# TECHNOLOGIES AND HEAT EXCHANGE EQUIPMENT FOR TREATMENT AND UTILIZATION OF WASTEWATER FROM THERMAL POWER PLANTS

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*The article considers the problems of hydrosphere pollution in Ukraine, in particular, those related to the activities of thermal power plants. The main sources of discharges that arise during their operation are described, including wastewater from cooling systems, exhaust gas desulfurization systems, as well as water contaminated with petroleum products. The classification of wastewater, its features and consequences for the ecosystem emphasize the relevance of compliance with discharge standards and, depending on their types, allow you to choose a method for their purification and disposal. The article describes in detail the processes of purification of polluted waters with an emphasis on the use of unique methods and equipment, such as rotary aeration and oxidation plants, which increase the efficiency of purification by using the method of discrete-pulse energy input. The authors propose modern technologies for emulsifying watered liquid hydrocarbons, which provides the possibility of utilizing wastewater from thermal power plants contaminated with petroleum products. The analysis showed that the design of the rotor-pulsation apparatus unit implements intensive homogenization and emulsification of the treated system. The processes of combustion of water-fuel emulsions are also considered, which allows reducing emissions of pollutants. The results of the study indicate the possibility of significantly reducing the negative impact on the environment due to effective wastewater treatment to maximum allowable concentrations of harmful substances in water bodies. The conducted studies allow making the right choice of treatment or disposal technology, their treatment mode depending on the type of wastewater, which will ensure compliance with environmental standards to ensure the purity of water resources of Ukraine.*

***Keywords**: water-oil emulsions, emulsification, combustion, wastewater utilization*

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## 1. Introduction

Today, one of the most significant environmental conservation issues for Ukraine remains the pollution of the hydrosphere [1]. Energy-generating facilities significantly impact water bodies [2]. However, without their operation, it is impossible to ensure the normal functioning of industrial production, enterprises, institutions, and the comfortable living conditions of the population. Alongside hydraulic and nuclear power plants, a large number of thermal power plants (TPP) have been built on the territory of Ukraine.

The operation of thermal power plants is associated with the use of a large amount of water. The main part of water (over 90%) is used in the cooling systems of various equipment: turbine condensers, oil and air coolers, moving mechanisms, etc. [3].

Wastewater is any water stream discharged from the power plant cycle. In addition to cooling water systems, wastewater or discharge water includes: discharge water from hydrochloric acid capture systems (WWT), spent solutions after chemical flushing of thermal power equipment or its preservation: regeneration and sludge water from water treatment plants (WWTs): oil-contaminated effluents, solutions, and suspensions arising from the washing of external surfaces of heating elements, mainly air heaters and water economizers of boilers burning sulfur fuel.

The composition of the listed effluents varies and is determined by the type of thermal power plant (TPP) and the main equipment, its capacity, the type of fuel used, the composition of the original water, the method of water treatment in the main production, and, of course, the level of operation.

The waters after cooling the turbine condensers and air coolers usually carry only so-called thermal pollution since their temperature is 8…10°C higher than the water temperature in the source. In some cases, cooling waters can introduce foreign substances into natural water bodies. This is because the cooling system also includes oil coolers, the density violation of which can lead to the penetration of petroleum products (oils) into the cooling water. Oil-contaminated effluents are formed at oil-fired TPPs.

The quantity of water in cooling systems is mainly determined by the amount of steam exhausted to turbine condensers. Therefore, most of this water is found at condensing TPPs (CPTs) and nuclear power plants, where the amount of water (t/h) cooling turbine condensers can be found using the formula $Q = KW$, where $W$ is the station's power, MW; $K$ is the coefficient: for TPPs, $K = 100…150$, for nuclear power plants – 150…200 [4].

The purpose of this work is to classify the wastewater from thermal power plants (TPPs), analyze existing technologies and equipment for their treatment, determine the compliance of wastewater indicators with the maximum allowable concentrations (MAC) of harmful substances specific to the energy sector before discharge into water bodies, and to present new energy-efficient equipment for wastewater treatment and utilization.

## 2. Classification of wastewater from TPPs

### 2.1. Wastewater from cooling systems

Wastewater from cooling systems is water used in turbine condensers and other heat exchange equipment, where it is only heated without undergoing mechanical or chemical pollution. However, thermal pollution poses a particular danger to water bodies and their inhabitants. Therefore, discharging heated water from power plants should be carried out in accordance with regulatory documents, allowing it only if the average monthly water temperature after discharge into the reservoir in summer does not exceed the natural temperature by 3…5°C [5].

