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STUDY OF EFFICIENCY AND ADVANCEMENT OF MARINE ENGINE OIL PURIFICATION AND FILTRATION TECHNOLOGIES

Oleg A. Onishchenko,[1] Oleksiy M. Melnyk*[2], Vladimir A. Yarovenko[2], Nadiia I. Aleksandrovska[2], Serhii V. Kurdiuk[1], Dana G. Parmenova[1], Oleksandr O. Storchak[2]

[1]National University "Odesa Maritime Academy", 8, Didrikhson str., Odessa, 65052, Ukraine

[2]Odesa National Maritime University, 34, Mechnikov str., Odessa, 65029, Ukraine

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Abstract

Efficient oil filtration is crucial for maintaining optimal engine performance and preventing damage, wear, and potential malfunctions in marine diesel engines. Contaminants present in fuel and lubricants can adversely affect combustion and engine operation. This article explores the significance of fuel and oil purification in marine diesel engines, focusing on techniques such as sedimentation, filtration, and centrifugation.The study highlights the substantial consumption of lubricants by marine diesel engines and their vulnerability to contamination. Increased lubricant consumption can result in wear and decreased efficiency. Thus, effective oil purification methods play a pivotal role in extending engine lifespan, reducing wear, and ensuring environmentally responsible operation. Three primary methods of oil purification are discussed: sedimentation, filtration, and centrifugation. Sedimentation allows particles to settle due to gravity, filtration employs filters to capture solid impurities, and centrifugation utilizes centrifugal force to separate impurities based on density differences. To assess filtration efficiency, a practical scenario is presented, comparing full-flow, partial-flow, and combined filters. The article emphasizes the need for real-world data to make informed decisions about oil filtration methods. Furthermore, it highlights the importance of mathematical models, such as the Darcy-Brinkman equation, for understanding fluid movement and contamination distribution. Effective oil purification is essential for marine diesel engines to ensure optimal performance, reduce wear, and minimize environmental impact. By employing efficient filtration methods and leveraging mathematical models, marine industries can enhance their maintenance practices and contribute to the longevity and sustainability of their engines.

Keywords: maritime transport; marine diesel engines; operation techniques; contamination; purification; lubricant consumption; filtration efficiency; engine performance; wear prevention; environmental impact.

ДОСЛІДЖЕННЯ ЕФЕКТИВНОСТІ ТА ВДОСКОНАЛЕННЯ ТЕХНОЛОГІЙ ОЧИЩЕННЯ ТА ФІЛЬТРАЦІЇ МАСТИЛ ДЛЯ СУДНОВИХ ДВИГУНІВ

Олег А. Онищенко[1], Олексій М. Мельник[2], Володимир О. Яровенко[2], Надія І. Александровська[2], Сергій В. Курдюк[1], Дана Г. Парменова[1], Олександр О. Сторчак[2]

[1]Національний університет "Одеська морська академія", вул. Дідріхсона, 8, м. Одеса, 65052, Україна

[2]Одеський національний морський університет, вул. Мечникова, 34, м. Одеса, 65029, Україна

Анотація

Ефективна фільтрація мастила має вирішальне значення для підтримки оптимальної продуктивності двигуна і запобігання пошкодженням, зносу і потенційним несправностям суднових дизельних двигунів. У цій статті досліджується важливість очищення палива і мастила в суднових дизельних двигунах. Дослідження підкреслює значне споживання мастильних матеріалів судновими дизельними двигунами і їх вразливість до забруднення. Таким чином, ефективні методи очищення мастила відіграють ключову роль у продовженні терміну служби двигуна, зменшенні зносу та забезпеченні екологічно відповідальної експлуатації. Розгля-нуто три основні методи очищення мастила: відстоювання, фільтрація та центрифугування. Відстоювання до-зволяє частинкам осідати під дією сили тяжіння, фільтрація використовує фільтри для уловлювання твердих домішок, а центрифугування використовує відцентрову силу для відокремлення домішок на основі різниці густини. Для оцінки ефективності фільтрації представлено практичний сценарій, в якому порівнюються повнопотокові, частково-потокові та комбіновані фільтри. Стаття підкреслює необхідність реальних даних для прийняття обґрунтованих рішень щодо методів фільтрації, важливість математичних моделей, на кшталт рівняння Дарсі-Брінкмана, для розуміння руху рідини і розподілу забруднень. Застосовуючи ефективні методи фільтрації і використовуючи математичні моделі, суднобудівна промисловість може вдосконалити свою практику технічного обслуговування і сприяти довговічності і стійкості своїх двигунів.

Ключові слова: морський транспорт; суднові дизельні двигуни; методи обробки; забруднення; очищення; витрата мастила; ефективність фільтрації; ефективність двигуна; запобігання зносу; вплив на навколишнє середовище.

Corresponding author: e-mail: m.onmu@ukr.net

Introduction

The cleanliness of lubricating oil is a crucial aspect since marine diesel installations consume a significant amount of oil. Contamination of lubricants can lead to increased wear of engine components, higher consumption, and reduced efficiency. Removing contaminants from the lubricating oil helps to extend the working life of machinery and equipment, reduce component wear, and prevent malfunctions.

The source [1] provides a comprehensive overview of research progress and prospects in the field of marine oily wastewater treatment. The authors delve into various techniques and technologies used for treating marine oily wastewater, shedding light on the challenges and advancements in this critical area of environmental concern.

