

МЕТОДЫ И ПРИБОРЫ КОНТРОЛЯ И ДИАГНОСТИКИ МАТЕРИАЛОВ, ИЗДЕЛИЙ, ВЕЩЕСТВ И ПРИРОДНОЙ СРЕДЫ/METHODS AND DEVICES FOR CONTROL AND DIAGNOSTICS OF MATERIALS, PRODUCTS, SUBSTANCES AND THE NATURAL ENVIRONMENT

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THERMAL IMAGING METHOD AS A TYPE OF ROBOTIC DIAGNOSTICS OF HYDRAULIC EXCAVATORS

Research article

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Abstract

The text discusses a type of thermal diagnostics based on the use of thermal cameras for detecting defects in the main components of hydraulic excavators used in mining operations. When hydraulic drives in high-power excavators operate, they generate heat due to turbulence in the hydraulic fluid as it flows through channels, cavities, and pipelines. However, additional heating inevitably occurs when specific defects arise in hydraulic power units, such as hydraulic cylinders and hydraulic equipment like valves and other components. Furthermore, the failure of sealing elements in hydraulic cylinder rods can lead to fluid leaks, which are not visually detectable at the initial stage of defect development. However, these leaks can be identified by measuring the changing thermal background of the sealing unit due to the leaks. Additionally, when filters become clogged or dirty, their housings experience intense heating, which can also be detected by thermal cameras, allowing for early predictions of potential failures. If this diagnostic method is widely adopted, it could lead to the creation of a robotic mechanism for predicting the failure of components and units in hydraulic excavators within a specific mining enterprise.

Keywords: thermal imaging method, robotic diagnostics, hydraulic excavators.

ТЕПЛОВИЗИОННЫЙ МЕТОД КАК ВИД РОБОТИЗИРОВАННОЙ ДИАГНОСТИКИ ГИДРАВЛИЧЕСКИХ ЭКСКАВАТОРОВ

Научная статья

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Аннотация

Рассмотрен вид тепловой диагностики, основанный на применении тепловизора для дефектовки основных узлов карьерных гидравлических экскаваторов. При работе гидравлических приводов карьерных экскаваторов большой единичной мощности происходит тепловой нагрев, причиной которого является турбулентность гидравлической жидкости при прохождении каналов, полостей и магистралей гидравлических приводов. Однако, дополнительный нагрев неизбежно появляется при возникновении отдельных дефектов гидравлических силовых агрегатов — таких как гидравлических цилиндров, а также гидроаппаратуры — золотников, клапанов и другого. В результате нарушения уплотнительных узлов штоков гидроцилиндров появляется протечки гидрожидкости, которые на первом этапе развития дефекта невозможно визуализировать, но можно дефектовать замерами меняющегося из-за протечек теплового фона уплотнительного узла. Кроме этого, при засоре и загрязнении фильтров происходит интенсивный нагрев их корпусов, который тоже можно обнаружить тепловизором и заранее спрогнозировать возможный их выход из строя. В случае массового применения этого способа диагностирования возможно создание роботизированного механизма прогнозирования выхода из строя агрегатов и узлов карьерных гидравлических экскаваторов в рамках отдельного горного предприятия.

Ключевые слова: тепловизорный метод, роботизированная диагностика, гидравлические экскаваторы.

Introduction

Modern means and methods of early warning (detection) of defects in the components and mechanisms of large (large unit capacity) mining machinery, e.g. quarry, walking, rotary and quarry hydraulic excavators, are based on time-consuming and long-term diagnostic measures such as vibroacoustic, ultrasonic, eddy current and other methods that are quite efficient when used during quite long-term (up to 3–5 shifts) field tests. Since the mining workflow involves large excavators, such “unplanned” downtime of mining equipment economically incurs losses. As new non–destructive testing devices emerge (thermal imagers), it is now possible to take prompt measures for non–destructive testing of operating mining equipment, such as hydraulic mining excavators, without interrupting the production cycle.

Tyazhmashservice company (Krasnoyarsk) specializing in maintenance services for mining equipment for open-pit mining has been actively using the thermal imaging diagnostic method in its activities since 2008 to detect incipient defects in quarry and walking excavators. The results of using this method are described in more detail in the corresponding articles of the author [1], [2], as well as in the textbook for universities [3, P. 277-279] and in the handbook for open-pit mining [4, P. 400-411].

