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ENERGY LOSSES AND ENVIRONMENTAL CONSEQUENCES OF THERMOTECHNICAL SYSTEM OPERATION

The paper examines thermodynamic causes of energy losses in thermal power plants and internal combustion engines and their environmental impact. The aim is to assess efficiency limits of thermotechnical systems and determine the relationship between energy degradation and environmental consequences such as thermal pollution and air emissions. The methodology is based on thermodynamic analysis of energy conversion processes, evaluation of thermal efficiency (including Carnot limits), exergy losses, and assessment of emission levels according to EURO environmental standards and international statistical data.

The results show that the real efficiency of thermal power plants is typically 35–40%, meaning that up to 60–65% of fuel energy is dissipated into the environment as low-grade heat. This leads to thermal pollution of water bodies and air, increases cooling water demand, and indirectly raises fuel consumption and greenhouse gas emissions. It is demonstrated that thermodynamic constraints between heat source and sink define fundamental, unavoidable energy losses regardless of technological improvements.

For internal combustion engines, it is shown that despite modern emission reduction technologies, they remain a significant source of CO₂, NO_x, hydrocarbons, and particulate matter. Transition from EURO-2 to EURO-6 standards significantly reduces specific emissions per unit distance; however, the total environmental burden remains high due to the large scale of vehicle usage worldwide.

The study confirms a direct link between energy inefficiency and environmental impact, including greenhouse gas accumulation, deterioration of air quality, and thermal stress on aquatic ecosystems. Waste heat and harmful emissions are identified as interconnected results of irreversible thermodynamic processes.

Keywords: thermodynamic analysis, thermal power plants, internal combustion engines, energy losses, exergy, thermal pollution, harmful emissions.

INTRODUCTION

Environmental protection remains one of the most pressing challenges of the modern era. The intensive development of industry, transportation, and the energy sector is accompanied by increasing emissions of harmful substances into the atmosphere, water resources, and soils, which adversely affects ecosystem stability and public health. The consequences of these processes include global warming, climate change, depletion of natural resources, and a decline in biodiversity. Particular attention should be paid to the operation of thermotechnical installations, which are significant sources of greenhouse gases, toxic compounds, and thermal pollution. In this regard, improving the environmental safety and energy efficiency of thermotechnical equipment has become strategically important in the context of sustainable development.

ANALYSIS OF LITERATURE DATA AND PROBLEM STATEMENT

The operation of thermotechnical equipment is accompanied by a range of environmental issues associated with fuel combustion processes, energy conversion, and heat transfer [1]. During the operation of boilers, heat exchangers, internal combustion engines, and other units, emissions of carbon, nitrogen, and sulfur oxides, solid particulate matter, soot, and unburned hydrocarbons are released into the environment. These components contribute to atmospheric pollution, intensify the greenhouse effect, participate in the formation of acid precipitation, and negatively affect the sanitary and hygienic condition of surrounding areas [2].

An additional contributing factor is heat losses through flue gases, insufficient thermal insulation, and suboptimal operating regimes, which lead to excessive fuel consumption and an increase in anthropogenic pressure on the environment.

The reduction of the negative environmental impact of thermotechnical equipment can be achieved through the implementation of energy-efficient and environmentally oriented technological solutions. The main directions for improvement include the modernization of boilers and heat exchangers, the use of high-efficiency burner systems, and the application of alternative and low-carbon fuels, including biofuels, natural gas, and hydrogen-based mixtures. An important role is played by the installation of flue gas cleaning systems for the removal of dust, sulfur oxides, and nitrogen oxides, as well as the automation of combustion processes aimed at optimizing equipment operating regimes.

An additional effect is provided by the utilization of secondary energy resources, which enables the reduction of heat losses, decreases fuel consumption, and lowers the level of harmful emissions [3]. Consequently, the thermodynamic analysis of environmental aspects of thermotechnical equipment operation

represents an important scientific and applied task aimed at improving the efficiency of energy systems and minimizing their environmental impact [4].

AIM AND OBJECTIVES OF THE STUDY

The aim of this work is to perform a thermodynamic assessment of energy losses in thermal power plants and internal combustion engines and to determine their impact on the level of environmental load, taking into account current energy efficiency requirements and environmental standards.

To achieve this aim, the following objectives were addressed:

to analyze the thermodynamic limitations of the efficiency of thermal energy systems based on the thermal efficiency (Carnot efficiency);

to evaluate the magnitude of energy losses in thermal power plants and their contribution to thermal pollution of the environment;

to investigate the structure and volume of pollutant emissions from internal combustion engines considering current EURO environmental standards;

to formulate recommendations for improving energy efficiency and environmental safety of energy and transport systems.