Focusing on nanofiber membranes, research paper [2] discusses the advancements in water treatment technology. The authors explore the potential of nanofiber membranes for water treatment, highlighting their effectiveness in removing contaminants and addressing the challenges of polluted water. The thesis [3] delves into the development of filtration technologies for water treatment. Investigating effective, cost-efficient, and robust water treatment methods, the research emphasizes the importance of advancing filtration techniques to ensure clean and safe water. Review [4] examines biofiltration techniques for the removal of volatile organic compounds and heavy metals from polluted water. The authors explore recent advancements in biofiltration technology and its potential in addressing water pollution challenges. Focusing on marine-derived renewable functional materials and biochar, the study [5] highlights progress in sustainable water purification methods. In [6] oilfield wastewater treatment using membrane filtration is discussed in comparison with conventional technology. The authors of [7] evaluate ceramic membranes for oilfield produced water treatment, with a focus on offshore units. By assessing the feasibility of ceramic membranes, the study contributes insights into enhancing the treatment of produced water in oilfield settings. The work [8] presents preliminary studies on the application of ceramic membranes for oilfield produced water management. In paper [9] the chemical approach to marine oil spill cleanup is explored. The authors investigate advancements in marine oil spill response technology s, providing insights into the challenges and progress in this critical area.

In [10] neutralization yield of crude marine fish oil is considered. This study examines the effects of filtration methods. By evaluating filtration techniques, the authors contribute to our understanding of optimizing oil processing in the food industry.

These studies [11; 12] present an innovative approach using lime to remediate marine oil spills through green and eco-friendly in situ salt formation and focus on prepaing a superhydrophilic and underwater superoleophobic stainless steel mesh for oil-water separation. Sources [13; 14] discuss advances in adsorption and filtration techniques for separating highly viscous crude oil/water mixtures and focusing on marine sponges, examinetheir sensitivity to marine oil snow and chemically dispersed oil pollution. Scientific work [15] reviews recent advances in fabricating superwettable layered double hydroxides materials for oil-water separation.

In [16; 17] vibrodiagnostics of marine diesel engines using IMES GmbH systems for monitoring marine diesel engine performance is researched. The authors proposed a concept of vibroacoustic diagnostics for fuel injection and electronic cylinder lubrication systems of marine diesel engines. Studies [18; 19] discussed measures to enhance the ecological safety of ships and reduce operational pollution to the environment, and also investigated measures to ensure effective freight transportation while minimizing environmental impact. Works [20] elaborated on equipment replacement terms, considering wear and tear and obsolescence. In [21], it is proposed to optimize the speed regimes of a vessel, which has an impact on the overall efficiency of maritime operations and affects the maintenance and performance of diesel engines, including their oil treatment systems. Research [22] addresses cyber resilience of ship information systems. The authors discuss strategies for ensuring the cybersecurity of ship information systems. Research works [23–25] focuson membrane filtration and investigate the treatment of synthetic decanted oily seawater using a pilot-scale hollow fiber membrane filtration process, experimental evaluation of diesel particulate filter (DPF) performance loaded over Pt and sulfur-resisting material for marine diesel engines, and environmentally friendly method to fabricate superhydrophobic cellulose fiber for oil absorption.

Study [26] examines the concept of autonomous ships and discusses important insights into the future of maritime technology. Studies [27; 28] focus on optimising the parameters of an automated robotic transmission system and present methods for optimising vehicle operating conditions using simulation software, providing valuable information for automotive engineering. Research [29] provides scientific justification for thermal leveling to address deformations in car structures, contributing to advancements in engineering while [30] introduces the ship critical equipment and systems protective measures. Studies [31; 32] focus on the diagnosis of marine low-speed diesel engines with regard to cylinder oil specifications and are dedicated to the use of fuel additives to improve the fuel efficiency and environmental performance of marine diesel engines.

Work [33] provides expert insights on the practice of engine oil analysis, offering guidance for engine maintenance and diagnostics, while [34] focuses on assessing petrol engine oil degradation using an affordable IR sensor, contributing to improved engine maintenance practices. Study [35] emphasises the importance of setting meaningful alarm limits for oil analysis, machine reliability and performance, maintenance and lubrication, covering the critical aspects of particulate matter pollution proposed in [36]. The factors leading to motor oil contamination, providing valuable insights into the causes and consequences of oil contamination in engines and comprehensive overview of oil-water separation techniques presented in [37; 38]. A review of research on materials for separating water-oil mixtures and lubricant technology with an emphasis on viscosity improvers for multi-grade oils, which is important for the development and use of lubricants, is given in [39; 40]. Technology of ship turbine oils purification by coalescent systems [41] focuses on the purification of oils using coalescent systems. Thesis [42] explores methods for enhancing engine oil purification in marine diesel engines, particularly through the use of magnetic hydrocyclones. Source [43] investigates the presence of heavy metals in both fresh and used engine oil, providing insights into potential environmental impacts. Recommen-dation [44] by the International Council on Combustion Engines offers guidance on the treatment of system oil in medium speed and crosshead diesel engine installations. In [45] information about ALCAP separators is provided, while [46] focuses on estimating performance fluctuations in equipment operating under conditions of unstable loading.