In the period from 2012 to the present, some mining enterprises began to purchase hydraulic excavators with a bucket capacity of 15 to 45 m^3 for their open-pit mining operations. Such excavators are used both in transport stripping and directly in the extraction of solid minerals. As a rule, these excavators are expensive imported products, and any downtime entails serious losses for mining owners. Therefore, the technical support in the operation of such machinery is a top priority for maintenance companies servicing such machines. The early diagnostics of incipient defects for equipment of this type is becoming a very relevant technical issue. The tools of such operational diagnostics include thermal (based on contact thermal sensors of various types) and thermal imaging (based on the contactless use of modern infrared thermal imagers). Thus, the specialists of the Voronezh Industrial University inspected the components of logging machines by thermal study of their hydrostatic transmission oils [5, P. 42-49]. This study has shown the efficiency of using the thermal diagnostic method for fault-finding in transmission components in heavy operating conditions of forest machinery.

In addition, the thermal imaging diagnostic method has already been successfully tested in the energy engineering industry, which has been successfully used in the diagnostics of large transformers [6, P. 337-342].

Taking into account our own experience in applying the thermal imaging method of non-destructive testing of quarry, walking and rotary excavators, as well as that new equipment (quarry hydraulic excavators) is actively employed at coal mines and mining enterprises of the Russian Federation, Tyazhmashservice is introducing its own method of non-destructive testing for main components and mechanisms of quarry hydraulic excavators, based on modern thermal imaging equipment and features of fluid and gas mechanics, which are typical of quarry hydraulic equipment with high installed unit capacity.

Main results

Hydraulic excavators of high unit capacity have occupied an ever-growing share in open-pit mining over the 40-year history of their practical operation. This is facilitated by the constant work of the manufacturers of these excavators aimed at improving the reliability of designs, the durability of individual components and mechanisms, as well as competitiveness in terms of the final cost of ownership. According to estimates by leading mining industry experts, in the near future, the share of hydraulic excavator supplies may reach 70–75% of the total excavator supply. Nevertheless, compared with electro-mechanical shovels, the total service life of hydraulic machines is 0,7–0,8x of the service life of dragline excavators. This is due to the lifetime of hydraulic drives, which, unlike mechanical and electric drives, are much more susceptible to operating conditions and the quality of maintenance. The second reason for the slightly shorter service life of hydraulic excavators compared to mechanical excavators is the low operating culture of hydraulic drives (untimely replacement of hydraulic fluid, filters, sealing assemblies, etc.). In addition, even with such a long service life of hydraulic excavators, emergency breakdowns of these machines occur very often (due to hidden defects), which reduce their already short service life compared to electromechanical excavators. That is why the issues of early warning of possible breakdowns of hydraulic drive elements in hydraulic excavators become especially important when choosing the type of excavators and the economics of their repair and maintenance cycle.

Currently, devices have been developed and are actively used in the diagnostics of technical systems of modern machines and mechanisms, requiring a short period of time to analyze the basic parameters of electrical, mechanical, hydraulic, and other drive units during the operation of a single machine. This article discusses the specifics of using the thermal (thermal imaging) diagnostic method to solve problems in troubleshooting and early warning of malfunctions of hydraulic drives of large hydraulic excavators.

There are various methods for diagnosing defects in hydraulic drives. They can be divided into direct and indirect ones. Direct methods include measurements of pressure, flow rate, and temperature of the hydraulic fluid, as well as the position and speed of the actuator. Indirect methods are vibration, noise (acoustic) characteristics, and the extent of hydraulic fluid contamination. These methods also include the intensity and variability of thermal radiation from hydraulic components and individual hydraulic devices. It is this method that is investigated in this article.