As means of reducing the temperature of wastewater from cooling systems, cooling towers, spray ponds, and various types of cooling towers have found the widest application.

### 2.2. Wastewater from flue gas desulfurization systems (FGD)

The slag formed during fuel combustion and the ash captured are removed by the fly ash removal system. Recirculating FGD systems, which have aeration to maintain a salt balance and, consequently, minimize deposit formation, are the most widespread. The blowdown water of the FGD system is considered one of the most toxic effluents, so the recirculating systems of all TPPs (planned, under construction, and under reconstruction) must be designed to be non-discharging. Lime has been widely used to reduce the harmful effects of blowdown water. In the treatment process, poorly soluble compounds containing arsenic, fluorine, and chromium, which precipitate, are formed. However, the application of only one treatment stage – lime, may not always purify the water to the required MPC. Therefore, for a deeper purification stage, other reagents (iron, magnesium, aluminum salts, etc.) are additionally introduced, or post-treatment is carried out using sorption methods [6].

### 2.3. Regeneration wastewater from water treatment plants (WTPs)

Water preparation at Water Treatment Plants (WTP) proceeds in two stages: initial purification and complete desalination. Therefore, effluents generated during WTP operation are divided into two streams: 1) waters obtained during coagulation and liming, containing a large amount of suspended solids; 2) waters of increased mineralization. Effluents after the first purification stage contain organic matter, aluminum and iron salts, as well as calcium carbonate, magnesium hydroxide, and unreacted reagent. To effectively utilize effluents from the water treatment system at Thermal Power Plants (TPP), sludge dewatering stations are constructed, where the obtained sludge is dehydrated, and the separated water is returned to the cycle. Waters with increased salt content (mineralization) are sent to the ash removal system for ash and slag removal, or for softening with subsequent return to the WTP, or for evaporation. In the future, replacing traditional direct-flow desalination with counter-current desalination may become an effective method of reducing the consumption of necessary reagents and minimizing effluents formed during the preparation of high-quality water. However, the use of the best and most advanced ion exchange systems does not exclude the formation of effluents. Therefore, numerous developments are being carried out to improve various methods of treatment and utilization of effluents. World experience shows that achieving complete effluent utilization is currently possible only through the use of evaporators with the precipitation of salts in solid form.

### 2.4 Wastewater Contaminated with Petroleum Products

Water pollution with petroleum products at TPPs occurs during processes such as: operation and repair of various equipment in the fuel oil economy; leaks from oil systems of turbines, electric generators, and exciters; accidental spills of fuel oil and oil; leaks from bearing cooling systems of pumps, chimney fans, ventilators, etc., as well as from garages and places where vehicles are washed. Purification of oil-contaminated water is an exceptionally important task due to the environmental impact of petroleum products. Therefore, methods for purifying these waters are constantly being modernized. For example, at modern TPPs, in addition to using conservative systems (Fig. 1), consisting of oil skimmers, mechanical filters, and filters loaded with activated carbon, alternative filters have also been applied [7].

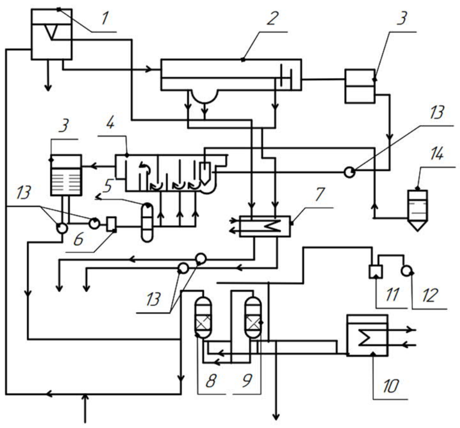


***Fig. 1.*** *Technological scheme for the purification of wastewater containing petroleum products: 1 - receiving tank; 2 - oil skimmer; 3 - intermediate tanks; 4 - flotation unit; 5 - pressure vessel; 6 - ejector; 7 - fuel oil receiving tank; 8 - mechanical filter; 9 - filter loaded with activated carbon; 10 - wash water tank; 11 - receiver; 12 - compressor; 13 - pumps; 14 - coagulant solution.*

One of the ways to modernize the wastewater treatment system is by using HVO sludge at the final stage of purification, which reduces the costs of wastewater treatment. In this regeneration scheme, the sludge will not be regenerated but will be co-incinerated with auxiliary fuel, greatly simplifying disposal.

