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Efficiency improvement of locomotive-type diesel engine operation due to introduction of resource-saving technologies for cleaning diesel and diesel locomotive systems

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Abstract

The influence of carbonic deposits on indices of diesel engine operation has been investigated. The technology of clean-in-place of fuel system, fuel injection equipment and cylinder-piston group of diesel locomotive engines using special cleaning agent has been developed on the basis of the analysis of mechanisms of the formation and accumulation of carbonic deposits on the parts and the elements of a diesel engine systems. The task concerning the choice of scientifically grounded terms of clean-in-place technology application has been solved relying on the experience of a developed mathematical model usage. The conclusion as to the possibility of making changes in the technology of maintenance and the increase of a diesel locomotive overhaul life has been made.

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Keywords: Carbonic deposits; Clean-in-place technology; Cleaning agent; Overhaul life increase.

1. Introduction

A global approach to the problem of lifetime is formed according to the strategy: resource is an economic category, not technical. The sense of this saying is that in the course of operating the resource, critical places can come into being in the structure which determine the level of the efficiency and the safety of operation.

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Critical places of the structure are fine-tuned during overhauls or recurrent maintenance, that can be done ad infinitum. The main criterion lies in the fact that the level of efficiency and safety must not decrease during lifetime. It is necessary to detect the beginning of efficiency decrease or failure of extremely responsible component parts that lead to emergency situations in time [1–4]. Naturally, the volume of works on supporting the efficiency and the level of safe operation inevitably increases with the increase of lifetime. The main factor when withdrawing traction rolling stock from service is obsolescence and earnings dilution due to the growing volume of additional works on supporting the efficiency level and traffic safety.

Under these conditions, the task to control technical condition of locomotives by means of the correction of the period of preventive and maintenance measures taking into account changing their technical condition and volumes of the works performed is getting more and more important.

2. Analysis

The given work is directed to the improvement of a very important stage of technological process of diesel locomotive maintenance – supporting the fuel-supply system of diesel engines in a satisfactory technical state. While operating diesel locomotives, deposits and accumulation of fouling of different structures and various building mechanisms takes place on the surfaces of the fuel-supply system elements. The accumulation of fouling on the elements of a diesel engine and diesel locomotive systems leads to the alteration of characteristics and the indices of a power plant performance and in separate cases can affect substantially a diesel engine lifetime in general.

By reference to the reviews of the works dedicated to the topic of the research, one can make the following conclusions:

- The structure of carbonic deposits depends on the structure of an engine, the place of formation, the type of fuel injection equipment, the type of petrol, the quality of oil [5–8]
- The problem is still acute for diesel engines of a new generation as well including the ones having fuel injection systems with Common Rail microprocessor control [9]
- The solution of the problems connected with carbonic deposit formation by means of changing the structure of diesel engines, utilizing various types of petrol and oil is not completely possible [10,11]

The existing maintenance technology does not anticipate the possibility to prevent the excessive deposit of fouling and in general comes to the removal connected with the stripping of elements or disassembling of diesel engine and diesel locomotive mechanisms (these operations are tightly tied to maintenance (MNT) diesel locomotives). Besides, mechanical carbon removal leads to the additional wear and tear of a cylinder-piston group and the damage of the protective coating of pistons.

That is why it is necessary to develop a method of optimal decision-making according to the cyclicity and the nature of carrying out preventive cleaning of diesel locomotive systems taking into account working conditions and operating modes.

3. Purpose and the tasks of the research

The purpose of the present work is the improvement of the technology of locomotives servicing due to the introduction of clean-in-place of fuel-supply system of a diesel engine and a cylinder-piston group (CPG) of a diesel engine. It will help increase the utilization efficiency, the reliability of locomotives and decrease the service and maintenance expenses. To achieve the target goal in the research it was necessary to solve the following tasks:

- To develop a structural-logical scheme of the influence of diesel fuel chemical transformations on the nods of a diesel engine and its systems; to make analysis of the formation and accumulation mechanisms of carbonic deposits on the elements of a fuel system, fuel injection equipment and CPG of a diesel engine
- To ground theoretically and to test experimentally analytical dependences which make it possible to estimate the level of fouling of the most important elements of a fuel-supply system (in a function)