When a hydraulic excavator operates, especially one having a high unit capacity, heat is actively generated. Permanent sources of hydraulic fluid heating in hydraulic drives are pumps, shut-off and control equipment, hydraulic motors, and hydraulic cylinders. In addition to these permanent heat sources, there are additional (discretely appearing and disappearing) sources. They include:

accelerations, vortices, additional turbulence of fluid flows associated with:

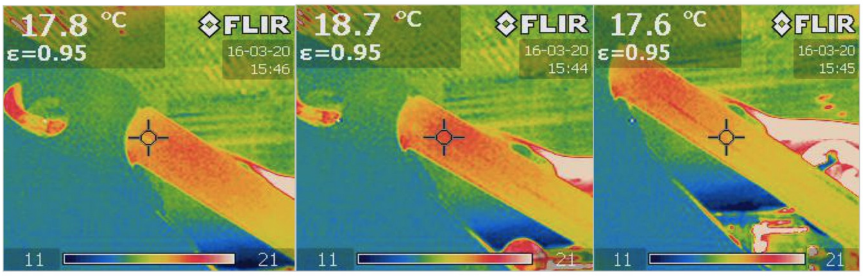
– defects of plunger pairs, spools, valves;
– defects in piston rings, seals, and surfaces of pistons, rods, and cylinders;
– defects in high-pressure hoses;
– filter blockages.

Since the actual method of testing hydraulic drive elements was developed exclusively for the factory conditions of the manufacturer (and also has limited corporate availability), it is almost inapplicable in the field operating conditions of hydraulic excavators. In such conditions, it is necessary to develop from scratch a procedure for operational diagnostics (including thermal imaging diagnostics) of a real hydraulic excavator in active operation. The features of this diagnostic method of hydraulic cylinders and hydraulic devices are:

– the hydraulic drive of the actuator (bucket) must be warmed up, the bucket itself is loaded and statically stationary (the “pressure into the side of the face” position or raised with a loaded rock mass);
– spatial circular capture of the thermal image along the body of the hydraulic cylinder (on all accessible external sides).

When diagnosing high-pressure hoses and filters, the thermal image should be captured with the start of the main pumps, i.e. in the “cold” state of the hydraulic fluid.

Fig. 1 show thermal images of the piston seal of the hydraulic cylinder of the dipper drive with a bucket of 26 cubic meters (“straight shovel” type). The dipper is loaded, the operating pressure in the rod cavity is 200 atm, the drain pressure in the piston cavity is 1 atm; the temperature of the outer surface of the cylinder body in the area of its rod cavity is 17.8 °C (Fig. 1a). Fig. 1b shows the temperature of the cylinder body in the area of its piston of 18.7 °C. Fig. 1c shows the temperature of the outer surface of the cylinder body in the area of its piston cavity of 17.6 °C.



a) *b)* *c)*

Figure 1 - Diagnosis of internal overflows across the piston seal of the dipper hydraulic cylinder:
a) the temperature of the outer surface of the cylinder body in the area of its rod cavity; *b)* the temperature of the cylinder body in the area of its piston; *c)* the temperature of the outer surface of the cylinder body in the area of its piston cavity
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A high temperature of the outer surface of the hydraulic cylinder in the area of the piston assembly indicates the influence of a discrete source of heating of the hydraulic fluid in this area. For a more complete study of the nature of such a heat source, computer software processing of the thermal conditions of the zones adjacent to the piston assembly (before and after the piston), as well as the piston itself in the sealing ring area, was carried out. The program (developed in Russia), based on spectral data from a thermal imager, as well as the geometric and chemical-physical parameters of the walls of the hydraulic cylinder and the piston itself, is able to simulate the temperature conditions of the internal crystal lattices of the cylinder walls and piston sealing assemblies depending on the measured temperatures of the outer layers of these parts. The calculation is based on Fourier’s law called “Thermal conductivity for a cylindrical wall” and can be described by the following formula:

$$q = \frac{Q}{F \cdot t} = \frac{2\pi\lambda(t_1 - t_2)}{\ln \frac{d_{out}}{d_{in}}},$$

where

Q is the heat flow; $\frac{J}{s}$;

q is the density of the heat flow; $\frac{J}{m^2 \cdot s}$;

λ is the the coefficient of thermal conductivity of the material; $\frac{\mathrm{J}}{\mathrm{m \cdot °C}}$.

Using the additional capabilities of the thermal imager, which is compatible with a heat flow sensor (thermograph), it is possible to measure the amount of heat flow passing through the heated part of the outer surface of the hydraulic cylinder and calculate the true temperature of the inner surface of the hydraulic cylinder located opposite the measured outer wall section.

The result of these software studies is shown in the form of installations in Fig. 2.

