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ДОСЛІДЖЕННЯ ЕКСПЛУАТАЦІЙНОЇ НАДІЙНОСТІ РУКАВІВ ВИСОКОГО ТИСКУ ТЕРМІНАЛЬНИХ ТЯГАЧІВ ПОРТОВИХ КОНТЕЙНЕРНИХ ТЕРМІНАЛІВ

Термінальні тягачі є невід'ємною частиною сучасної портової інфраструктури і незамінним інструментом для портових операцій з перевалки вантажів, де важлива кожна година, а ефективність - ключ до успіху. Кожен термінальний тягач-це не просто машина, а складне інженерне рішення, розроблене з урахуванням специфічних вимог портових операцій. Його міцність і маневреність дозволяють з високою точністю переміщати великогабаритні контейнери в обмеженому просторі, від причалів до складських терміналів, на інші види транспорту, оптимізуючи весь логістичний процес. Інтегровані системи навігації і телеметрії дозволяють відстежувати місце розташування тягача і контейнера в режимі реального часу, забезпечуючи безперебійну роботу всього логістичного комплексу.

У роботі проаналізовано причини виходу з ладу рукав високого тиску термінальних тягачів, які працюють у чорноморських портах. Аналіз експериментальних даних показав, що основні відмови рукавів високого тиску обумовлені механічним впливом, втомними процесами, порушеннями технологій монтажу та умовами роботи. Найбільш вразливою зоною є ділянка рукавів високого тиску поблизу фітинга, де концентрація напружень і корозійні процеси викликають раптові розриви при тисках нижче номінальних робочих значень.

Ключові слова: *термінальний тягач, надійність, порт, контейнер, рукав високого тиску.*

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RESEARCH OF OPERATIONAL RELIABILITY OF HIGH-PRESSURE HOSES OF TERMINAL TRACTORS OF PORT CONTAINER TERMINALS

Terminal tractors are an integral part of modern port infrastructure and an indispensable tool for port transshipment operations, where every hour counts and efficiency is the key to success. Each terminal tractor is not just a machine, but a sophisticated engineering solution designed to meet the specific requirements of port operations. Its strength and maneuverability allow it to move bulky containers with precision in confined spaces, from berths to storage terminals and then to transfer points for other modes of transportation, optimizing the entire logistics process. Integrated navigation and telemetry systems allow you to track the position of the tractor and container in real time, ensuring the smooth operation of the entire logistics complex.

Their short wheelbase and powerful engine provide drivers with exceptional control, allowing them to maneuver through the maze of container piles and other heavy equipment. The driver's cabin, located high above the ground, offers excellent visibility, which is crucial for safe and efficient task execution. In the high-traffic environments of port areas, where time is of the essence, these trucks demonstrate their value. The standardization of containers plays a significant role, as their uniform dimensions facilitate loading, unloading, and stacking, maximizing the productivity of the truck. The basis of its functionality is a powerful hydraulic system that allows containers to be lifted and moved with high precision.

The speed of processing ships, the timeliness of deliveries and the overall efficiency of the port depend on the reliability and performance of these machines.

The paper analyzes the causes of failure of the high-pressure hoses of terminal tractors in the Black Sea ports. A study of the causes of high-pressure hose failures revealed that more than 50% of incidents are related to the effects of impulse loads and mechanical damage. The most common type of defect is the rupture of the hose itself. The majority of hose failures are caused by factors related to their operating conditions. It has been established that high-pressure hoses on terminal tractors fail much more often in winter. This is due to a combination of factors: frost, thick working fluid, sudden pressure fluctuations, corrosive effects of salt, and increased abrasive wear. All of these winter conditions significantly accelerate the deterioration of the high-pressure hose, so even minor installation or usage issues that are not critical in summer can lead to rapid breakdowns and accidents in winter. A study of damaged areas of the sleeves using electron microscopy revealed that the wires that make up the reinforcement layer are breaking down due to fatigue.

Keywords: *terminal tractor, reliability, port, container, high pressure hose.*

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Introduction

In the modern port infrastructure, terminal tractors occupy a central place, being an indispensable link in the chain of transshipment operations, where every second counts and efficiency is the key to success [1-4]. These vehicles are not just machines, but carefully designed engineering solutions tailored to the specific needs of port operations (Fig. 1). With their powerful engines and specially engineered structures, terminal tractors are capable of handling heavy loads and maneuvering them efficiently in the confined spaces of port terminals. His task is not just to move the container from point A to point B, but to do it as quickly and safely as possible, because every minute spent at the port is a loss of time and money.

