the ratio of failure occurrences in the time interval Δt to the number of functioning elements in the system at the end of the interval.

The failure rate functions λ_g for parts A_2, A_6, A_{11} are:

$$\lambda_{A_2} = \frac{1}{2819 \cdot 100} = 3.547 \cdot 10^{-6} \; failures\,/\,hour$$

$$\lambda_{A_6} = \frac{1}{2819 \cdot 530} = 0.669 \cdot 10^{-6} \; failures\,/\,hour$$

$$\lambda_{A_{11}} = \frac{1}{2819 \cdot 586} = 0.605 \cdot 10^{-6} \; failures\,/\,hour$$

The failure rate of the rotary cup atomizer of a marine boiler subsystem, according to (2) amounts to:

$$\lambda_A = \lambda_{A_2} + \lambda_{A_6} + \lambda_{A_{11}} = 4.821 \cdot 10^{-6} \; failures\,/\,hour$$

2.3.2 Light oil igniter

The light oil igniter is a subsystem comprising 14 basic parts which are shown in Fig.3, according to [9]. Each basic part may consist of a number of elements.

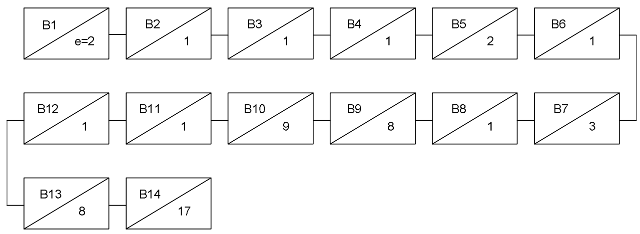

Fig.3. Block diagram of the light oil igniter

Where:
e - number of elements;
B_1 - electrodes;
B_2 - nozzle;
B_3 - filter;
B_4 - butterfly air damper;
B_5 - high-voltage cables;

B_6 - high-voltage point;
B_7 - electromagnetic valves;
B_8 - fuel oil pump;
B_9 - nuts;
B_{10}- shims;
B_{11}- fuel oil line;
B_{12}- flexible air line;
B_{13}- seals;
B_{14}- studs.

The light oil igniter subsystem experienced failures in basic parts: B_2 after 149 hours and 450 hours of operation, B_3 after 160 hours, 325 hours and 550 hours of operation, B_7 after 495 hours of operation, B_{11} after 580 hours of operation.
There were altogether 7 failures of 4 basic parts of the light oil igniter. The total number of the light oil igniter parts is 56, i.e. this makes a total of 1120 parts for 20 burners.

The failure rate functions λ_g for parts B_2, B_3, B_7, B_{11} are:

$$\lambda_{B_2} = \frac{2}{1118 \cdot \dfrac{149+450}{2}} = 5.962 \cdot 10^{-6}\ failures/hour$$

$$\lambda_{B_3} = \frac{3}{1117 \cdot \dfrac{160+325+550}{3}} = 7.784 \cdot 10^{-6}\ failures/hour$$

$$\lambda_{B_7} = \frac{1}{1119 \cdot 495} = 1.805 \cdot 10^{-6}\ failures/hour$$

$$\lambda_{B_{11}} = \frac{1}{1119 \cdot 580} = 1.54 \cdot 10^{-6}\ failures/hour$$

The failure rate of the light oil igniter subsystem, according to (2), amounts to:

$$\lambda_B = \lambda_{B_2} + \lambda_{B_3} + \lambda_{B_7} + \lambda_{B_{11}} = 17.091 \cdot 10^{-6}\ failures/hour$$

2.3.3 Oil compound regulator

The oil compound regulator is a subsystem comprising 12 basic parts. Each of these parts may consist of a number of elements, as shown in Fig.4, according to [9].