- To analyze (by means of experimental research) the influence of the fouling of fuel-supply system elements, fuel injection equipment and CPG of a diesel engine on the alteration of their characteristics and the parameters of work
- To develop means of clean-in-place of fuel-supply system elements, fuel injection equipment and CPG of a diesel engine and to test it in laboratory and field conditions
- To solve the task of the choice of scientifically grounded terms of a clean-in-place technology application on the basis of the developed mathematical model

4. The main part of study

The conducted research of the distribution of the time necessary for the performance of works while carrying out routine maintenance to the extent of MNT (see Fig. 1) showed that the substantial part of works accounts for fuel-supply system, fuel injection equipment and a diesel engine.

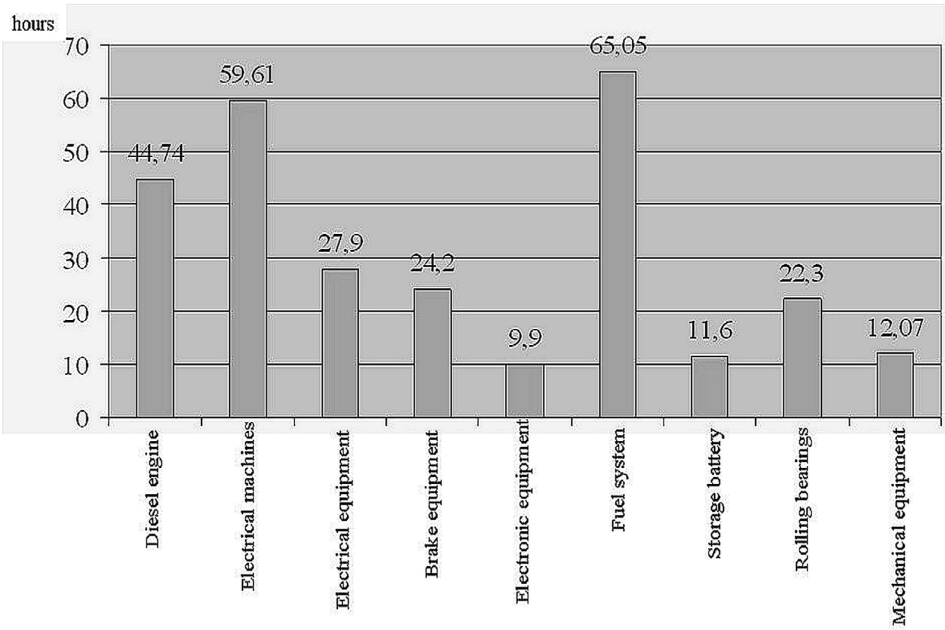

Fig. 1. The distribution of time necessary for the performance of works while carrying out routine maintenance (ТО-3 and ПР-1) of shunting locomotives.

Structural-logistics scheme of the influence of chemical transformations of diesel fuel on a diesel engine systems and its nods (presented in Fig. 2) has been developed as a result of the analysis of the works [12-16]. The analysis of the works [17-19] and visual inspection of the state of a diesel engine nods while repairing showed that the formation and accumulation of carbonic deposits on different elements of a diesel engine have various mechanisms, different structure and primary components. So, two kinds of deposits are typical for a fuel injector nozzle: deposits of carbon and deposits of gum, for high pressure fuel pump which are typical only for lacquer-like and gum-like deposits.

Carbon in nozzles is accumulated in holes of an injector spray nozzle, and gum deposits is accumulated in other zones of fuel injector nozzles, Fig. 3. The deposit that is formed in injector spray nozzles is of a fuel nature and it differs from the carbon of oil origin. It consists of carbenes and carboids, sulfur compounds, ashes and mechanical impurities of inorganic origin which are evenly spread throughout all the carbon layer. The knowledge of the mechanisms of carbonic deposit formation and structure is of great importance for the organization of diesel locomotive engine operation during all their lifetime. The nature of deposit formation is still the subject of intensive research within the frames of physics and chemistry of the phenomena taking place in condensed media with different scale of structural ordering. Despite the existing today number of hypotheses and assumptions there is no generally accepted conception as to the deposit formation and the structure of carbonic deposits so far. In general terms the solution of the problem of the improvement of diesel locomotive technical operation efficiency nowadays is realized in two ways. According to the principles of carrying out activities to prevent from fouling or remove its components from fuel system, fuel-injection equipment and CPG of an engine, the activities can be divided into two main groups.