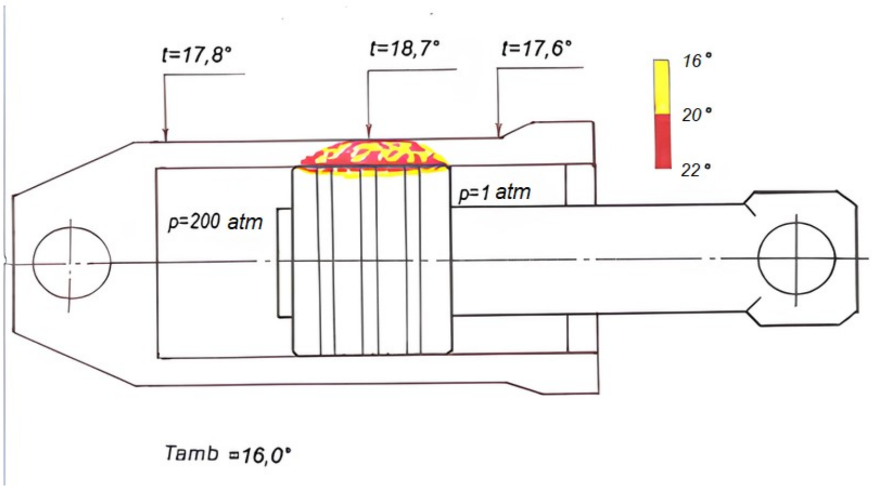

Figure 2 - Model of the internal state of the piston and cylinder
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The above model of the internal state of the piston-cylinder wall friction pair shows a sharp increase in temperature (up to 1 °C) of the outer contact zone of the piston sealing assembly and the cylinder wall at a specific measured location of the cylinder opposite the contact spot. The inner surface of the cylinder in the area of the piston center rose to 36 °C, while the temperature of the cylinder walls at the boundaries of the piston group was 30 °C (the total temperature of the hydraulic fluid inside the cylinder). Such a sharp drop in heating the contact zone can unequivocally indicate a defect in the sealing of the piston group — a strong flow of hydraulic fluid through the seal noted as a result of the partial destruction of the sealing parts.

This overflow reached such a level that the pumping unit was no longer able to develop the operating pressure in the system, with all the resulting losses of hydraulic drive power.

In addition to these, the thermal imaging method allows identifying some other internal defects of hydraulic cylinders.

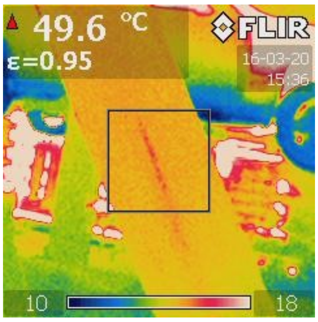


Figure 3 - Incipient defect (burrs of the inner surface of the cylinder)
DOI: https://doi.org/10.60797/ENGIN.2025.9.1.3

Thus, Fig. 3 shows the thermal diagram of the outer surface of the cylinder at the location of the piston. At the same time, the excavator is loaded and stationary. After 10–12 minutes of continuous observation of this area of the cylinder surface, local heating is clearly manifested in the form of a linear strip. This is possible when the hydraulic fluid flows from one cavity to another, not through the piston seal, but through possible grooves and burrs on the inner surface of the cylinder. This thermal diagram shows that there is a defect in the inner (“mirror”) surface of the cylinder — local burrs and furrows that could result from foreign (including metal) particles or abrasives entering the hydraulic fluid.

Internal defects in hydraulic devices, such as valves, spools, distributors, etc., also significantly reduce the efficiency (mainly volumetric and hydraulic) of the hydraulic drive of excavators. As a result of internal overflows in these devices, an abnormal early communication of high-pressure lines with discharge lines occurs. In addition to the loss of power, this also leads to incorrect operation of the shutoff and control elements of the entire drive: instead of smooth controlled movement of the actuator, its operation is jerky, ragged, with deceleration and acceleration, which parameters are sometimes beyond the control of the excavator operator. Fig. 4 shows a model of the internal state of the sliding spool valve of the boom lifting/lowering drive.