**2.5 Wash waters**

During combustion at power plants of various types of fuels: mazut and solid fuels, ashes of various compositions settle in the regenerative air preheaters system and on the walls of the flue gas duct. The wash waters from these surfaces after use have relatively high acidity, and the content of toxic substances exceeds the norm (V, Ni, Cu, etc.). Most often, a two-stage neutralization method is used to neutralize and dispose of wash waters: at the first stage, treatment with caustic soda is carried out to pH = 4.5…5, and at the second stage - with lime (pH = 9.5…10) (Fig. 2). The purified water is then reused for washing.

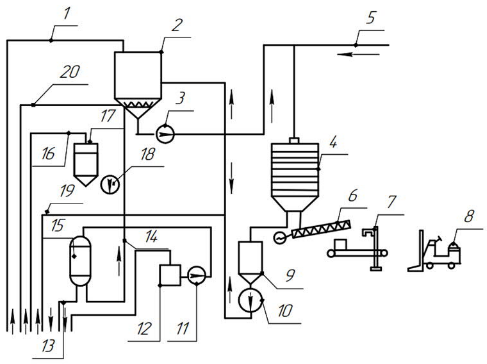


***Fig. 2.*** *Scheme of wash water neutralization and disposal installation: 1 - wash water; 2 - neutralization tank; 3 - pump; 4 - filter press; 5 - technical wash water; 6 - screw conveyor; 7 - bag sewing machine; 8 - loader; 9 - collection tank; 10 - filtrate pump; 11 - salt solution pump; 12 - salt solution metering tank; 13 - filtrate; 14 - regeneration solution; 15 - cation exchange filter; 16 - lime milk; 17 - mixer; 18 - pump; 19 - clarified water; 20 - compressed air.*

### 2.6 Wastewater from Chemical Cleanings and Equipment Preservation

The choice of the technology for cleaning and the chemical composition of the required reagents depends entirely on the deposits (composition, type) that need to be removed and the type of equipment being cleaned. The chemical cleaning of equipment is carried out in several stages: preliminary washing with water, degreasing with an alkali, washing with the necessary solution, and finally, passivation. Various reagents are used for chemical cleaning: inhibited hydrochloric acid, sulfuric acid with hydrazine, complexones, etc. The use of reagents for which no Maximum Allowable Concentration (MAC) standard is established or which cannot be neutralized is prohibited. To reduce the volume of such wastewater, it is advisable to use preservation methods based on dry processes, treatment of heat exchange surfaces with complexones, regeneration of expensive chemical solutions used for cleaning, and preservation of equipment with contact corrosion inhibitors. The best way to reduce the number of cleanings is to supply the Thermal Power Station (TPS) with exceptionally high-quality makeup water.

To mitigate the negative impact of washing water, toxic substances are isolated and subsequently oxidized. After sludge separation, the purified water is reused for equipment cleaning [8].

### 2.7 Surface Runoff and Meltwater

The type and composition of contaminants in the surface runoff from power plants depend on weather conditions (intensity and duration of rainfall, snow volume, and the method of snow collection) and the landscaping and improvement of the area. The main contaminants of this type of wastewater include petroleum products and suspended solids.

Therefore, each TPS has its algorithms for calculating the volume of surface water, which generally depends on the location of the station and the area it occupies. The runoff data include stormwater (water from irrigation and washing of road surfaces).

To reduce soil and groundwater pollution levels, local treatment facilities for wastewater purification are constructed at thermal power plants. Another method is collecting wastewater in specially created tanks, followed by purification in sedimentation tanks and filters, which use anthracite or activated carbon as filter materials.

Uncontaminated rain and meltwater can be used for internal needs: replenishing closed-loop water supply systems, water treatment, etc.

Purified wastewater from TPS, which is not used for specific needs, is discharged into water bodies for municipal or fishery purposes. Table 1 presents the maximum allowable concentrations (MAC) of harmful substances characteristic maximum permissible content of substances in the water of water bodies of the energy sector.