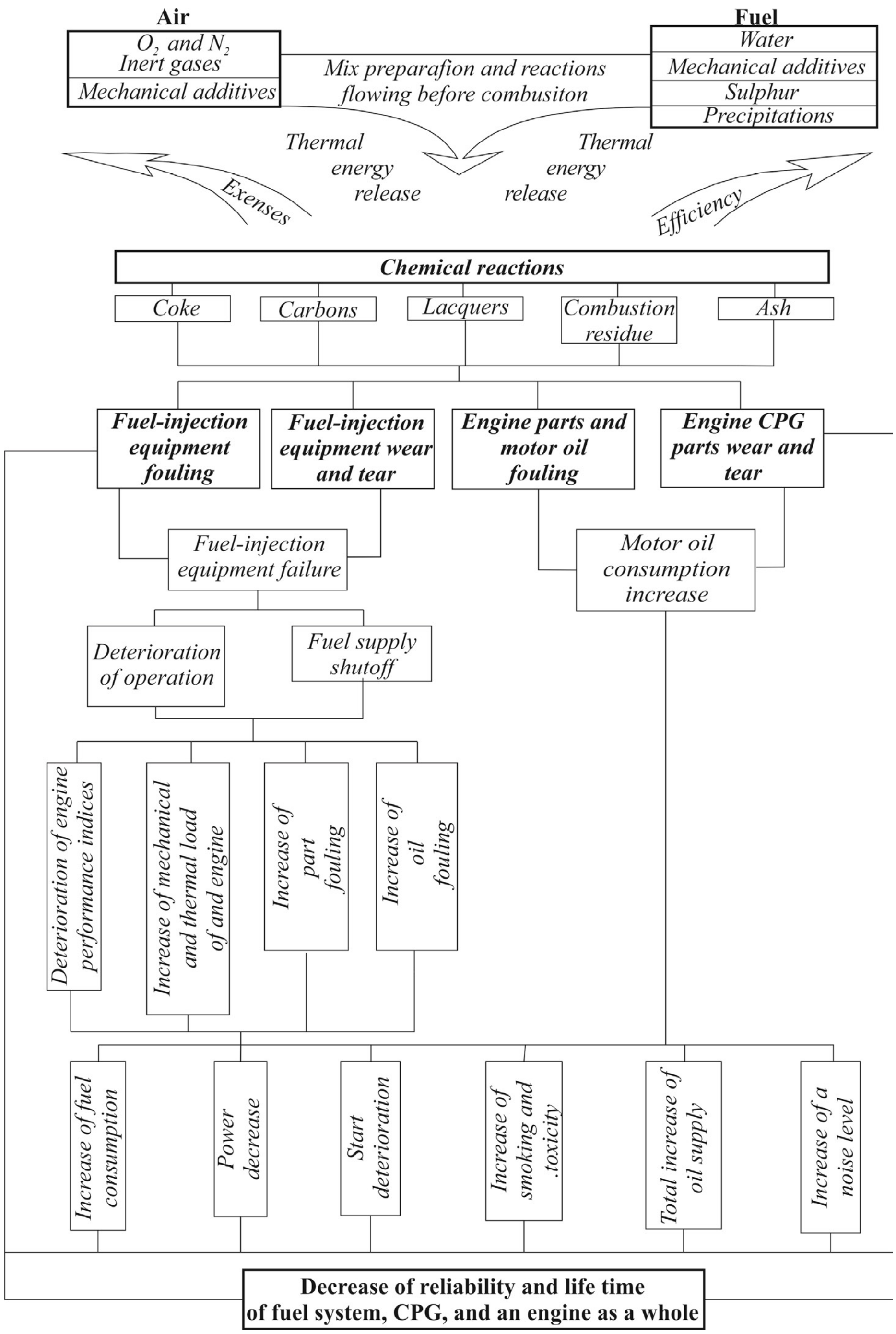

Fig. 2. Structural-logical scheme of the influence of chemical transformations of diesel fuel on a diesel engine systems and its nods.