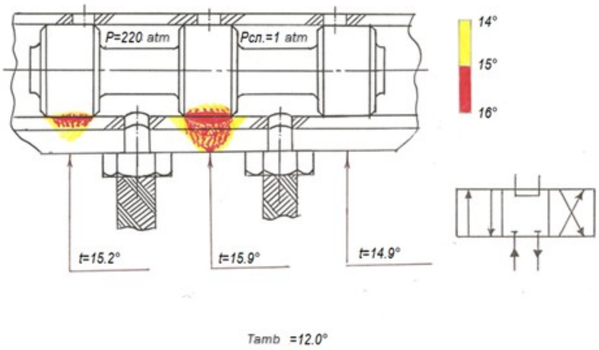
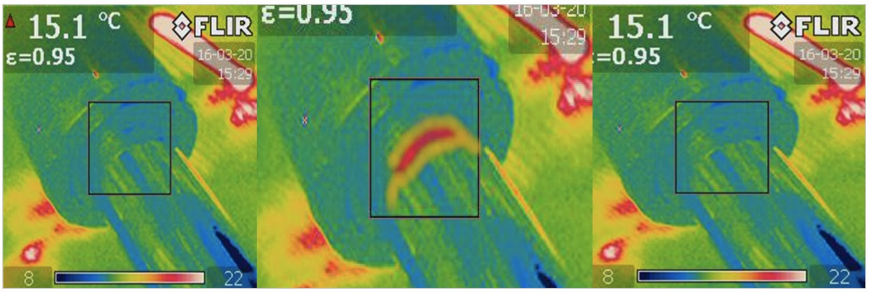


Figure 4 - Model of the internal thermal condition of the sliding spool valve
DOI: https://doi.org/10.60797/ENGIN.2025.9.1.4

The model was obtained as a result of processing the thermal condition of the outer surfaces of the valve housing in the area where the plunger of the main spool pair is located using the computer program mentioned above (on page 3). This model clearly shows that the hydraulic fluid flowing from the pressure line into the drain area through the gaps in the plunger-sleeve pair. Especially significant gaps are found along the central “barrel” of the spool. This is indicated by the characteristic pattern of the difference in the thermal state before and after the alleged defect (up to 1 °C on the outer surface).

The possibility of using the thermal diagnostic method to detect hidden defects in power hydraulic cylinders is illustrated in Fig. 5. Thus, while in Fig. 5a (in “the rod is completely retracted the hydraulic cylinder” position), the thermal conditions of the sealing assembly of the hydraulic cylinder and the cylinder rod of the dipper stick are uniform and correspond to the general thermal conditions of the unit itself, in Fig. 5b in “the rod is extended by 50% of its stroke” position, there is a distinct pattern of high temperature of the surface of the stem seal and the cylinder cover with a temperature difference of up to 1 °C. In Fig. 5c in the “rod extended to the end” position, the temperature again acquires a uniform character, without focal bursts of heating of the mating surfaces. Such a picture of the thermal condition of the lip seal assembly of the hydraulic cylinder cover and its stem may indicate the presence of local leaks in this sealing assembly precisely in the middle of the stem stroke, i.e. when its transverse linear deviation from its own axis of symmetry is maximum. This can only happen in the case of a curvature of the cylinder stem, which occurred earlier under the influence of extreme loads with the maximum elongated position of the dipper stick with the bucket. As a result of the pressure of the curved surface of the rod on the lip assembly, the gap opens on the opposite side of the "lip-cylinder cover" seal pair, which causes additional leaks of the hydraulic fluid, the heating of which is recorded by the thermal imager.



a) *b)* *c)*

Figure 5 - Curvature of the cylinder rod:
a) "the rod is completely retracted the hydraulic cylinder" position; *b)* "the rod is extended by 50% of its stroke" position; *c)* "rod extended to the end" position
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Fig. 6 shows a model of the internal thermal state of the investigated "hydraulic cylinder rod — hydraulic cylinder cover outer lip" assembly. In the middle position of the rod (lower diagram), the high internal temperature of this assembly is clearly visible. This is possible if there is an additional source of heating — leakage of the hydraulic fluid under high operating pressure. This fact, along with the fact that there is no such heating at the extreme points of the rod (retracted and fully extended), confirms the initial conclusion: the rod of the hydraulic cylinder under study has a vertical deviation of its surface position along the horizontal axis, i.e. it is curved. The amount of curvature and the conclusion about the malfunction of the assembly must be made after appropriate linear instrumental measurements.