The short base and powerful engine give drivers full control, allowing them to confidently navigate through piles of containers and other equipment. The high-mounted cab provides excellent visibility, which is crucial for safe and

efficient execution of tasks. In the fast-paced environment of port areas, where time is money, their value is undeniable. With their power and maneuverability, they can accurately move massive containers within the limited space of the port, from ships to warehouses and then to other modes of transportation, optimizing the entire cargo flow [1-7].

Fig. 1. Terminal tractors in ports

Integrated navigation and telemetry systems provide the ability to track the location of the tractor and container in real time, facilitating the smooth operation of the entire logistics complex.

The powerful hydraulics allow for precise lifting and moving of cargo. The efficiency and speed of these machines directly impact the timely processing of ships, the timeliness of deliveries, and the overall efficiency of the port.

The standardization of containers is particularly important, as their standardized dimensions greatly simplify the processes of loading, unloading, and stacking, maximizing the productivity of the tractor. Its robust steel construction protects the cargo from external influences, and its standard dimensions make it easy to transfer from one mode of transportation to another. The interconnection between the tractor and the container creates a unified, highly efficient system that allows millions of tons of cargo to be transported around the world with remarkable speed and precision.

Related Work

As practice shows, even today, for equipment with an increased level of reliability, the problem of sudden failures of hoses operating under high pressure remains unresolved [8-14]. It should also be noted that issues related to the service life of high-pressure hoses (HPH) of port terminal tractors remain insufficiently studied [1-4,5-7]. As part of the research [8], a methodology and an appropriate installation for conducting impulse tests of hydraulic hoses were developed. Based on the collected experimental data and statistical analysis using the Weibull distribution, the predicted resource (number of cycles before failure) for a specific HPH specification was determined. However, these estimates do not take into account the full range of factors that are typical for real-world operating conditions.

This is because the service life of the HPH depends on the operating conditions, pressure, temperature, quality of the hose itself, and maintenance, rather than on the tractor model itself. In the context of port terminals, where equipment operates under intense loads and is often exposed to corrosive environments such as seawater and salt, the durability of the HPH becomes particularly important. Failure to address this issue properly can lead to unexpected downtime and significantly increase the operating costs associated with port terminal tractors.

In order to maintain continuous operation and increase the service life of port terminal tractors, it is necessary to carefully study the factors that affect the durability of their high-pressure hydraulic hoses.

Materials and methods

Terminal tractors that have been operating in the Black Sea ports for 12...15 years, both in winter and in summer, were selected for the study. High-pressure hoses are flexible hoses reinforced with metal threads, designed to transmit hydraulic fluids under high pressure within the system. They are used in all hydraulic components of machines, such as lifting control units, steering cylinders, pumps, and more. It should be noted that the service life of the high-pressure hoses (HPH), the performance, the work cycles, and the load levels of the forklifts had minimal differences.

The tractors were inspected once a year for five years. Additionally, the drivers performed visual inspections and checks of the hydraulic systems and brakes before and after each work shift.

Results and discussion

Based on the averaged data obtained from the analysis of the mechanic department's logs, a histogram was constructed to illustrate the distribution of HPH failures during the summer and winter operating periods (Fig. 2). From these data, it can be seen that the main causes of HPH failure are:

1) dynamic and impulse loads;
2) abrasion;
3) corrosion and rubber aging;
4) bending and material fatigue;
5) other factors (installation, faulty fittings, etc.).

The analysis of the causes of high-pressure hose failures shows that operational and installation factors have a significant impact on reducing the service life of high-pressure hoses. The majority of failures are caused by dynamic and impulse loads, which lead to pressure-related ruptures, accounting for 35% of all failures. This factor causes fatigue damage to the reinforcement layer and is the primary cause of premature hose failure.

The second most significant factor is mechanical damage caused by abrasion and rubbing (21%), which indicates insufficient protection of the sleeves and incorrect installation in areas where they may come into contact with structural elements. Corrosion and aging of the rubber due to moisture and salt exposure (12%) also have a significant impact, leading to the destruction of the metal reinforcement and accelerated degradation of the materials, especially when the equipment is used in harsh climatic and road conditions.