Technical means and technologies used while operating a vehicle: coarse and fine fuel filters; the utilization of fuel detergent additives can be referred to the first group.

The second group incorporates various technologies of cleaning the fuel system and CPG of an engine while conducting maintenance activities. The so-called clean-in-place technologies of cleaning fuel system and CPG are getting more and more popular. The specialists of UkrSURT (the Department of OMRS with Tartakovsky E.D. as the chief), locomotive facilities of Ukrzaliznytsia, SPA «TOP» has developed a clean-in-place technology of cleaning fuel systems and CPG using special cleansing agents [20].

Fig. 3. The structure of carbon on an injector spray nozzle (magnified by a factor of 250).

The developed technology has undergone a number of tests [21] organized and carried out to determine the efficiency.

The technology testing took place simultaneously in several directions in order to estimate the influence of a cleaning agent on carbonic deposits and the application of clean-in-place technology on:

- The indices of a diesel engine performance under stationary tests
- Technical state of a fuel system and fuel-injection equipment
- The indices of diesel locomotive field operation

Thus, to remove fouling from the surfaces of an engine, a cleaning agent possessing high surface-active properties at first, pushes the fouling off the surface and then disperses particles and converts them into a solubilized state [22]. To determine the influence of a cleaning agent on carbonic deposits, the investigations of physics-chemical properties of original diesel fuel and the mixture of diesel fuel with a cleaning agent before and after the conducting the cleaning of fuel systems under laboratory conditions have been carried out. Such physics-chemical indices as size range, concentration of actual gums, ash content, carbonization of a 10% residue. The results of laboratory investigations let us make a conclusion that a cleaning agent removes not only gum deposits of organic compositions but mineral (ashes) as well from the surface of a diesel engine fuel-supply system contacting with diesel fuel. The following facts demonstrate this:

- The increase of the content of gum substances in the mixture of fuel with a cleaning agent from 4 mg per 100 cm^3 before cleaning fuel system up to 742 mg after cleaning, i.e. by a factor of 185
- The increase of ash content of these mixtures from 0,004% to 0,008%, i.e. twice
- The increase of the “carbonization” index from 0,2% before cleaning to 1,77% after cleaning, i.e. by a factor of 8,85

The estimation of the influence of clean-in-place technology application on the technical state of a fuel system and fuel-injection equipment was held by means of testing diesel locomotive engine nozzles on the test bench of A106 type before and after the application of clean-in-place technology. The pressure of injection, hydraulic compactness of nozzles as well as the quality of fuel spaying by the nozzles were controlled attesting. The results of the test showed that the application of clean-in-place technology had not influenced the injection pressure and hydraulic compactness of nozzles. The quality of spraying is estimated visually, that makes it possible to detect only grave failures in the work of a nozzle. To estimate the influence of clean-in-place technology application on the quality of fuel spraying, it is necessary to apply a more accurate and reliable method [23]. To determine the effect of clean-in-place technology on the quality of fuel spraying, the method of drop entrapment by glycerin with further microscopic analysis and processing the results with the help of special software was applied at testing.

The research showed that with the pressure of fuel supply being saved, the clean-in-place technology application leads towards the reduction of a drop size. This entails the increase of a specific surface area, acceleration of fuel evaporation and, as a result, the improvement of mixture preparation. While conducting stationary testing of diesel locomotives with clean-in-place technology application, the following tasks that can be expressed through the given array have been formulated:

$$Z = \begin{pmatrix} Z_1 \\ Z_2 \\ Z_3 \end{pmatrix} = \begin{pmatrix} \text{Determination of the main indices of a diesel performance;} \\ \text{Analysis of a technology influence on diesel performance indices,} \\ \text{Giving recommendations as to the possibility of using the measure.} \end{pmatrix} \tag{1}$$

How the indices showing diesel engine performance have been chosen:

- The results of rheostatic testing ($I_{\text{г}}$, $U_{\text{г}}$, $N_{\text{к·в}}$, $P_{\text{г}}$) before and after the application of clean-in-place technology of cleaning fuel system and CPG
- The pressure of compression (P_c)and maximum pressure of combustion (P_z)measured before and after the application of clean-in-place technology of cleaning fuel system and CPG
- Fuel-consumption rate (g_e)before and after the application of clean-in-place technology of cleaning fuel system and CPG
- The concentration of the following contaminants in exhausted gases of a diesel locomotive engine: carbon monoxide (C_{CO}) and nitrogen oxide (C_{NO}), simultaneously the concentrations of carbon dioxide (C_{CO2}) and oxygen were measured additionally (C_{O2})

The analysis of the index alterations chosen to prove the efficiency of clean-in-place technology of cleaning fuel system and CPG has been carried out according to the results of the works. So, the following data have been obtained for the locomotive of CMEZ No.2257series (Poltava locomotive depot):

- The power of diesel-generator of the locomotive after clean-in-place conducting increased by 7,14 % and 3,13 % at positions 7and 8 of control handle position correspondently
- The value of the pressure of compression after clean-in-place conducting increased by 1–2 kg /cm^2
- The value of the pressure of combustion after clean-in-place conducting increased by1–11 kg /cm^2

So, the reduction of the specific fuel-consumption rate made 21,88%, which was ensured at the expense of rehabilitation of the 1st cylinder (the pressure of combustion increased from 59 kg /cm^{2}up to 70 kg /cm^2), and the pressure amplification P_z in cylinders 2-6 as well.

The following results have been obtained according to the selected indices while carrying out works on the locomotive of 2TE116 series No.1505:

- The power of diesel-generator of the locomotive after clean-in-place conducting increased by 11,5% and5,0 %at positions 12 and 13 of control handle position correspondently
- The value of the pressure of compression after clean-in-place conducting increased by 1-4 kg /cm^2
- The value of the pressure of combustion after clean-in-place conducting increased by1-4 kg /cm^2

Additionally, the weighing of a cleansing filter element of fine filters before and after the application of clean-in-place technology of cleaning fuel system and CPG (4 of 8 cleansing filter elements mounted on a diesel engine have been weighed) has been done. The weighing fixed weight increase at the expense of contaminant accumulation by 191,6g. A corrected overhaul life schedule of locomotives of 2TE116, CMEZ series has been developed according to the results of the works conducted.

To adopt the clean-in-place technology into the system of maintenance and preventive measures of locomotives, it is necessary to solve the task of choosing scientifically grounded terms of its application.

The development of a mathematical model of an object was conducted by means of the methods of a regression analysis on the basis of the methods of mathematical statistics corresponding to the appropriate physical laws of a production facility– the fuel supply system– functioning.

In general terms, the formula of a functional connection between “inlet” and “outlet” can be expressed by a function

$$y = f(x_1, x_2, \ldots, x_i, \ldots, x_u) \tag{2}$$

where y is a dependent variable and x_i is an independent variable.

The factors of the influence of carbonic deposits on the fuel supply system are the change of effective total internal cross section of high-pressure piping and nozzles.
In our case the expression (2) will be:

$$q_{ö} = f(\mu f_{ÏÏ}\ , \mu f_{Ô}, \mathrm{T}) \tag{3}$$

where $\mu f_{ÏÏ}$ is an efficient section of a fuel pipe m^2, $\mu f_{Ô}$ is an efficient section of an injector spraynozzlem^2 and T is a shunting locomotive run, days.

To construct a mathematical model of the connection between a response quantity to be measured y and the controlled variable factors $f=(x_1,\ldots, x_i)$ one can apply regressive analysis methods as the results of measurement y_u, $u=1,\ldots,N$ are independent, normally distributed random values, the dispersion of responses in different points i of a factor space is the same and does not depend on the absolute values y_u, the factors are measured with a negligible error in the comparison with an error while determining y.

The levels of factors are boundary and mean values of the alteration of an effective internal cross section of fuel-injection equipment elements caused by carbonic deposits. The value of the factors corresponding to these levels and the codes of these levels are given in Table 1.

Table 1. The value of the factors.