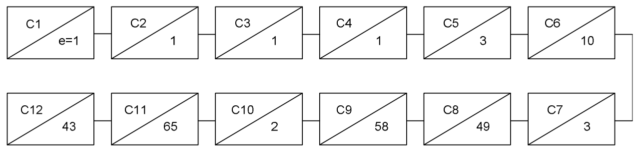

Fig.4. Block diagram of the oil compound regulator

Where:
e - number of elements;
C_1 - servomotor;
C_2 - control disc;
C_3 - rotary valve;
C_4 - micro-switch;
C_5 - levers;
C_6 - slide bearings;
C_7 - fuel oil lines;
C_8 - nuts;
C_9 - shims;
C_{10}- shafts;
C_{11}- studs;
C_{12}- round wedges.

During 600 hours of operation of the oil compound regulator, two failures occurred in the basic parts: C_7 failed after 530 hours of operation due to fuel oil leaking in the return fuel oil line, while C_5 failed after 597 hours of operation due to the broken lever for regulating the primary air damper.
The overall number of the observed elements of the oil compound regulator subsystem is 237, i.e. there are 4740 such elements in 20 oil compound regulators.

The failure rate functions λ_g for parts C_7 and C_5 are:

$$\lambda_{C_5} = \frac{1}{4739 \cdot 597} = 0.353 \cdot 10^{-6}\ failures/hour$$

$$\lambda_{C_7} = \frac{1}{4739 \cdot 530} = 0.398 \cdot 10^{-6}\ failures/hour$$

The failure rate of the oil compound regulator subsystem, according to (2), is:

$$\lambda_C = \lambda_{C_5} + \lambda_{C_7} = 0.751 \cdot 10^{-6} \textit{ failures / hour}$$

2.3.4 Combustion air fan

The combustion air fan is a subsystem comprising 6 basic parts, and each part may consist of a number of elements, as shown in Fig.5, according to [9].

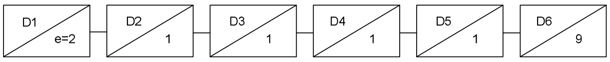

Fig.5. Block diagram of the combustion air fan

Where:
e - number of elements;
D_1 - ball bearings;
D_2 - impeller;
D_3 - shaft;
D_4 - safety cover;
D_5 - electromotor;
D_6 - studs.

During the observation period there was only one failure that occurred after 593 hours of operation, due to the seizure of one of the electromotor ball bearings. The total number of the observed elements in the combustion air fan is 15, which makes a total of 300 elements in 20 combustion air fans.

The failure rate of the combustion air fan subsystem is:

$$\lambda_D = \frac{1}{299 \cdot 593} = 5.639 \cdot 10^{-6} \textit{ failures / hour}$$

2.4 Determining the confidence limit of the rotary cup burner's operation in the case of the exponential distribution of failures

A total of 20 burners were observed over a period of 600 hours of operation. According to the engine log data, the overall operation time of the rotary cup burners amounted to 8,900 hours. During that time there were 8967 functional elements.
The lower confidence limit for the confidence interval (1-α) = 0.75 is obtained according to the expression (4).

$$\hat{\theta} \geq \frac{2 \cdot t_r}{\chi^2_{0.25;2}} = \frac{2 \cdot 8900}{2.773} = 6419.04 \textit{ hours}$$

The value χ^2 is obtained from Table 1

The upper failure rate value for the functional elements during the confidence interval (1-α) = 0.75, according to the expression (5), is:

$$\hat{\lambda} = \frac{1}{\hat{\theta}} = \frac{1}{6419.04} = 15.5786 \cdot 10^{-5} \textit{ failures / hour}$$

If the obtained value is divided by the number of functional elements, the upper value of the failure rates for each separate element in the given confidence interval:

$$\hat{\lambda}_{EL} = \frac{15.5786 \cdot 10^{-5}}{8967} = 17.37325 \cdot 10^{-9} \textit{ failures / hour}$$

2.5 Determining the operational reliability of the rotary cup burner of a marine boiler

Calculation of failure rates for individual parts of the rotary cup burner of a marine boiler can be performed using the obtained upper failure rate in the given confidence interval:

- For the rotary cup atomizer of a marine boiler:

$$\lambda_{A_{uk}} = \lambda_A + n_A \cdot \hat{\lambda} = 4.821 \cdot 10^{-6} + 2817 \cdot 17.37325 \cdot 10^{-9} = \\ = 53.76114 \cdot 10^{-6} \textit{ failures/ hour}$$