The summary effectively captures the essence of the collective contributions of these studies to the field of fluid treatment, particularly in the context of offshore oil spill response, water treatment, engine diagnostics and environmental sustainability. The diversity of topics and approaches presented in these studies emphasizes the interdisciplinary nature of addressing the complex challenges in these areas. By exploring different technologies, materials, and strategies, these studies collectively contribute to understanding and application of sustainable and effective solutions to improve oil treatment, enhance purification, as well as protect the environment.

Materials and methods

The problem of contamination of viscous liquids and solutions

The cleanliness of fuel and lubricants is critically important to ensure optimal engine performance and prevent breakdowns, component wear, and potential malfunctions. Pre-cleaning of fuel before its use in marine diesel engines aims to remove impurities that may negatively affect fuel combustion and engine operation. Various methods, such as settling and heating to remove water, filtration to eliminate solid particles, separation, homogenization, and others, are employed for this purpose.

The modern merchant fleet actively uses diesel engines as the main type of drive for ships. The operating costs of such marine diesel engines include maintenance, fuel and oil purchases. It is noted that marine diesel engines consume a large amount of oil. Specific oil consumption can range from 2 to 5 grams per kilowatt-hour, depending on the type and design of the engine.

In particular, crosshead two-stroke low-speed diesel engines can have lower lubricant consumption because of their specific design. In contrast, in high-speed trans engines, lubricant consumption can be higher due to their different design. In addition, the lubricant consumption depends on the engine's operating mode, operating conditions, and the age of the engine itself.

A significant role in solving the problem of saving and rational use of fuels and lubricants (F&L) is the use of highly effective methods of lubricant cleaning. Oil cleaning helps to reduce wear and tear on engine parts and improve engine performance and efficiency. It is important to use effective cleaning methods, as the annual cost of fuel and lubricants can exceed the cost of the engine itself. Optimal use of fuels and lubricants is a key factor in increasing the efficiency of marine diesel engines, reducing operating costs and ensuring their reliability. However, the use of highly efficient lubricant treatment methods helps

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to reduce overall costs and conserve resources for fleet maintenance [33].

As a result of engine oil operation, its chemical composition changes slightly. But the oil is continuously contaminated by external and internal sources. External sources include dust, airborne dust, sulfur oxides and soot from incomplete combustion, fuel, and water. Internal contamination means wear products of the metal parts of the engine in contact with each other, decomposition products, both lubricants and additives. The maximum permissible water content is 0.5 %, fuel – 2 % and air (which can lead to foaming) – 12 %. The size of solid particles varies widely from 0.1 to 200 microns. The highest concentration of insoluble solid particles in the lubricant is observed in transaxle engines and can reach 4–5 % [34; 35].

The faster and more completely wear products are removed from working fluids, the longer machines and mechanisms operate, the more efficient their performance is, and the less wear and tear on parts. For example, contamination leads to accelerated wear of parts: 75 % to 85 % of failures of hydraulic pumps, hydraulic motors, hydraulic cylinders and valves are caused by contamination. Due to the extremely small clearances in modern hydraulic systems, even invisible particles can cause damage. The main cause of metallic impurities in engine oil is the wear of cylinder bushings, shafts, gears and piston rings. There are the following types of wear: adhesive wear, abrasive wear and corrosion wear shown in Fig. 1.

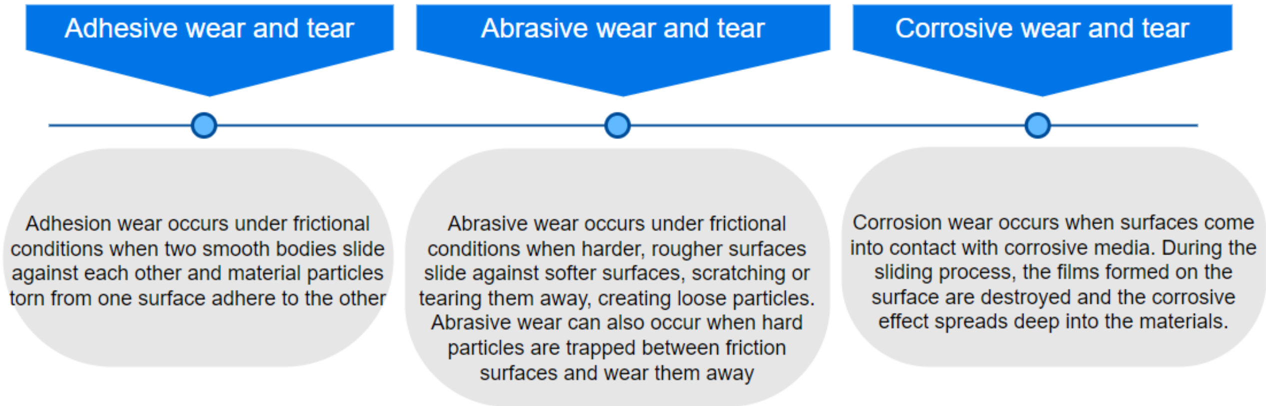

Fig.1. Types of wear of machine and mechanisms parts

In addition to the types of wear listed above, there is surface fatigue, oxidative wear, and thermal wear [36; 37]. These types of wear are determined by the type of particles, shape and size ratio presented in Table 1.