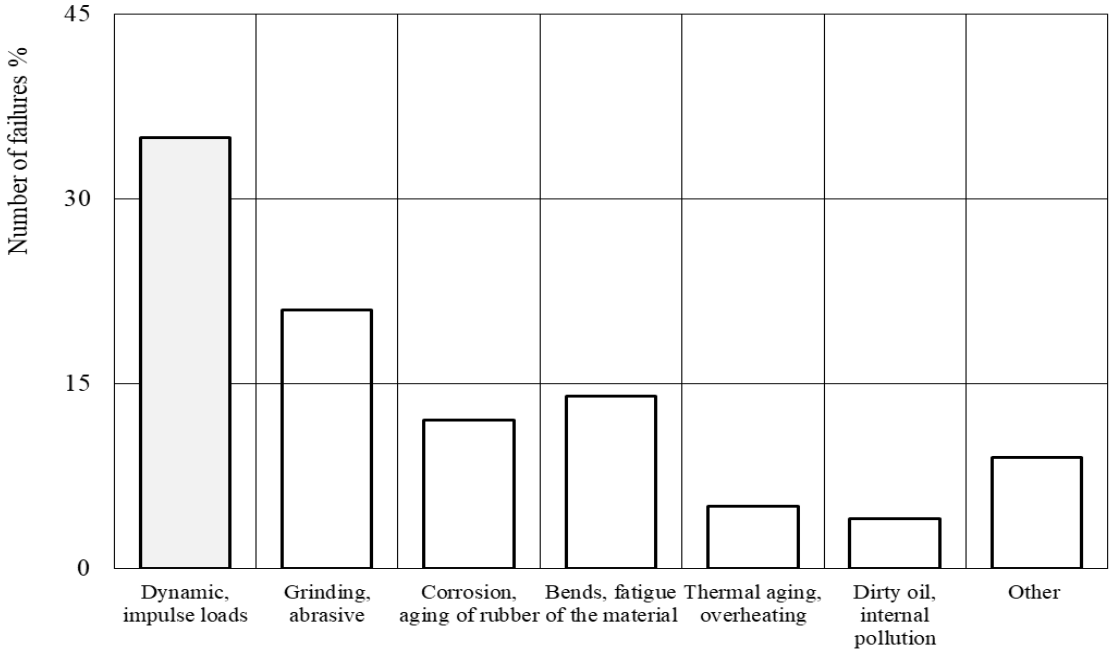

Fig.2 Distribution of high-pressure hose failures

Bends and material fatigue associated with exceeding the permissible bending radii, axial twisting and violation of the requirements for the installation of the HPH, cause 14% of failures, which highlights the importance of compliance with the rules of installation and laying of the sleeves. Thermal aging and overheating account for 5% of failures, and contamination of the working fluid and internal contamination account for 4%, having a less pronounced but systemic effect on the accelerated degradation of the inner layer of the sleeve and sealing elements.

The share of failures classified as other reasons (installation errors, fittings defects, production defects, etc.) is 9%, which indicates the need to strengthen quality control of assembly and components. In general, the data obtained indicate that the majority of HPH failures are premature and are not related to design flaws in the products, but rather to operating conditions and installation quality.

It should be noted that the most vulnerable area is the high-pressure hose section near the fitting, where stress concentration and corrosion processes cause sudden ruptures at pressures below the nominal operating values. These are among the other causes of HPH failures.

In general, more than 50% of HPH failures are caused by operational and installation factors rather than natural wear and tear or aging. The most common type of failure is sleeve rupture.

A study of the destroyed sleeves using electron microscopy revealed that the mechanism of destruction of the reinforcing layer wires is of a fatigue nature.

The increase in the number of failures during the winter months compared to the summer period is due to the negative impact of low temperatures on the physical and mechanical properties of the hoses. At negative temperatures, the elasticity of the rubber and polymer layers of the HPH hoses decreases. The material of the outer and inner shells loses its ability to compensate for deformations caused by pressure, bending, and vibrations. As a result, even the design-tolerable stresses during the winter period lead to stress concentration in the reinforcement layer zone, which accelerates the development of fatigue damage and the formation of microcracks. Additionally, the brittleness of the outer layer increases, increasing the likelihood of its cracking and subsequent moisture penetration to the reinforcement.

In conditions of low temperatures, the viscosity of the working fluid increases dramatically, which leads to an increase in flow resistance in the hydraulic lines. When the hydraulic system is started and the actuators are abruptly activated, increased impulse loads and hydraulic shocks are generated. These phenomena are the main cause of HPH failures and are most pronounced during the winter season.

Terminal tractors are operated under conditions of high cycle frequency and intense loads, including frequent maneuvers, abrupt changes in direction, operation with maximum cargo weight, and constant activation of the hydraulic system. In winter, these modes are combined with minimal plasticity of the materials and increased hydraulic loads, which creates conditions for accelerated destruction of the HPH.

An additional risk factor is the short-term but significant increase in pressure in the hydraulic system during startup and in the first minutes of operation.