Factor levels	Level code	Factors		
		Effective internal cross section of a high-pressure fuel pipe $\mu f_{ÏÏ}$	Effective internal cross section of a nozzle $\mu f_{Ô}$	Diesel locomotive run T, days
Main	0	5,5	0,52	225
Upper	+1	6,7	0,64	450
Lower	-1	4,3	0,41	0

After conducting experimental researches, a regression equation which describes the alteration of injection rate in accordance with the chosen parameters has been obtained. After taking into account the coefficients of significance at each component, the given equation gets the form of a second-order polynomial. It is evident from the analysis of the influence of hydraulic resistances on the response function, performed with the help of full-scale and estimated experiments that linear approximation is not enough, that is why the second-order polynomial is taken as an approximating function.

The residual form of the obtained equation will look like:

$$\begin{aligned} y &= 1.46 + 0.021\, x_1 + 0.124\, x_2 + 0.055\, x_3 + 0.006\, x_1 x_2 - 0.0012\, x_1 x_3 - \\ &- 0.048\, x_2 x_3 - 0.012\, x_1^2 - 0.005\, x_2^2 + 0.006\, x_3^2 \end{aligned} \tag{4}$$

The unity of parameters has been chosen by the optimization criterion, namely the error estimation dispersion. A conclusion as to the adequacy of the proposed model can be made on the basis of the F-ratio test utilization.

On the basis of the obtained dependences we can make a conclusion that there is a determined connection, which is prohibitive to ignore by the maintenance system, between the chosen factors and the performance indicators of a fuel supply system and a diesel engine. The data analysis testifies to the fact that the estimation of a fuel efficiency of shunting diesel locomotive engines is not sufficient according to specific fuel consumption at nominal power. It is reasonable to conduct such an assessment according to the mean specific fuel consumption (see Fig. 4):

$$g_{e.ñð} = \sum_{i=1}^{k}\left(G_{Ti}K_i\right) \Big/ \sum_{i=1}^{k}\left(N_{ei}K_i\right). \tag{5}$$

where:

G_{Ti} - is time fuel consumption in *i* mode

K_i -is the coefficient reflecting a time share of the performance in the given mode

N_{ei} - is a diesel engine power in *i* mode

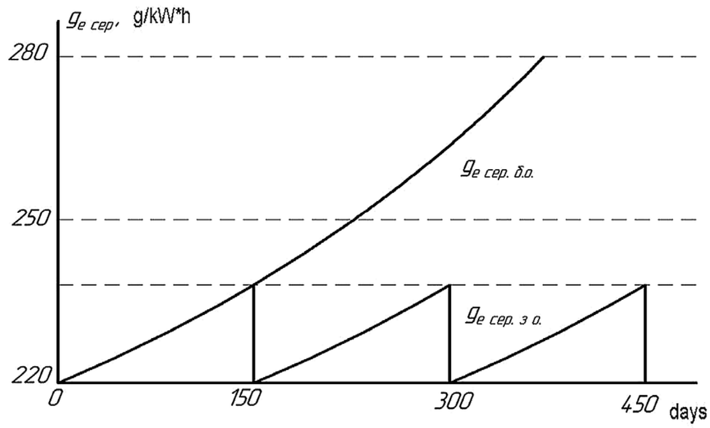

Fig. 4. The dependency of the mean efficient fuel consumption alteration $g_{e.cep}$on a locomotive operating time: $g_{ecep.\ б.о.}$– without cleaning, $g_{e\ з.о.}$ – with cleaning.

To determine the influence of clean-in-place technology on the quality of fuel spraying the method of drop entrapment by glycerin with further microscopic analysis and processing the results with the help of special software was applied at testing.

As a result, it became possible to develop the method of optimum decision making according to the cyclicity and the nature of carrying preventive cleaning of fuel supply systems of diesel locomotive engines from carbonic deposits taking into account working conditions and their operating modes.

The calculations of cost-effectiveness of clean-in-place technology application to clean fuel system and CPG of diesel engines at changing the schedule of diesel locomotive overhaul life have been conducted.

Automated program calculation complex has been developed and it helped determine economic effect from the organization of clean-in-place of a fuel system and CPG of diesel engines of operational diesel locomotive fleet of locomotive depot during base period and the term of lump-sum costs refund. The calculation results are shown in Fig. 5.

