Development of a model of the technical condition of the engine according to the data of operational observations

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Abstract. The article considers an approach to the use of in-place methods and diagnostic tools in the practice of operating power plants of marine transport vessels, which allow maintenance of engines on demand, depending on their technical condition. It has been determined that under operating conditions it is necessary to know the quantitative values of the wear of the main engine parts and the level of formation of soot and deposits on them without disassembling the engine using indirect diagnostic parameters. For this, a conditional reference model of the actual change in its technical condition has been developed, obtained from the data of operational observations, in the form of quantitative values of wear of parts from their operating time. The model included information about the intensity of carbon deposits in the engine cylinder, which can be used to judge the thickness or amount of carbon deposits formed at a given moment, without disassembling the engine; information about the permissible possibilities and terms of engine operation at the rate of carbon formation established by the model. The raw materials were obtained during the cleaning of the engine cylinders, in which the methods for measuring wear of parts and evaluating carbon deposits were slightly expanded compared to conventional measurement methods. The presence of such a model, which characterizes the change in the technical condition of the engine as it is developed in the form of quantitative characteristics of the wear of its parts and quantitative characteristics of carbon formation, reflecting close to real changes occurring in the engine, makes it possible to expand the information content of in-place diagnostics, increase the controllability of engine reliability; will optimize the timing and frequency of maintenance, more accurately predict the consumption of spare parts and regulate the frequency of maintenance.

1 Introduction

The use of in-place diagnostic methods and tools in the practice of operating the power plants of marine transport vessels makes it possible to carry out maintenance of engines on demand, depending on their technical condition.

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However, in-place engine diagnostics by indirect parameters is mainly focused on the limiting state of the engine elements and does not reflect the quantitative changes that occur in the engine cylinder during its operation in relation to wear of parts and carbon formation.

At the same time, under operating conditions, it is almost always necessary to know the quantitative values of the wear of the main engine parts and the level of formation of soot and deposits on them without disassembling the engine using the same indirect diagnostic parameters.

2 Materials and methods

In order to constantly have such information for each type of engine, a conditional reference model of the actual change in its technical condition, obtained from operational observations, can be developed in the form of quantitative values of wear of parts from their operating time, i.e., the usual wear characteristics of such parts of the cylinder-piston group (CPG), like a piston, cylinder liner, piston rings, valves, as well as the main parts of fuel equipment (TA) and various bearings.

It is imperative that such a practical model should include information on the intensity of carbon deposits in the engine cylinder, by which it would be possible to judge the thickness or amount of carbon deposits formed by this moment, without disassembling the engine.

All these data for the developed model can be obtained by the method of disassembly diagnostics as an addition to in-place diagnostics in the form of decoding the content of the actual technical condition of the engine elements at the moment. The raw materials must be obtained during cleaning of the engine cylinders, in which the methods for measuring wear of parts and evaluating carbon formation should be slightly expanded compared to conventional measurement methods. These may include, for example, the weighing of piston rings, valve wear parts, etc., as well as carbon deposits and deposits on pistons, piston rings, cylinder liners, valves, injector nozzles, etc.

The presence of such a model that characterizes the change in the technical condition of the engine as it is developed in the form of quantitative characteristics of the wear of its parts and quantitative characteristics of carbon formation, reflecting close to real changes occurring in the engine, will expand the information content of in-place diagnostics, increase the controllability of engine reliability, optimize timing and frequency Maintenance; and will help prevent accidents.

The model can be adjusted under the influence of operational factors associated with the use of fuels of different viscosities, different grades of oils used, as well as operating conditions.

The basis for the development and creation of an engine model are its logbooks, the records of the ship's mechanic, logbooks, the ship's technical report, information about failures, set in the form [1]. The analysis of these materials makes it possible to build graphical dependencies in the form of wear and carbon formation characteristics from the operating time with the necessary correction, extrapolating which makes it possible to predict the parts resources and the magnitude of carbon formation.