Table 1

Particle type, shape and size ratio by wear type

Types of wear	Description
Normal wear and tear	Particles formed by sliding and having the shape of flat plates. Particle size is 0.5...15 microns and less, particle thickness is 0.15...1 micron. The ratio of large particle size to thickness ranges from 10 : 1 for larger particles to 3:1 for particles of about 0.5 microns.
Fatigue staining	Fatigue staining particles have the shape of flat plates in the form of flakes with a smooth surface and a chaotic, disorderly periphery. The particle size is 10...100 microns and more, the ratio of large size to thickness is 10 : 1.
Microcuts	Micro-cut wear particles are in the form of chips 25...100 microns long and 2...5 microns thick. Abrasive wear particles are needle-shaped with a length of 5 microns and a thickness of 0.25 microns.
Bullies	Particles formed by the increased slippage of one part relative to another with grooves on the surface and protruding straight edges. Particle sizes are from 15 microns, the ratio of the main size to the thickness of the particles is 10 : 1. Often, mechanical impurities are magnetic in nature, so it is advisable to use a magnetic field to intensify the engine oil purification process.

The service life of an internal combustion engine is 80 % due to wear and tear of parts, with wear caused by abrasive contaminants accounting for an average of 60 % of the total wear and tear of parts. Existing maximum permissible concentrations of mechanical impurities caused by wear are not universal. They do not take into account the operating modes of diesel engines, different operating conditions, boosting, the distinction between the fuels used in terms of both quality and composition, the specifics of the

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lubricants themselves, etc. In most cases, the existing recommendations are vague and blurred.

The fractional composition of metal particles in the used engine oil in an internal combustion engine is shown in Figures 2 and 3.

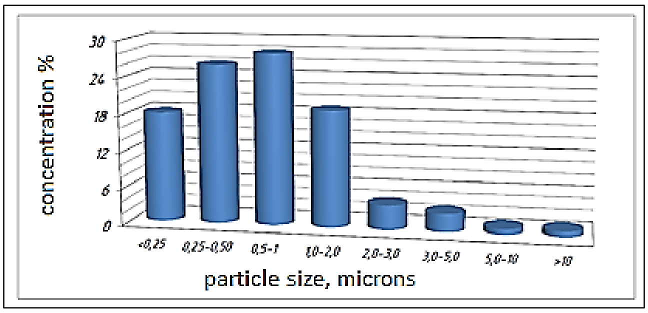

Fig.2. Metal impurities in used engine oil: fractional composition [42]

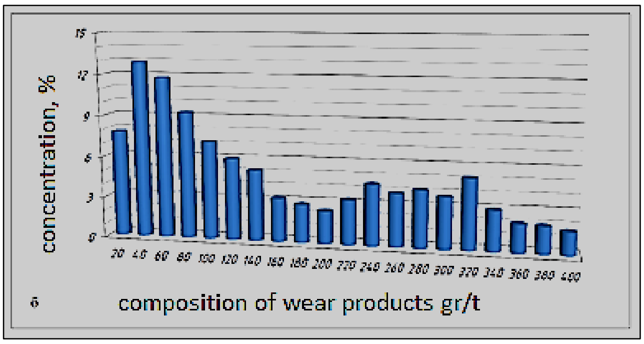

Fig.3. Metal impurities in used engine oil histogram of the distribution of iron impurities in samples of used diesel cylinder oil [42]

There are maximum permissible concentrations of impurities for motor oils, and they depend on what kind of substances they are, how, where and under what conditions they are used. These values are strictly regulated by diesel engine manufacturers. The standards specify not only the maximum permissible concentration but also the maximum permissible size of impurities.

The graph on Figure 4 shows the relationship between the particle size ranges (0–8 microns, 8–18 microns, 18–30 microns and 30–60 microns) and their effect on engine wear. It is evident that as the particle size range increases, the corresponding size value also increases, peaking in the 18–30 micron range. This indicates that particles within this range have the most significant impact on engine wear. The graph provides a concise but insightful visual representation of how different particle sizes can affect engine durability, highlighting the critical importance of controlling impurities in engine oils for optimum engine performance and longevity;

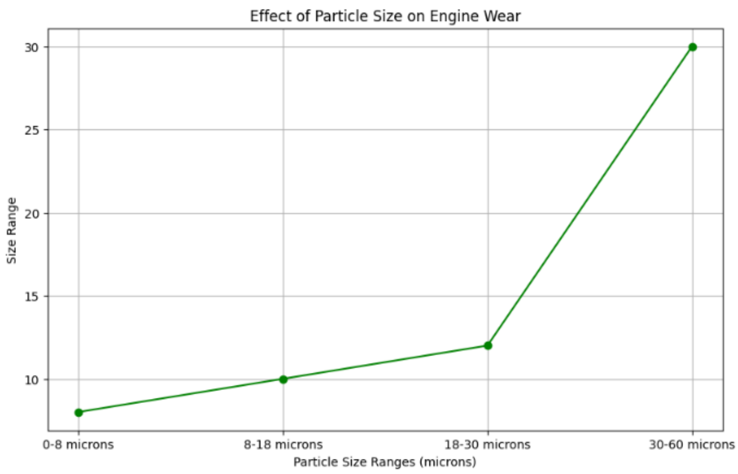

Fig. 4. The relationship between particle size and engine wear

Due to the above facts, the problem of cleaning viscous media from magnetic impurities is acute not only in terms of energy efficiency and resource conservation, but also in terms of environmental protection. There are four basic principles of mechanical impurities removal: settling under the influence of gravity (sedimentation tanks/settlers); sieve effect, which retains impurities larger than the size of the "pore" (filters); inertial, based on the action of centrifugal forces (hydrocyclones, centrifuges); separation under the influence of external influences (magnetic, electric and ultrasonic fields). In addition, it is also possible to combine different devices.