TPS wastewater is varied, and the chemical composition of each type of wastewater is different. The technology for wastewater treatment is complex and multi-stage, requiring a large amount of diverse equipment.

### 3. Equipment for Purification and Utilization of Wastewater Contaminated with Petroleum Products

At the Institute of Thermoelectricity and Thermal Engineering of the National Academy of Sciences of Ukraine, a multifunctional research-industrial (Figure 3) and industrial (Figure 4) rotary-type aeration-oxidation installations (AOI) have been developed, which operate using the discrete-impulse energy injection method (DPIE) [10, 11].


***Fig. 3.*** *Research-industrial rotary-type aeration-oxidation installation (AOI): 1 - collector-accumulator; 2 - aerator-oxidizer; 3 - filtration-oxidation column; 4 - spraying head; 5 - water meter; 6 - manometer; 7 - vacuum meter; 8 - air supply valve; 9 - two-way valve.*

These installations accelerate the rate of heat and mass transfer in chemical reactions in water and water systems by 25-30%. They allow for reducing the duration of purification processes, decreasing energy consumption and reagent consumption by 2-3 times, and by 20-25%, respectively. The AOI installation is used for purifying wastewater from iron, manganese, hydrogen sulfide, carbon dioxide, sulfates, and nitrates. It can also be utilized to adjust the pH of water [12-14].


***Fig. 4.*** *Industrial Equipment: 1 - aeration-oxidation installation; 2 - start-up and control unit; 3 - intermediate water supply tank to the filter; 4 - filter; 5 - collection tank for finished product*

The AOI installation allows for the intensification of mixing, dissolution, heating, dispersion, aeration, and degassing processes. These effects are achieved because the AOI installation operates based on the DPIE method. The implementation of the DPIE method involves creating a large number of uniformly distributed working elements in a dispersed medium, which transform stationary thermal, mechanical, or other types of energy into powerful energy impulses, discrete in time and space.

Accompanying these phenomena are shock waves, surface turbulence, microcavitation, flowing cumulative microjets, and vortices that induce instabilities of the Rayleigh-Taylor or Kelvin-Helmholtz type on phase boundaries, leading to the intensive fragmentation of dispersed inclusions, significant increase in the total contact surface area of phases, and intensification of heat and mass transfer processes.

Similar effects are usually unattainable when using traditional methods for water and water system treatment, even with significantly higher specific energy consumption levels.

The most effective operation based on the DPIE method is achieved with a single-rotor, two-stator rotary-pulsation apparatus (RPA). [15], the design of which is presented in Figure 5.

The working unit of the rotary-pulsation apparatus contains a housing 7, in which coaxial rotor 1, internal 2, and external 3 stators, each with longitudinal slots 4, are arranged with clearance between them. For example, the external stator 3 is made of two parts 5 and 6 in terms of thickness, installed with the ability to rotate relative to each other and fix in a predetermined position (Figure 5).

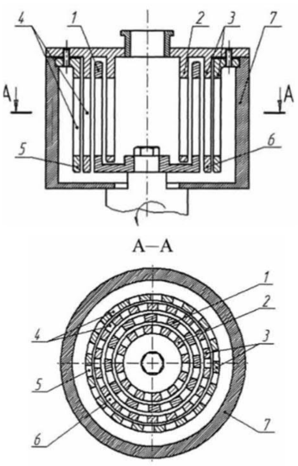


***Fig. 5***. *Rotary-pulsation apparatus with a single rotor and two stators: 1 - rotor; 2 - internal stator; 3 - external stator; 4 - longitudinal slots of the rotor and stators; 5, 6 - parts of the external stator; 7 – housing*

The working unit of the rotary-pulsation apparatus operates depending on the parameters and properties of the processed liquid medium by mutual rotation to the required angle of parts 5 and 6 of the external stator 3 to achieve the necessary degree of mutual overlap of longitudinal slots 4, after which the positions of parts 5 and 6 of the external stator 3 are fixed between each other. The working unit of the rotary-pulsation apparatus is supplied with a liquid system. Due to the rotation of the rotor 1, located on the shaft, a centrifugal force arises, which, along with the pressure drop, causes the liquid to pass sequentially through the longitudinal slots of the stator 2, rotor 1, and stator 3, as well as between-cylinder clearances. During this process, the flow undergoes significant hydro-mechanical action from the longitudinal slots of the rotor 1 and stators 2, 3, and their between-cylinder clearances, due to significant gradients of shear stresses, accelerations, and pressure.