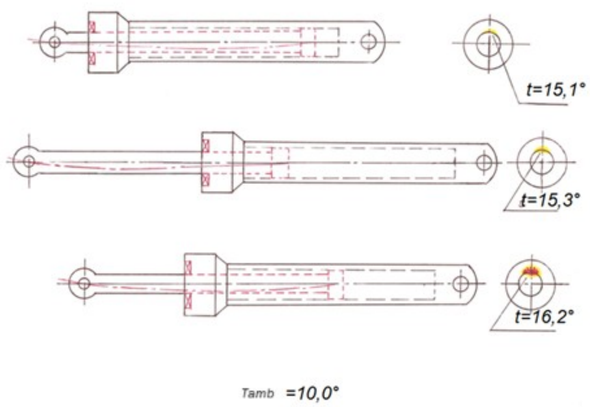
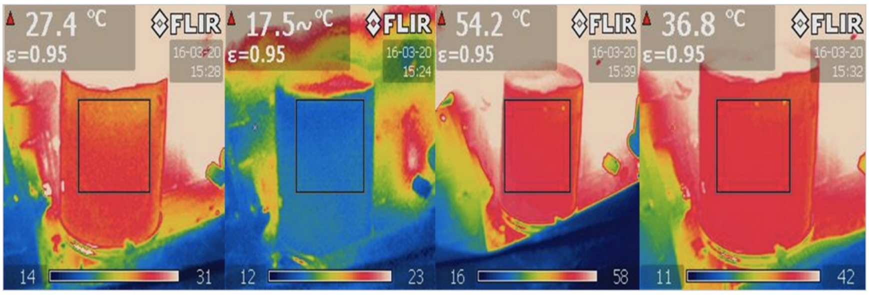


Figure 6 - A model of the internal thermal condition of the rod and the outer lip assembly of the hydraulic cylinder
DOI: https://doi.org/10.60797/ENGIN.2025.9.1.6

Another application of the thermal imaging method is related to the diagnosis of the condition of filters. As we know, when the filter elements of modern filter packages are contaminated, heat is released. This is due to the additional resistance of the contaminated filter packages during the passage of the hydraulic fluid. Fig. 7 illustrate a thermal condition of the filter packages of the main filters of the general hydraulic system of a hydraulic excavator.

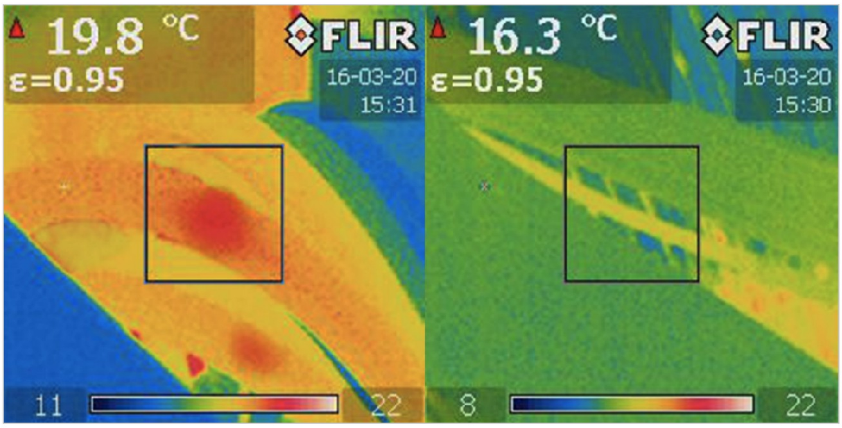


a) *b)* *c)* *d)*

Figure 7 - Diagnostics of filter contamination
DOI: https://doi.org/10.60797/ENGIN.2025.9.1.7

Fig. 7c clearly shows the increased height of the hydraulic fluid passing through the filter. Its temperature rises noticeably during the passage of filter packages due to the contamination of these filter elements (and the associated additional hydraulic resistances). In Fig. 7a and 7d, filter contamination was detected in the inception stage: in an almost critical state in Fig. 7d, in a precritical state in Fig. 7a. The state of the filter in Fig. 7b corresponds to its normal value.