Marine lubrication systems and engine oil parameters

Lubrication systems are designed to lubricate the friction surfaces of diesel parts and to remove heat from them. When choosing a lubrication system, many factors are taken into account, including engine type, rotational speed, piston stroke speed, operating conditions, quality of the lubricant used and its additive composition, cleaning efficiency, durability, redundancy, maintainability, unification, ease of use, reliability, durability, and others.

There are two types of lubrication systems for marine internal combustion engines:

- wet crankcase systems, which are used in engines of relatively low power and are characterized by storing all the lubricating oil in the crankcase, the capacity of which is limited and this negatively affects the rate of aging of the lubricating oil and the time of its replacement (250–500 hours). In this system, the diesel crankcase sump is used as a circulating oil tank, from which the oil enters the system through a filter and cooler

- systems with a "dry" crankcase, used on all powerful low-speed and medium-speed internal combustion engines. The system involves storing lubricating oil in a separate tank and pumping it into this tank with a separate pump, while the lubricating crankcase always remains without lubrication.

The ship's engine oil purification system must meet the following requirements: to pass as much oil as possible per unit of time; to ensure the maximum degree of purification from impurities of various kinds.

Figure 5 shows a typical layout of a medium-speed or crosshead diesel engine oil cleaning system. The oil treatment system consists of two main parts: purification system: to keep the level of contaminants in the oil at an acceptably low level and protection system: protects the engine from harmful particles that are not removed by the cleaning system;

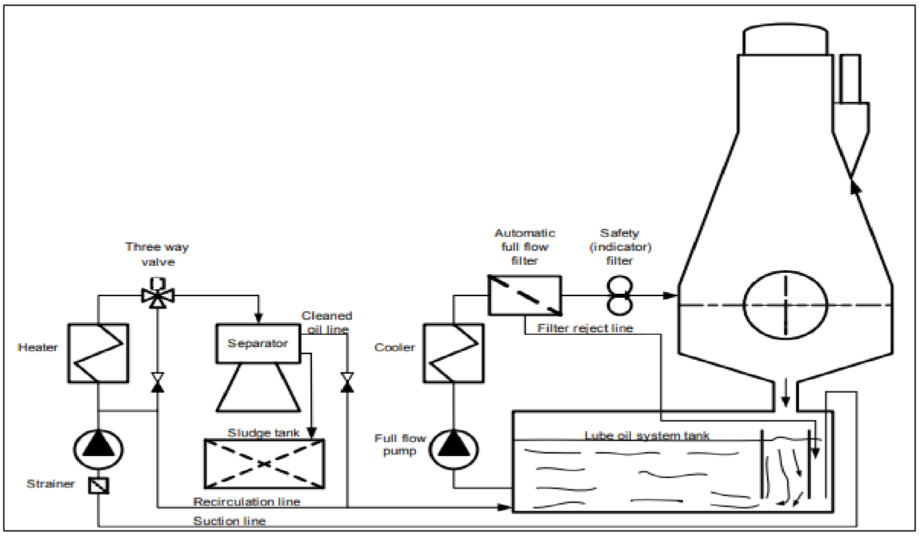

Fig. 5. Ship's luboil treatment system [44]

However, these two requirements contradict each other: the higher the degree of purification, the greater the hydraulic resistance of the system, and a large flow system should have a low hydraulic resistance. In connection with the above, there are three types of lubrication systems.

1. Full-flow. In this system, the oil filter is connected to the lubrication system in series and passes the entire volume of oil through it. The main advantage is the high speed of lubricant cleaning, and the disadvantage is that it quickly clogs.

2. Partial-flow. The filter is connected to the lubrication system in parallel. Unlike a full-flow filter, only part of the lubricant passes through it, so the cleaning speed is significantly reduced, but the filtration is better. The degree of protection of the power unit from wear products is approximately the same for a partial-flow and full-flow oil filter.

3. Combined. The combined type of oil filter is characterized by the presence of both full-flow

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and partial-flow filters in the lubrication system. The principle of its operation is that 90% of the oil passes through the full-flow filter, and the remaining 10% through the partial-flow filter. This solution allows for almost complete cleaning of the oil, an increase in its service life and more reliable engine protection. The most common is the partial-flow scheme with coarse and fine filters. Practical comparative efficiency of filtration methods shown in Figure 6;

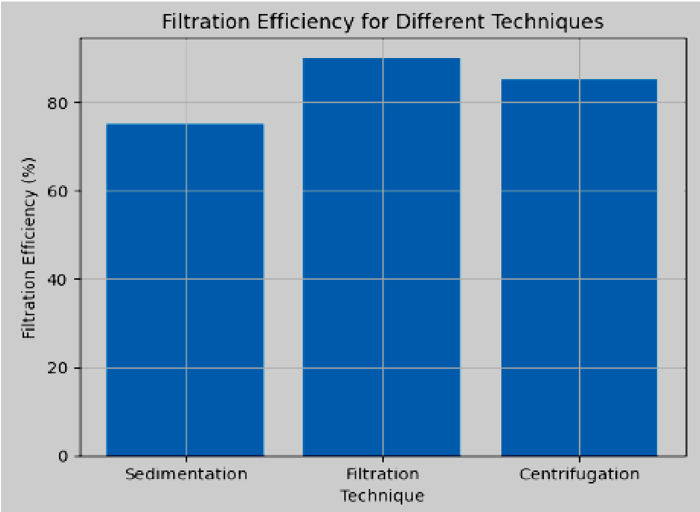

Fig.6. Practical comparative efficiency of filtration methods

The choice of the type of lubrication system and cleaning devices is a complex engineering task. For example, in case of incomplete combustion of fuel, it is recommended to install a device that captures this product well, the cleaning scheme will be partial-flow; in the presence of a large number of abrasive particles, a full-flow cleaning system with fine screening is required.