- For the light oil igniter:

$$\lambda_{B_{uk}} = \lambda_B + n_B \cdot \hat{\lambda} = 17.091 \cdot 10^{-6} + 1113 \cdot 17.37325 \cdot 10^{-9} = \\ = 36.4274 \cdot 10^{-6} \textit{ failures / hour}$$

- For the oil compound regulator:

$$\lambda_{C_{uk}} = \lambda_C + n_C \cdot \hat{\lambda} = 0.751 \cdot 10^{-6} + 4738 \cdot 17.37325 \cdot 10^{-9} = \\ = 83.0655 \cdot 10^{-6} \textit{ failures / hour}$$

- For the combustion air fan:

$$\lambda_{D_{uk}} = \lambda_D + n_D \cdot \hat{\lambda} = 5.639 \cdot 10^{-6} + 299 \cdot 17.37325 \cdot 10^{-9} = \\ = 10.8336 \cdot 10^{-6} \textit{ failures / hour}$$

The prediction of the failure rate values for the rotary cup burner of a marine boiler components amounts to:

$$\lambda_g = (53.7614 + 36.4274 + 83.0655 + 10.8336) \cdot 10^{-6} = $$
$$= 184.0879 \cdot 10^{-6}$$

The mean time between failures of the rotary cup burner of a marine boiler, according to the expression (3), is:

$$M_g = \frac{1}{\lambda_g} = 5432.187 \ hours$$

The overall operational reliability of the rotary cup burner of a marine boiler is:

$$R_g = e^{-\lambda_g t} = e^{-0.11045274} = 0.8954$$

3 Conclusion

The obtained operational reliability of the rotary cup burner of a marine boiler is higher than the reliability that is required, amounting to 0.75. The analysis of the failure rates of the rotary cup burner subsystems and the elements within the subsystems results in the conclusion that the light oil igniter is the most sensitive component of the burner.
The most common reasons for failure in this subsystem include:

- fuel oil filter clogging due to impurities in fuel oil;
- contaminated electrodes;
- due to vibrations during the operation of the system, a change in the distance between the electrodes may occur, so that the electric arc intended for oil ignition can not be produced between them.

This implies that it is necessary to undertake further research on new technological and design solutions in manufacturing the burners.

References

[1] *Operator's manual of the rotary cup burner* SAACKE, type SKV 60...150, Bremen, Germany, 2003.
[2] Ivanović, G. and Stanivuković, D., *Pouzdanost tehničkih sistema*, Faculty of Mechanical Engineering - University of Belgrade,1983.
[3] Levit, G. T., Optimizing the control of combustion in steam boilers equipped with pulverizing fans, in: *Thermal Engineering*, Vol. 47, 2000, pp. 715-718.
[4] Nikolić, I., *Pouzdanost tehničkih sistema i ljudskog faktora, Teorija, primeri, softver*, Faculty of Organizational Sciences, University of Belgrade, Beograd,2003/2004.
[5] Pavlić, I., *Statistička teorija i primjena*, Tehnička knjiga Zagreb, Zagreb,1985.
[6] Prelec, Z., *Brodski generatori pare*, Školska knjiga, Zagreb,1990.
[7] Solberg, B., Andersen, P., Maciejowski, J. M. and Stoustrup, J., Optimal switching control of burner setting for a compact marine boiler design, *Submitted in March 2008 for journal publication,*2008.
[8] Solberg, B., Andersen, P. and Stoustrup, J., Modelling and Control of a Turbocharged Burner Unit, *Proceedings of the 21st International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy System*s (ECOS 2008), June 24-27, 2008, Kraków, Poland.
[9] Vujanović, N., *Teorija pouzdanosti tehničkih sistema*, Vojno izdavački novinski centar / Military Publishing and Press Center, Belgrade, 1987.
[10] Dvornik, J., Dvornik, S., Operational Realiability of the Rotary Cup Burner Type SAACKE-SKV 60 of Marine Boiler, *Transactions on Maritime Science TOMS*, Vol. 2, No. 1. April 2013.