Another area of application of the thermal imaging diagnostic method is the prevention of high-pressure hose bursts.



a) *b)*

Figure 8 - Diagnostics of high-pressure hose bursts:
a) thermal picture of the internal condition of four high-pressure hoses located in parallel and under operating pressure;
b) an example of the normal state of the hose
DOI: https://doi.org/10.60797/ENGIN.2025.9.1.8

Fig. 8a shows a thermal picture of the internal condition of four high-pressure hoses located in parallel and under operating pressure. Because these hoses constantly change their geometry during the movement of the excavator’s actuators, they create additional turbulence of the hydraulic fluid in certain internal sections. The liquid flows gradually “wash out” individual layers of the rubber-cord inner tissues of the hoses, especially in the places of kinks, tear their microstructure, and new oncoming liquid jets continue the process of destroying the inner surface of the hoses. In such places, the liquid is additionally heated, and since the metal-cord-rubber material is particularly thermally conductive, the heating of such sections of high-pressure hoses is well recorded by a thermal imager. The second hose on the left, visible in Fig. 8a, has a critical heating (3 °C higher than the rest of the temperature), and appears almost immediately after starting the hydraulic system and remains stable until it stops. This defect threatens to rupture the hose in this place. A less developed similar defect is observed on the first hose. The third hose is just starting to heat up — there may be a defect in the distant future. The condition of the fourth hose is not alarming. Fig. 8b shows an example of the normal state of the hose — it is heated evenly along its entire length and has no local heating, and hence no zones of internal turbulence.

Thus, the application of the thermal imaging method of operational diagnostics of hydraulic drives of hydraulic excavators allows:

– in a short period of time (no more than 1–2 shifts), getting a picture of the general technical condition of all the main and auxiliary hydraulic drives of an operating excavator;

– compiling a real defective list of hydraulic systems and shut-off and control devices of the excavator being prepared for scheduled repair;

– adjusting the planned shutdown time of the excavator for its repair, both in the longer term and in the shorter term;

– optimizing the costs of the upcoming repairs, in advance, with a certain vision, by logistical preparation for this repair;

– accurately, up to one shift, predicting the duration of the upcoming repair impact.

Conclusion

The possibilities of the proposed type of diagnostics can be expanded by introducing elements of artificial intelligence, such as accumulating an array of statistical data, followed by analysis and prediction of pre-emergency situations for the studied assemblies and mechanisms. In this case, it is proposed to have continuous thermal imaging monitoring of the assemblies discussed in this article among the entire fleet of hydraulic excavators actually operating at a particular mining or coal enterprise. The procedure of such monitoring was developed by the specialists of Tyazhmashservis. The main parameters of this technique are filling in temperature values according to the survey route maps and transmitting them to the processing server. In addition, data is added on the current operating time, total loads and accumulated productivity of a particular excavator, and a number of other data (ambient temperature, total service life of the observed excavator, its actual availability coefficient, etc.). The considered thermal imaging diagnostic method has another advantage: it can identify a potentially dangerous defect in the dynamics of its development by measuring the temperature conditions of the same assembly after several cycles of its operation. If the thermal field rises during its operation, there is a real opportunity to predict the beginning of a pre-emergency situation. The developed digital program (of the “digital override” type) makes it possible, based on the statistical data downloaded from such route maps, to provide a fairly accurate forecast of the technical condition of the monitored assemblies and warn about the possibility and timing of their failure.

The key aspects of this article are unique in terms of scientific novelty, namely:

– the use of an operational thermal imaging diagnostic method to search for early defects in hydraulic drive elements of large-capacity quarry hydraulic excavators;

– the opportunity to use an automatic robotic diagnostic system in a mining enterprise based on the collection and processing of statistical data and introduction of artificial intelligence systems based on early warning of failure of the main components and mechanisms at large mining enterprises.

Конфликт интересов

Не указан.

Рецензия

Все статьи проходят рецензирование. Но рецензент или автор статьи предпочли не публиковать рецензию к этой статье в открытом доступе. Рецензия может быть предоставлена компетентным органам по запросу.

Conflict of Interest

None declared.

Review

All articles are peer-reviewed. But the reviewer or the author of the article chose not to publish a review of this article in the public domain. The review can be provided to the competent authorities upon request.

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