Recently, there has been a trend towards the development of combined cleaning systems that protect friction units from abrasive particles and have a high overall efficiency of engine oil cleaning.

Viscosity is one of the main characteristics of a lubricant. To facilitate the task of choosing the optimal lubricant viscosity, the concept of viscosity index was introduced, which characterizes the ratio of viscosity to temperature, i.e. viscosity-temperature properties of oils. Dynamic viscosity (unit of measurement in the SI system is Pa s, in the CGS system – Poise; 1 Pa s = 10 Poise) and kinematic viscosity (unit of measurement in the SI system is m^2/s, in the CGS system – Stokes, non-system unit – Engler's degree) are distinguished. The kinematic viscosity can be obtained as the ratio of the dynamic viscosity to the density of the substance.

High viscosity engine oils are recommended for use in engines with low speeds, high loads, friction surface pressure and high temperatures. Low viscosity engine oils are used for engines with low loads but high speeds; in this case, friction losses will be minimal.

The density of motor oils is 860–930 kg/m^3. Paraffin-based lubricants have a lower density, while naphthenic-based lubricants are characterized by high density values. During operation, the density changes; this is due to the dilution of the lubricant with a lighter fuel (decrease in density), contamination with soot, wear and oxidation products or water ingress (increase in density), etc.

The viscosity can decrease by up to 10% or increase by up to 30% from the viscosity of fresh oil while still being considered within permissible limits. The viscosity of different types of lubricants is shown in [40].

In crosshead diesel engines, the outlet temperature of the engine oil is usually maintained at 60–65 °C, in forced diesel engines it is 75–78 °C. In high-speed engines, up to 110° is allowed. Due to the fact that with the inertial method of cleaning, mechanical impurities are more easily removed from the lubricating oil at low viscosity, to improve the separation efficiency, the lubricating oil must be heated to the highest possible temperature (80–85 °C), at which the water in the separator does not yet boil. It is desirable that this temperature range is maintained within ± 20 %.

Conventional marine engine oil purification systems review

Lubricating oil treatment in marine diesel engines is essential for the economical and trouble-free operation of a ship. To purify oil on ships, settling, filtration and separation under the influence of inertia (centrifugation) are used. Settling takes place in a sewage and circulation tank or in a storage tank when the vessel is at a standstill. To accelerate the process, the lubricant is heated to a temperature of 70–90 °C. After three to four days, moisture and light fractions of fuels evaporate from the lubricant.

All filtering devices are divided into coarse (the size of the removed impurities reaches 40–100 microns) and fine (5–40 microns) filters. The filter consists of a robust metal housing with a filter element built inside. Depending on the needs, the replaceable filter can be equipped with various components, for example, different filter materials, a backflow blocker, a bypass valve, etc. The fluid to be treated enters through concentric holes located on the lid, passes through the filter element and exits purified through the central connection.

Most modern filters are self-cleaning. This is achieved by having at least two filters in one housing with a switching device (for example, a three-way valve) or with a switching device that disconnects (changes) the filter material that is not working. Cleaning is carried out with compressed air under a pressure of 0.6–0.8 MPa or with a reverse flow of lubricating oil. An example of a backwash filter is shown in Fig. 7. The lubricating oil enters the filter housing through nozzle and flows through the vertically arranged filter elements in the form of a circle from the inside out; the purified oil is discharged through nozzle. One of the filter candles does not participate in this flow, as it is cut off from the filter circulation circuit for backwashing with clean lubricating oil. For this purpose, the filter design provides a flushing element, which is continuously rotated by the drive unit. During its rotation, the flushing element alternately communicates the internal cavity of the flushed spark plug with the sludge outlet. At an operating pressure of the filtered oil of approximately 0.15 MPa, the valve pusher compresses the spring and opens the channel for the flushing oil to exit [38; 39; 41; 42].

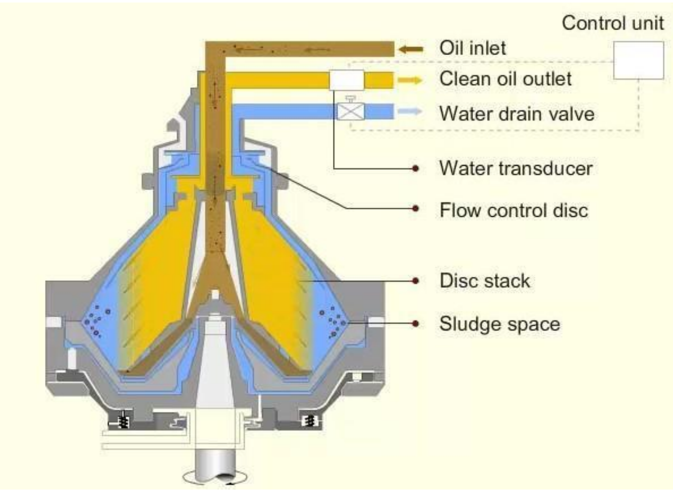

Fig. 7. Lubricant cleaning devices [45]

The filter material can be brass or copper mesh, paper or cardboard impregnated with a special compound, felt, thick fibrous material, cotton yarn, slag wool, porous fiber, etc. In coarse filters, the filter material is divided into slotted (plate-slotted or wire-slotted) and mesh. Filter materials cannot be made absolutely homogeneous throughout the entire volume and therefore often particles larger than the average mesh size pass through the filter. At the same time, the filter captures particles that are smaller than the mesh size of the filter material.