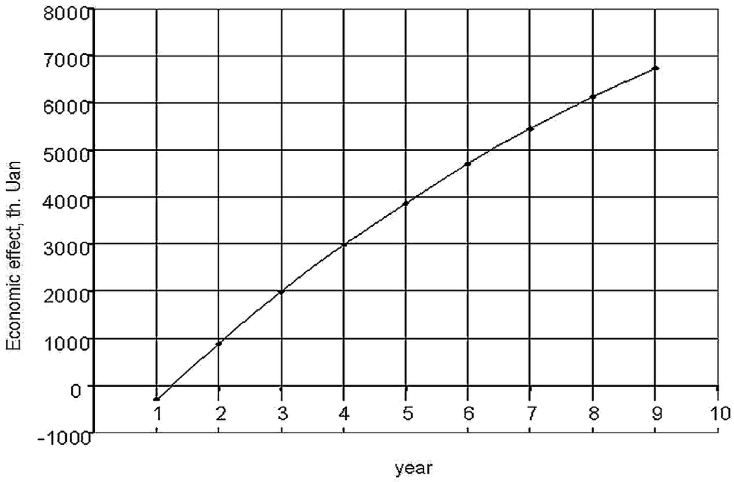

Fig. 5. Economic effect from the organization of clean-in-place of fuel system and CPG of diesel engines of operational diesel locomotive fleet of locomotive depot during base period.

Thus, the economic effect from the organization of clean-in-place of fuel system and CPG of diesel engines of operational diesel locomotive fleet of locomotive depot during base period makes over 6,744 million UAH and the period of lump-sum costs refund does not exceed 1 year.

5. Conclusion

While carrying out the research work on the introduction of clean-in-place technology the following has been fulfilled:

- The substantial influence of carbonic deposits on the chosen indices of diesel engine performance has been proven experimentally, namely:
  - Combustion pressure
  - Compression pressure
  - Power of diesel-generator
  - Specific fuel consumption

  The given indices have been chosen with the purpose of determining the efficiency of clean-in-place technology application and its influence on a technical state of fuel system an CPG of locomotives under operating conditions.
- The analytical dependency that makes it possible to estimate the level of fouling of the most important elements of fuel-supply systems has been theoretically grounded and experimentally tested. It is recommended to determine the grounded terms of clean-in-place technology application on the basis of this dependency. It has been proved that within the period between carrying out MNT, the changes of technical state of fuel-injection equipment and CPG that took place after the first application of clean-in-place technology remain the same or change insignificantly. That is why the second cleaning must be carried out in 3-4 MNT.
- The clean-in-place technology for cleaning fuel systems and CPG of diesel locomotive engines of K6S310DR (6CH31/36)type of a diesel locomotive of CMEZ series and 1A-5D49 (16CH26/26) locomotive of 2TE116 series ensures:
  - The removal of the deposits from the elements of fuel-injection equipment and CPG of diesel engines of the mentioned above types
  - The duration of changes in the technical state of the elements of fuel-injection equipment and CPG during 40-50 days of field operation

- The possibility to estimate the actual technical state of the elements of fuel-injection equipment (high pressure fuel pumps, nozzles) and CPG (cylinder liners, piston rings, inlet and outlet valves) without disassembling according to the alteration of indices of compression pressure in the cylinder P_c and combustion pressure P_z

- The economic effectiveness from the introduction of the clean-in-place technology for cleaning fuel systems and CPG of diesel engines will be higher if to apply it along with other technical means controlling technical state of the given systems of a diesel engine. With reference to the stated above, the conclusions as to the expediency of engineering changes of the system of maintenance and preventive measures of locomotives including the clean-in-place technology have been made. The clean-in-place works are proposed to be carried out twice a year for diesel locomotives which are in constant operation combining them with the routine types of maintenance. The application of the technology is also possible under the deterioration of diesel locomotive fuel efficiency. In this case it is proposed to apply the clean-in-place technology at the nearest Locomotive Technical Inspection No.3.

Thus, with the purpose of the improvement of the locomotive maintenance technology, it is proposed to correct the existing system of servicing and diesel locomotive overhaul life.

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