This is especially dangerous for a terminal tractor, where the hydraulic system constantly operates in

intermittent modes (start-stop, maneuvering, and lifting/lowering the saddle).

This confirms that increasing the resource and reliability of high-pressure hoses is primarily possible by following the operating conditions.

Based on the experimental data obtained, the probability of failure was calculated HPH [11-14]:

$$P(t) = \frac{n(t)}{N} \quad (1)$$

where $n(t)$ - the number of sleeves that failed;

N – the total number of sleeves that participated in the tests.

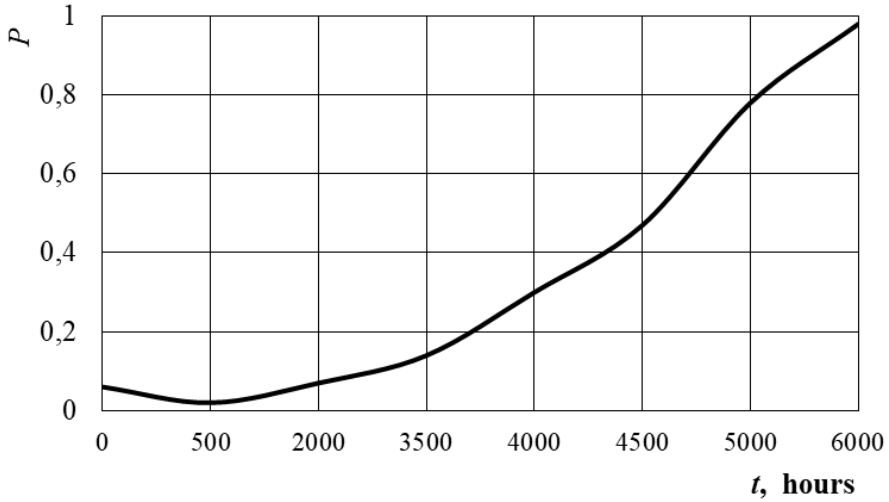

Fig.3 Dependence of the probability of failures P on the operating time t of high-pressure hoses

From the graph (Fig.3) it follows that:

1. in the interval 0…..500 h – the number of failures is explained by possible installation errors or hidden defects, by 500 hours the risk drops to a minimum, as the system “got used to”;

2. in the interval 500 h…3500 h - the safest period, the probability of failure grows very slowly;

3. at the point 4 000 h the risk reaches 30%, this is the optimal moment for preventive replacement to avoid the downtime of the vessel;

4. after 4500 hours, the risk is already 47%, which means that almost every second hose on this waste is potentially defective due to the effects of salt and constant hydraulic shocks;

5. after 5000 hours, the probability of failure increases to 78%, and by 6000 hours, it reaches 98%. Operating a hose is extremely dangerous, as a hose rupture in the port can lead not only to equipment downtime, but also to environmental fines for oil spills.

Based on the data obtained, the critical replacement window for critical lines (saddle lift) is 4,000 h ... 4,200 h.

High-pressure hoses on terminal tractors fail more often in winter than in summer, due to the combined effect of low temperatures, increased oil viscosity, increased impulse loads, and an aggressive external environment. Winter conditions intensify the main mechanisms of high-pressure hose failure, which are much less pronounced in summer..

To ensure maximum reliability and prevent sudden failures, it is recommended to integrate sleeve condition monitoring into routine maintenance. It is important to consider the specific operating conditions, use wear monitoring systems, and replace components based on their actual condition.

Conclusions

Analysis of the causes of failure of high-pressure hoses shows that more than half of the cases are caused by impulse overloads and mechanical impact, and the most common form of defect is a rupture of the hose. Thus, the results obtained indicate that the majority of failures of high-pressure hoses are not due to design flaws of the products, but to the operating conditions.

The most vulnerable area is the section of high-pressure hoses near the fitting, where stress concentration and corrosion processes cause sudden ruptures at pressures below the nominal operating values. The results of electron microscopic analysis of the destroyed sleeves indicate a fatigue mechanism of wire failure in the reinforcement layer.

The higher frequency of high-pressure hose failures on terminal tractors in winter is caused by the combined effect of low temperatures, increased viscosity of the working fluid, increased impulse loads, aggressive salt environment, and increased abrasive wear. Winter conditions multiply the main mechanisms of high-pressure hose failure, which means that even minor installation and operational defects that are acceptable in summer can lead to premature and catastrophic failures in winter.

Long-term sleeve performance is achieved through systematic monitoring during maintenance, assessment of the impact of the working environment, and the use of wear monitoring and condition-based replacement systems.

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