Thus, the presence of the model allows you to more accurately predict the consumption of spare parts and regulate the frequency of maintenance. In addition, the availability of information on the dynamics of changes in the technical condition in the form of wear and carbon formation rates makes it possible to choose the optimal grades of fuels and oils for a given engine, as well as to clean the cylinders from carbon deposits and deposits in a timely manner. In special cases, the model can be compiled on the basis of the technical requirements for the engine and its main elements, and then it can serve as a standard for assessing the reliability of the engine and the quality of manufacturing its spare parts.

If we link these models with indirect diagnostic parameters, then it will be possible to obtain quantitative indicators of the technical condition of the engine during the on-site diagnostics.

Special operational thermal tests of the main engine of the motor ship «Rostov» (vessel of the «Astrakhan» series) of the MAN type K5SZ70/125-V made it possible, using ship documents, to develop an approximate model of the technical condition of this engine, which can be extended to ships of this series. The engine type K5SZ70/125-V has a continuous power of 7600 kW at a speed of

145 min-1. In this case, the average effective pressure is 1,31 MPa, and the purge air pressure is 0,21MPa.

The measurement of cylinder liner pumps made it possible to obtain, over a period of operation of about 20 thousand hours, a characteristic diagram of their wear along the generatrix (Figure 1), from which it can be seen that the greatest wear of the liner occurs in the second measurement zone at a distance of 40 mm from its shoulder. Obviously, this belt is decisive in assessing the performance of the bushing, the wear limit of which, according to the manufacturer's data, is 4,5 mm.

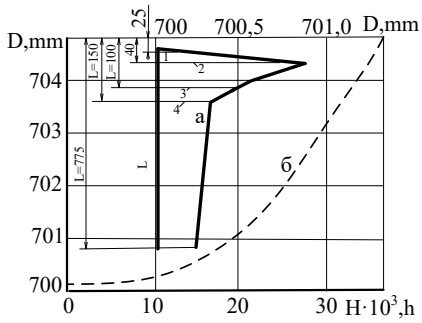

Fig.1 Dependence of the change in the diameter of the cylinder liner D of the engine K5SZ70/120-V from H: a - diagram of wear of the cylinder sleeve along the generatrix, obtained from the measurement belts L from the shoulder of the sleeve (1,2,3,4,5); b-extrapolation of the experimental dependence for resource prediction

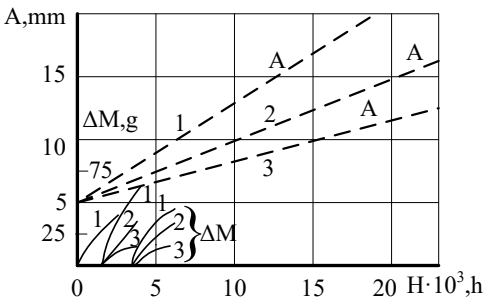

Fig. 2. Changing the gaps in the caps of the piston B of the K5SZ70/120-V engine depending on the operating time H: 1 and 2 - gaps in the piston caps at rings No.1,2 and 3,4,5; 3- gaps in the piston caps at ring No.6; — — — - extrapolation of dependencies for predicting the piston resource

Wear data of three cylinder bushings in two sections along the connecting rod and along the engine axis make it possible to obtain the dynamics of the increase in the diameter of the bushing over a period of operation of about 20 thousand hours (Figure 1). Extrapolating this curve to the level of the maximum allowable clearance, we obtain a bushing life of no more than 40 thousand hours. The average maximum wear rate of the bushing for the period under study is determined by the value of 0,12 mm/1000 h, which also predetermines its service life of about 40 thousand hours. The piston resource is estimated by the wear of the piston grooves. The decisive factor is the gap between the piston ring and the piston groove. According to the manufacturer, the maximum average clearance for the two upper rings is 1,2 mm, and the maximum allowable is 2 mm. For the next three rings, the allowable gap is 1 mm, and for the lower oil ring, an average gap of not more than 0,4 mm is allowed.