This is due to a decrease in mesh size as a result of filter clogging and coagulation of particles in the oil. Therefore, the longer the filter operates, the greater its cleaning efficiency, but the greater the hydraulic resistance. It should be noted that during the filtration process, the particle size distribution and qualitative composition of impurities in the filter bed changes. The "sludge effect" occurs, which reduces the fineness of cleaning and increases the hydraulic resistance due to clogging of the filter bed. The disadvantages of filter systems are low efficiency and insufficient cleaning fineness. The need to flush cartridges and the short service life of filter materials limit the use of filters, so other methods of purifying marine engine oils must be sought.

A new trend is the use of combined cleaning equipment, including an inertial-type device with an applied magnetic field. The most famous companies that produce filters and separators for purification of marine engine oils are the following: Alfa Laval, Mitsubishi SJ, Sofrance, SCAM Filtres, GEA Westfalia Separator, Winslow, Rellumit and others.

Results and discussion

Mathematical modeling of filtration allows for numerical calculations for various filtration conditions and optimization of filter system parameters. This allows for prediction of contaminant removal efficiency, optimization of filter design and selection of the best conditions for marine oil purification. This approach is an important tool in the development of effective technologies for cleaning and filtering marine oil, which contributes to the increase in the productivity of ship installations and the improvement of environmental sustainability of marine transport.

One of the models of the oil filtration process can serve as a basic equation describing the motion of the fluid through the filtering element, represented by the Navier-Stokes equation, which describes the motion of an incompressible fluid, and can also be used to take into account the viscosity of the fluid and other parameters. A Kolmogorov-Chaplygin equation for the particle size distribution in the lubricating oil may be used to describe particle contamination of the lubricating oil during engine operation. Models may also include heat transfer and temperature distribution in the lubricant when heated to an optimum cleaning temperature.

Mathematically, the Navier-Stokes equation is one of the basic equations for describing the movement of a fluid (lubricant) through a filter element, which takes into account the pressure, viscosity and inertia of the fluid, and for three-dimensional fluid movement has the form:

$$\rho\left(\frac{\partial v}{\partial t}+(v\cdot\nabla)v\right)=-\nabla P+\mu\nabla^2 v+F \tag{1}$$

where: ρ – density of the fluid (lubricant), v – velocity vector of the fluid (lubricant), t–- time, ∇ – gradient operator, P – fluid pressure, μ – kinematic viscosity of the fluid, $\nabla^2 v$ – Laplacian vector operator describing the fluid viscosity, F – external forces that can affect the fluid motion (for example, inertial forces).

This equation takes into account the laws of conservation of mass and fluid motion and allows one to calculate the velocity distribution of the fluid through the filter element.

In addition, the Navier-Stokes equations in various forms, such as the Reynolds-Average and turbulence equations, can be used to account for oil viscosity and other features of the filtration process. These equations allow the turbulent oil flows and the dynamic properties of the filtration medium to be taken into account.

One of the common models for filtration is the Darcy-Brinkman equation, which is widely used to model the filtration process and the deposition of contaminant particles in the filter media. This equation is an extension of the Darcy equation, which describes the fluid flow through a porous medium, with added terms to account for the interaction of the contaminant particles with the filter media, and which accounts for forces acting on the contaminant particles, such as drag force and gravitational force. This equation allows one to describe the movement of contaminant particles and their deposition in the filter media. The Darcy-Brinkman equation can be written as follows**:**

$$\frac{\partial u}{\partial t}=\frac{\mu}{\rho}\nabla^2 u-\frac{\nabla p}{\rho}-a-\frac{\mu}{\rho}\nabla(u\cdot\nabla u), \tag{2}$$

where: u – velocity of fluid flow, t – time, μ – dynamic viscosity of fluid, ρ – density of fluid.

The equation takes into account the forces acting on the contaminant particles, including drag and gravitational forces. This makes it possible to describe the movement of particles in the filter media and their deposition due to gravitational forces, and also allows one to predict the distribution of contaminant particles in the filter media depending on various parameters such as flow rate, media permeability, particle density, etc. This makes it possible to optimize the design of the filter system and select the best conditions for removing contaminants from the ship oil.

$$\frac{\partial u}{\partial t}=-\frac{\mu}{k}\left(\nabla P-\rho g\right)+\frac{\mu}{\rho}\nabla^2 u, \tag{3}$$

where: k – permeability of the filtering medium, μ – dynamic viscosity of the liquid, P – pressure of the liquid, ρ – density of the liquid, g – acceleration of free fall.