Additionally, the flow of the medium passes through a system of high-intensity kinematic vortices, which arise in the slots of the rotor 1 and stators 2, 3.

These factors lead to intense homogenization and emulsification of the processed system within the rotary-pulsation apparatus assembly.

Using this apparatus, tests were conducted to prepare water-oil emulsions (WOEs). Thermal power plant (TPP) wastewater contaminated with oil products was used as the aqueous phase in the emulsion. The use of TPP wastewater contaminated with oil products as the aqueous phase in preparing WOEs allows for their complete utilization through fire degreasing. This eliminates the need for treating wastewater from oil products. In preparing WOEs, the content of wastewater contaminated with oil products can reach up to 50%. Burning water-oil emulsions with the addition of moisture in the form of TPP wastewater contaminated with oil products leads to a reduction in temperatures in the zone of maximum nitrogen oxide generation and, accordingly, to a significant 30-50% decrease in their concentration in flue gases.

The successful use of water-fuel emulsions is primarily justified by the choice of the device used to prepare them. In this case, a rotary-pulsation apparatus was chosen fig. 5.

The quality of any emulsion is determined by its dispersion, i.e., the surface area of the dispersed phase. The dispersion of the emulsion characterizes the uniformity of water distribution in the fuel mass and affects the stability, viscosity, electrical conductivity, and other qualities of the emulsion. The higher the dispersion, i.e., the more water droplets and the smaller their size, and the less they differ in size, the more evenly water is distributed in the fuel, the more stable the emulsion, and the higher its quality.

Calculations and experimental data convincingly demonstrate that switching boilers to burn water-oil emulsions is justified because it improves the environmental cleanliness of emissions.

In the composition of fuel emulsion, water itself does not burn, but water vapor decomposes into radicals that catalyze oxidative reactions during fuel combustion. It is known that the rate of the chain chemical reaction is proportional to the concentration of radicals that drive the process. For water-in-mazut, the concentration of such centers will always be higher than for non-water-in-mazut. With an increase in the water content of the mazut emulsion, the partial pressure of water vapor increases, and accordingly, the number of dissociated molecules of water vapor increases. In addition to thermal dissociation of water vapor into hydrogen and oxygen according to the equation $2H_2O = 2H_2 + O_2$, dissociation into hydrogen and hydroxyl is possible, that is, the existence of equilibrium $H_2O = H^+ + OH^-$. During combustion, positive ions easily interact with neutral molecules, resulting in the formation of free radicals.

Free radicals can also be formed during the recombination of positive ions with electrons or negative ions. The energy released in this process is sufficient to break down newly formed molecules into radicals. During the recombination of the hydroxonium ion $H_3O^+$, energy equal to 821 kJ per mole is released, which is sufficient for the complete splitting of $H_2O$ into $H^\bullet$ and $OH^\bullet$ radicals. The advantage of fuels containing water over non-water-containing fuels is that even at low temperatures in the combustion zone, they always provide higher initial concentrations of active centers of atoms and radicals. The appearance of a larger number of active centers of atomic hydrogen $H^\bullet$ and hydroxyl radical $OH^\bullet$ in the combustion zone of water-containing fuel can significantly accelerate the oxidation and combustion reactions of hydrocarbon fuel due to the development of reactions via the chain-thermal mechanism.

The accelerating effect of water vapor in the combustion of carbon oxide is explained by the overall reaction:

$$H_2O + CO = CO_2 + H_2, \qquad (1)$$

which produces easily flammable hydrogen. The subsequent homogeneous oxidation of hydrogen leads to the formation of $OH^\bullet$ radicals and $H^\bullet$ and $O^\bullet$ atoms (that are also radicals), which contribute to the development of the chain-basic reaction through processes such as

$$OH^\bullet + CO = CO_2 + H^\bullet \qquad (2)$$

and

$$H^\bullet + CO + O_2 = CO_2 + OH^\bullet, \qquad (3)$$

as well as their branching

$$H^\bullet + O_2 = O^\bullet + OH^\bullet \quad (4)$$

and

$$O^\bullet + H_2 = H^\bullet + OH^\bullet, \quad (5)$$

or

$$O^\bullet + CO + O_2 = CO_2 + O^\bullet + O^\bullet. \quad (6)$$

This explains the increased combustion rate of $CO_2$, which always occurs in the presence of water vapor.