Operating experience shows that piston rings wear very little in height. In addition, they are replaced after 15÷20 thousand hours of work. Therefore, the determining value for assessing the life of the piston is the gap between the ring and the piston groove - the width of this annular groove. The results of measuring the gaps between the piston groove and the piston ring for different groups of rings give a certain pattern of piston wear within the operating period of about 20 thousand hours (Figure 2). The average rate of wear of the grooves in height obtained during testing for the two upper rings is 0,03 mm/100 h, for the three subsequent rings 0,025 mm/thousand h and for the lower ring 0,003 mm/thousand h. If we extrapolate the obtained dependences of actual wear, we will obtain a piston resource of about 40 thousand hours for the two main groups of rings.

In addition to the wear of the piston grooves, the guide bronze rings on the piston bore wear out, which wear out on the starboard side for 20 thousand hours by about 3% of their perimeter with a wear value of not more than 0,2 mm. Of all the parts of the CPG, the piston ring wears out the most with a loss of mass from 34 to 3 g per 1000 h of operation, depending on their location on the piston.

The top ring is chrome plated, but it and the next two rings still wear the most. The amount of wear of the rings is greatly influenced by the quality and viscosity of the fuel. With the use of lower quality fuel with a viscosity of 190 mm/s at 500C instead of fuel with a viscosity of 90÷100 mm/s at 500C, the wear rate of the rings more than doubles - on average 8 to 17 g/1000 h. Each of the rings, depending on from the location on the piston and the fuel used, it wears out at different rates (see table 1).

Table 1. Wear rate

Cylinder number	Fuel viscosity, mm2/s	Ring numbers (top to bottom)						Mean
		1	2	3	4	5	6	
3	190	33.8	33.8	14.4	10.7	18.4	2.3	19.1
	100	20.3	11.0	8.4	5.1	5.9	1.7	8.7
4	190	21.5	22.3	21.5	7.7	13.8	3.1	15.0
	100	11.8	8.4	10.2	0	5.9	1.3	6.2

The farther the ring is removed from the combustion chamber, the less its wear, which indicates a significant effect of gas pressure and ring temperature on the amount of its wear. The table shows that the wear rate of the piston rings in cylinder No. 3 is greater than the wear rates of the rings in cylinder No. 4. This is explained by the fact that these cylinders in operation had different loads, and the difference in loads exceeded the allowable one and amounted to 6÷7%, and the difference in the maximum pressure values was 8÷9%.

Such a difference in the loads on these cylinders was forced to be preserved before the start of the tests due to the lack of the possibility of re-adjusting the engine. Thus, it is obvious that the wear of the piston rings significantly depends on the engine load, i.e. on the pressure of gases and their thermal state.

When specified in the load, the wear rate of the two upper rings of the loaded cylinder No. 3 increases by 30÷35%, and on average for a set of rings - by 20÷25%. This once again confirms the dependence of the amount of piston ring wear on the pressure of gases on it and the effect of temperature on it.

However, under operating conditions, during cleaning, piston rings are not weighed, and their technical condition is assessed mainly by changing the gap in the lock. This indicator is less informative than the mass loss of the ring obtained by weighing, but the criterion here is the degree of compression pressure drop. So, for this engine, the manufacturer has set the allowable clearance in the locks of the rings of 20 mm. The initial gap for five rings is set to $5{,}7^{+0{,}5}$ mm and for the top – $6{,}5^{+0{,}5}$ mm. The change in the gap in the lock, as well as the loss

of mass of the ring, is proportional to the operating time of the engine, all other things being equal (Figure 3).

If we extrapolate the change in the gaps in the locks for different groups of rings, then upon reaching 20 mm, you can get the resources of each of the groups. So, for rings No. 1,2 and 3, it is approximately 17 thousand hours, for rings No. 4 and 5 - about 26 thousand hours and for ring No. 6 - about 35÷40 thousand hours. The measurement of the rings in three sections shows that the wear of the ring occurs mainly along its width and averages 0,1 mm/1000 h.