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For an example of calculating the filtration process of ship oil, let us use a simplified version of the Darcy-Brinkman equation, which takes into account only the drag force of the contamination particles, without taking into account the gravitational force and other influencing factors.

$$\frac{\partial u}{\partial t} = -\frac{k}{\mu}(\nabla P), \quad (4)$$

where: u – oil flow velocity, t – time, k – permeability of the filter medium, μ – dynamic viscosity of oil, P – oil pressure.

For the filtration process, let us assume that the oil flow velocity is constant and equal to u_0 (average value). Then the equation takes the form: $\frac{\partial u}{\partial t} = 0$. The solution of this equation is a constant value of the flow velocity $u = u_0$.

Now, to evaluate the efficiency of contaminant removal, we assume that the contaminant particles have size d. We will also assume that when passing through the filter media, the contaminant particles remain in the media and do not pass through it. This corresponds to the assumption that the filter medium has sufficient permeability for oil but is impermeable to contaminant particles of size d.

Suppose we have a filter media through which ship oil passes. Let us assume that the filter medium is homogeneous and has constant permeability k, u is the oil flow rate through the filter medium. Let us simplify the Darcy-Brinkman equation to the form:

The contaminant removal efficiency can then be defined as the ratio of the volume of contaminants retained in the filter medium to the total volume of contaminants in the oil.

The grouped bar chart illustrates the filtration efficiency (%) for different types of lubricant filters (Full-flow, Partial-flow, and Combined) with respect to three particle types (Type X, Type Y, and Type Z). The chart provides a visual comparison of the performance of each filter type in removing specific types of contaminants from the lubricant shown in Fig.8.

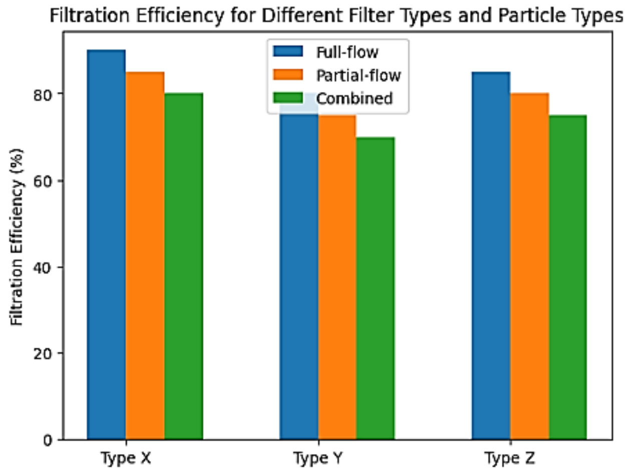

Fig.8. Filtration efficiency comparison of lubricant filters for different particle type

Analyzing the graph data, we can arrive at the following conclusions:

The Full-flow filter exhibits the highest filtration efficiency among the three types for Type X particles, boasting an impressive rate of approximately 90 %. It is especially effective at removing larger contaminants of this type. For Type Y particles, the Full-flow filter maintains a solid filtration efficiency of around 80 %, demonstrating consistent performance across different particle sizes. Similarly, for Type Z particles, the Full-flow filter showcases efficient filtration, achieving an approximate rate of 85%. This indicates its ability to effectively capture contaminants of varying sizes. Comparatively, the Partial-flow filter displays slightly lower efficiency rates. It achieves around 85 % efficiency for Type X particles, 75 % for Type Y particles, and approximately 80% for Type Z particles. The Combined filter lags behind the other two options in terms of filtration efficiency. It registers roughly 80 % for Type X particles, 70 % for Type Y particles, and about 75 % for Type Z particles. This suggests that while the Combined filter offers moderate filtration capabilities, it might not be as effective as the other filters.

In summary, the Full-flow filter stands out as the most efficient in removing contaminants across all particle types, while the Partial-flow filter follows closely behind. The Combined filter, though offering reasonable filtration performance, falls short in comparison. The choice of the most suitable filter should be guided by specific application needs and desired levels of contaminant removal. Overall, the Full-flow filter demonstrates the highest efficiency in removing particles of all three types, making it the most effective choice for maintaining clean lubricant in the system. However, the choice of filter type depends on the specific application, flow rates, and the required level of filtration. Engineers and operators should consider the characteristics of the lubricant, the nature of contaminants present, and the filtration needs of the machinery to select the most appropriate filter type for optimal performance and system longevity.

Conclusions

Research in lubricant treatment technologies is indeed a cornerstone for enhancing the performance, longevity, and environmental sustainability of engines and machinery. It encompasses crucial aspects like filtration efficiency, which directly impacts the reliability and safety of equipment. Additionally, mitigating contaminants in oils and lubricants is paramount to prevent efficiency loss and potential breakdowns. This research contributes not only to the field of engineering but also aligns with broader environmental and economic goals.

To address these challenges, various techniques are employed, including sedimentation, filtration, and centrifugation. Sedimentation involves allowing heavier particles to settle due to gravity, while filtration uses filter media to trap solid impurities, and centrifugation separates impurities based on their density difference. The choice of technique depends on factors such as the type of contaminants, the volume of oil, and the desired level of purification.

Research into the effectiveness and improvement of marine oil purification and filtration technologies is essential to ensure reliable and efficient operation of marine engines. This research helps to identify the best methods for cleaning oil from impurities and contaminants, as well as improving filtration technologies, which helps to increase engine life and prevent premature engine wear. In addition, this research develops current understanding and regulations in the field of marine engine service and maintenance, contributing to the overall efficiency and reliability of marine vehicles.

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