Water is not only an initiator of chain reactions, but also participates in the development of the chains themselves. This is evidenced by changes in the intensity of luminescence observed with an increase in water content in the mixture. Additionally, when burning water-diluted fuel oil, the amount of smoke caused by the usual oxygen deficiency of fuel cracking and the release of free hydrocarbons is reduced. These hydrocarbons can burn according to the reaction

$$C + H_2O = CO + H_2, \quad (7)$$

for which the presence nearby of fuel cracking molecules with sufficient quantities of combustion products containing water vapor is necessary.

Apparently, in water-diluted fuel, there is always a sufficient amount of water vapor, so even without oxidation $H_2$ into $OH^\bullet$, oxidation C into CO, and then CO into $CO_2$ will be mandatory. Emulsification of water-diluted liquid hydrocarbons provides the possibility of utilizing wastewater from thermal power plants contaminated with petroleum products, with water-fuel emulsions stably burning with water content up to 50 volume percent.

## 4. Conclusions

The presented heat exchange equipment in the form of a plate heat exchanger operating by the DPIE method can be used not only for treating wastewater from thermal power plants (TPPs) but also for their disposal by using them in the preparation of water-fuel emulsions.

When burning water-fuel emulsions made from TPP wastewater, the combustion efficiency of fuel oil increases due to changes in combustion mechanisms. The content of CO decreases in the flue gases, minimal soot formation occurs in the combustion chamber, and the temperature of the flue gases decreases, which positively affects their composition.

Wastewater treatment from TPPs is an important and necessary factor. The choice of a rational treatment regime depends on the chemical composition of the wastewater, which in turn depends on the type of TPP, installed equipment, TPP capacity, initial composition of the raw water, chosen method of water treatment, and operating level.

The paper presents a classification of wastewater from TPPs, as well as technology and equipment for their treatment. The maximum permissible concentrations of harmful substances characteristic of the energy industry in wastewater are indicated. A new energy-efficient equipment is proposed, which allows treating water from a wide range of harmful substances to their maximum permissible concentrations and below.

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# ТЕХНОЛОГІЇ ТА ТЕПЛОМАСООБМІННЕ ОБЛАДНАННЯ ДЛЯ ОЧИЩЕННЯ ТА УТИЛІЗАЦІЇ СТІЧНИХ ВОД ТЕПЛОЕЛЕКТРОСТАНЦІЙ

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*У статті розглядаються проблеми забруднення гідросфери України, зокрема, пов'язані з діяльністю ТЕС. Описано основні джерела скидів, що виникають при їх експлуатації, в тому числі стічних вод систем охолодження, систем десульфурації вихлопних газів, а також вод, забруднених нафтопродуктами. Класифікація стічних вод, їх особливості та наслідки для екосистеми підкреслюють актуальність дотримання норм скидів і, залежно від їх типів, дозволяють вибрати спосіб їх очищення та утилізації. У статті детально описані процеси очищення забруднених вод з акцентом на використання унікальних методів та обладнання, таких як роторні аераційно-окислювальні установки, які підвищують ефективність очищення за допомогою методу дискретно-імпульсного введення енергії. Авторами запропоновано сучасні технології емульгування зволожених рідких вуглеводнів, що забезпечує можливість утилізації стічних вод теплоелектростанцій, забруднених нафтопродуктами. Аналіз показав, що конструкція роторно-пульсаційної установки забезпечує інтенсивну гомогенізацію та емульгування оброблюваної системи. Також розглянуто процеси горіння водопаливних емульсій, що дозволяє зменшити викиди забруднюючих речовин. Результати дослідження свідчать про можливість значного зниження негативного впливу на навколишнє середовище за рахунок ефективного очищення стічних вод до гранично допустимих концентрацій шкідливих речовин у водоймах. Проведені дослідження дозволяють зробити правильний вибір технології очищення або утилізації, а також режиму їх очищення в залежності від виду стічних вод, що забезпечить дотримання екологічних норм для забезпечення чистоти водних ресурсів України.*

**Ключові слова:** *водомазутні емульсії, емульгування, спалювання, утилізація стічних вод*