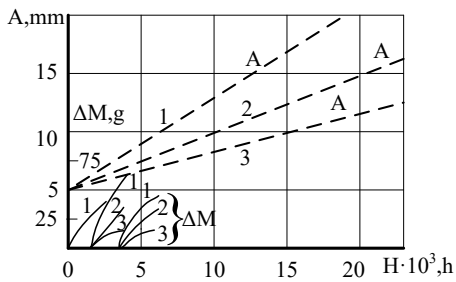

Fig. 3. Dependences of the change in the gap in the lock of the piston rings A and the mass loss of the piston rings ΔM on the operating time H: piston rings: 1-No. 1,2,3; 2- No 4.5; 3- No 6; — — — - extra-trapolation of dependencies for predicting the resource of piston rings

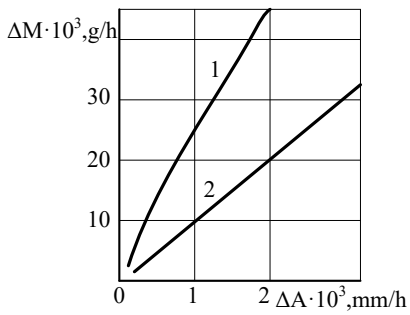

Fig. 4. Relationship between the lost mass of the piston ring ΔM of the K5SZ70/120-V engine and the value of the gap increase in the lock ΔA: piston rings: 1-No. 1,2,3,4,5; 2-No 6

There is a need to link at least two indicators: the loss of mass and the gap in the lock. The obtained dependence (Figure 4) allows us to determine for different rings the approximate mass loss of the ring with an increase in the lock by 1 mm, which for rings No. 1,2,3, 4 and 5 is 23÷24 g, and for ring No. 6 - within 10÷11 g. In this case, it turns out that with an increase in the gap in the lock from the initial 6 mm to the maximum allowable 20 mm, the ring loses a mass of 336 g, i.e. 8.6% of the total mass of the ring 3900 g. You can set the specific mass loss of the ring from its total mass per 1 mm increase in the gap in the lock, which will be 0.6% for the upper rings and 0.3% for the lower ring.

The need for disassembly of the engine is dictated mainly by the amount of deposits deposited on the parts of the CPG, and the replacement of worn parts is timed to coincide with these disassemblies.

Estimates of the rate and dynamics of carbon deposits make it possible to supplement the model of the technical condition of the engine with the characteristics of carbon formation. They will significantly depend on the type of fuel used and engine operating modes. During these tests, the amount of deposits deposited over a certain period was determined by removing them during cleaning and weighing. When operating on high-viscosity fuel (it was about 180 mm^2/s), the largest amount of deposits is deposited on the bottom of the cylinder cover and is approximately 180 g / 1000 h (Figure 5, a). During the period between cleanings, the maximum amount of carbon deposits on the cover will be 1300÷1500 g with a linear increase in the amount of carbon deposits from the engine running time.

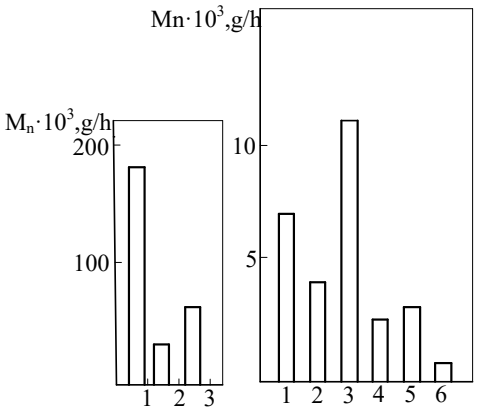

Fig. 5. Average statistical data on the mass of deposits Mn on the parts of the CPG(a) and on the piston rings (b) of the K5SZ70/120-V engine, related to 1000 hours of operation: 1-cylinder cover (bottom); 2-piston bottom; 3-side (cylindrical) surface of the piston; 1-6 - numbers of piston rings (from top to bottom)

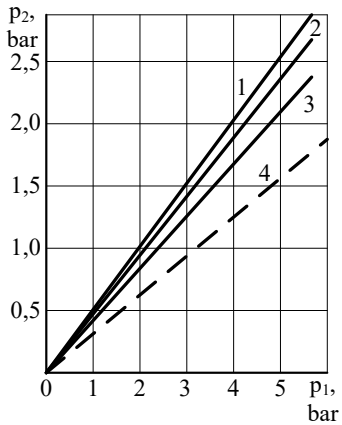

Fig. 6. Results of purge of the cylinders of the K5SZ70/120-V engine with a pneumatic indicator (p1-initial pressure in front of the pneumatic indicator, p2-pressure of the resistance of the cylinder to air leakage): cylinders: 1-No.4; 2- No.3 and 5; 3-No.1 and 2; 4- limiting pneumohydraulic characteristic of the cylinder

To a lesser extent deposits are deposited on the piston crown (approximately 20 g/1000 h). On the side surface on the head and on the trunk part, the amount of deposits is 80 g/1000 h. It depends mainly on the quality of the cylinder lubricant and its dosage. The resulting rates of carbon formation can be considered standard, at which cylinder cleaning is carried out after 7÷8 thousand hours, when fuel with a viscosity of 140÷180 mm/s is used.

A characteristic piston defect in the K5SZ 70/125-V engine is the burnout of the bottom in the places where the fuel jets of the nozzle hit the piston. In these places, under the imprints of the jets, oval recesses are formed with the largest burnouts on the port side and closer to the stern. For 10 thousand hours of operation, the maximum burnout value was 3,5 mm. With a minimum wall thickness of 20 mm, a threatening thickness of 10 mm can reach the piston in 60 thousand hours.

The presence of deposits in these places no thicker than 0,2 mm creates favorable conditions for cooling the bottom. Another thing is the burning of the piston along the periphery of the head in places where carbon deposits from cylinder oil are deposited. Along the generatrix of the cylinder sleeve, at the points of supply of cylinder lubrication, recesses up to 0,5 mm deep are formed from deposits deposited opposite the points of supply of lubricant on the piston head. These deposits of high hardness reach a thickness of 2 mm and wear out the bushing when the piston moves. On the piston, under the deposits of these deposits, burnouts form due to overheating. The reason for these burnouts is associated with overheating of the piston in the region of the periphery of the piston head and a high concentration of cylinder oil in the places of its supply.

The deposits on the piston rings are deposited unevenly. The largest amount of them is deposited on ring No.3 and amounts to 11 g/1000 h (Figure 5, b). Deposits on ring No. 1 are deposited at a rate of 7 g/1000 h and on ring No.2 - about 4 g/1000 h. A significant defect in the operation of piston rings is their non-adherence to the cylinder sleeve at the end sections. For this reason, the upper ring of cylinder No.4 was rejected after 6 thousand hours of

operation, in which the non-adherence reached 250 mm. After 2 thousand hours of work on the new ring of this cylinder, the non-adherence was 100 mm from each end. On other engine cylinders, the non-adherence of the upper ring for 12÷15 thousand hours of operation reaches 200 mm, and this sometimes causes the rings to be rejected and significantly reduces its performance. As the gas pressure in the cylinder decreases, the non-adherence value of the rings next in height to the piston decreases and usually for ring No.2 it is 70÷80 mm, for ring No.3 - within 40÷50 mm, etc. Obviously, the piston rings for this engine must be adjusted accordingly at the ends in the lock area.

The most significant carbon deposits on the cylinder liner occur in the purge and exhaust ports. Hard deposits are deposited in the outlet windows, which are removed mainly with a chisel and when cleaning with a scraper. The largest amount of soot is deposited on the two extreme exhaust windows, on which, for 1000 hours of operation, the thickness of its lower part reaches 30÷40 mm, and on the remaining windows - up to 20 mm in the lower part, and 5÷10 mm in the middle.

In the purge windows, a soft, loose deposit is deposited, which is easily cleaned off with a scraper. The greatest amount of soot is deposited on three aft windows, where for 1000 hours of operation its thickness reaches 30 mm in the lower part, and from 2 to 5 mm on the remaining windows.

The results of purging the engine cylinders with the help of a pneumoindicator are given in figure 6.

Analysis of the graph shows that cylinder No.4 is the most sealed, which has a new upper piston ring. The satisfactory condition of the cylinders is characterized by the data of the purge of cylinders No.1 and 2, the rings of which have worked for about 4 thousand hours. Curve 4 characterizes the limiting technical state of the cylinder. According to the purge data, we can draw a methodological conclusion that the cylinders should be purged at a supply air pressure of at least 0.4 MPa, when the difference between the cylinders is most pronounced.

3 Results and discussions

Based on the reviewed material, the following conclusions can be drawn on the K5 SZ 70/125-V engine and on the methodology used in this study regarding the development of the engine technical condition model:

1. The wear rate of the cylinder liner in the most wear zone, equal to 0.12 mm/1000 h, determines its resource of about 40 thousand hours, which is clearly not enough for a modern main engine, and therefore, during operation, one should look for ways to increase its resource by choosing optimal fuels, adjustment and dosage of cylinder oil supply and optimization of its operating modes.

2. The piston resource, determined by the wear of the annular grooves, which is approximately 40 thousand hours for a modern main engine, is also insufficient. Ways to increase the resource lie in ensuring optimal engine operation modes, optimizing the dosage of oil supply and ensuring uniform distribution of the oil film around the cylinder perimeter.

3. The resource of piston rings depends on a large number of factors, including fuel quality and viscosity, oil dosage, engine operating modes and loads. It also depends on the location of the rings on the piston, the pressure of the gases and their thermal state.

4. The greatest amount of carbon deposits is deposited on the cylinder cover when operating on high-viscosity fuel, deposits on the bottom of the piston are insignificant, but burnouts occur under fuel jets, and carbon deposits are deposited on the trunk part of the piston two times less than on the cover.

5. The largest amount of deposits is deposited on ring No.3. Piston rings have a non-adherence to the sleeve along the edges of the ring in the lock area, which sometimes causes them to be rejected.

6. To eliminate intense carbon deposits on the purge and exhaust ports of the cylinder liner, as well as to reduce carbon formation on CPG parts, a device for applying washing liquid should be installed in the purge receiver.

4 Conclusion

The use of quantitative characteristics of the wear of CPG parts and data on carbon deposits in the engine cylinder obtained as a result of operational observations during collapsible diagnostics makes it possible to create a unified model of the technical condition of an engine of a certain type to predict the resources of spare parts and regulate the frequency of maintenance, increasing thereby driving reliability of the engine.

References

1. RD 31.22.01-81 "The quality of the technical means of the vessels of the Ministry of the Navy. The system of collection, generalization and use of information about reliability. Basic provisions, as well as the results of various heat engineering and special tests "
2. Geissler S., Durier F, REHVA European HVAC Journal. **2**. 9-12 (2017)
3. Rakhmatova M. U., Ergashev H. A., Young scientist **9,** 270-271 (2016)
4. M.T Chaichan, IOSR Journal of Mechanical and Civil Engineering **12**, 6, 72-79 (2015)
5. Senchenkov V.I., Models, methods and algorithms for the analysis of technical condition. (Saarbrücken: LAP LAMBERT Academic Publishing, 2013)
6. Capozzoli A., Lauro F., Khan I., Expert Systems with Applications **9,** 4324-4338 (2015)
7. Guoliang Lu, Yiqi Zhou, Changhou Lu, Xueyong Li., Mechanical Systems and Signal Processing **83**, 533-548 (2017)
8. Saadat B., Kouzou A., Guemana M., Hafaifa A., Diagnostics **18(2),** 3-11 (2017)
9. Muscat Jo, Functional Analysis: An Introduction to Metric Spaces, Hilbert Spaces, and Banach Algebras (Springer, 2014)
10. Absalyamov D.R., Engineering and construction magazine **2(28).** 39-47 (2012)
11. A. Mattiussi, M. Rosano, P. Simeoni, Decision Support Systems **57**, 150-159 (2014)
12. S. Plitsos, P.P. Repoussis, I. Mourtos, Christos D., Decision Support Systems **93**, 88-97 (2017)
13. Hsiao-Hui Lee, Jianer Zhou, Po-Hsuan Hsu, Decision Support Systems **76**, 35-44 (2015)
14. Alyasiri, A.M.M., Kurnaz, S. *Passive islanding detection in microgrids using artificial neural networks.* Apple Nanosci (2022). https://doi.org/10.1007/s13204-021-02197-5