RESULTS OF RESEARCH

1. Thermodynamic analysis of environmental challenges associated with thermotechnical equipment operation

The intensive development of industry, transport, and the energy sector requires an ever-increasing consumption of energy resources in the form of heat and electricity. These processes are accompanied by a continuous growth in emissions of harmful substances into the atmosphere, water bodies, and soils, leading to climate change, global warming, depletion of natural resources, and a reduction in biodiversity. According to the International Energy Agency, global energy-related CO₂ emissions in 2025 reached nearly 38.4 billion tonnes [1].

Among the significant sources of greenhouse gases and thermal pollution are thermotechnical installations. These include boiler units, internal combustion engines, gas turbines, steam power plants, industrial furnaces, drying equipment, heat exchangers, and other energy systems. The primary energy source for most of these installations is the chemical energy of fossil fuels, which is converted during combustion into thermal energy and subsequently into mechanical or electrical energy. The efficiency of these conversion processes largely determines fuel consumption levels and the magnitude of harmful emissions.

During the operation of thermotechnical equipment, emissions of carbon, nitrogen, and sulfur oxides, solid particulate matter, soot, and unburned hydrocarbons are released into the environment. These pollutants deteriorate air quality, contribute to acid rain formation, intensify the greenhouse effect, and negatively affect human health. According to IEA assessments, the power generation sector remains one of the largest global contributors to energy-related CO₂ emissions [2].

From a thermodynamic perspective, the primary cause of environmental losses is the imperfection of real energy conversion processes. A significant portion of heat is irreversibly lost with exhaust gases, cooling media, through insufficient thermal insulation, and due to irreversibilities in combustion, heat transfer, and friction processes. This leads to reduced efficiency of energy systems, increased fuel consumption, and higher specific emissions per unit of useful energy produced.

Exergy analysis is an important tool for evaluating such losses, as it allows the degree of thermodynamic imperfection of equipment to be determined, the main sources of irreversible energy losses to be identified, and directions for system modernization to be justified [3]. Unlike conventional energy balances, the exergy approach assesses not only the quantity of energy but also its ability to perform useful work.

The main approaches to reducing the environmental impact of thermotechnical equipment include improving system efficiency, optimizing combustion regimes, implementing advanced burner technologies, recovering secondary energy resources, utilizing flue gas heat recovery, enhancing thermal insulation, and automating process control. Additional benefits can be achieved through the transition to low-carbon energy sources such as natural gas, biofuels, hydrogen mixtures, and the use of electrified heating systems. According to IEA projections, the development of clean technologies already contributes to limiting the growth of global emissions despite increasing energy demand [1].

Thus, thermodynamic analysis of environmental challenges associated with thermotechnical equipment operation represents an important scientific and engineering task that integrates energy efficiency, resource conservation, and environmental safety objectives.

The main environmental challenges include thermal pollution and atmospheric pollution.

2. Thermal Pollution

Prior to the full-scale war, the total installed capacity of combined heat and power plants (CHPs) and thermal power plants (TPPs) in Ukraine was estimated at approximately 20 GW [4]. As a result of military actions, damage to generation facilities, and the loss of part of the energy infrastructure, the available capacity of thermal power generation has significantly decreased. According to open sources, the current available capacity of TPPs is about 5387 MW, while during peak load periods thermal generation has provided up to 90% of electricity production, compensating for the deficit in the power system [5].

For a quantitative assessment of the thermal impact of energy systems on the environment, it is appropriate to use the theoretical thermal efficiency, which defines the maximum possible efficiency of heat engines under idealized conditions of heat-to-work conversion. This parameter is fundamental in thermodynamic analysis and allows the estimation of inevitable energy losses that are dissipated into the environment in the form of thermal pollution [6]:

$$\eta = 1 - \frac{T_2}{T_1},$$

where η is the theoretical thermal efficiency of energy systems;

T_1 is the temperature of the heat source, K;

T_2 is the temperature of the heat sink, K.

In thermodynamic analysis, the temperature levels T_1 and T_2 are key parameters for evaluating the limiting (ideal) efficiency of heat-to-work conversion. The difference between the heat source temperature and the heat sink temperature fundamentally determines the maximum theoretical thermal efficiency of the cycle.

The temperature T_1 is constrained by the thermal resistance of structural materials and the reliable operating conditions of boiler components under high heat loads, which for modern thermal power plants is approximately 800 K. The lower temperature T_2 , at which heat is rejected, is determined by environmental conditions and the capabilities of the cooling system and is typically assumed to be around 300 K, corresponding to average ambient conditions. In practical installations, heat rejection and steam condensation are mainly carried out using water from natural or technical water reservoirs.

From an environmental perspective, the existence of a finite temperature T_2 close to ambient conditions fundamentally limits the possibility of complete conversion of heat into useful work. According to the second law of thermodynamics, a portion of the supplied heat must inevitably be rejected to the environment, forming so-called irreversible thermal losses. In real thermotechnical systems, these losses manifest as thermal pollution of water bodies (through cooling systems), increased thermal loading of the atmosphere, and higher fuel consumption required to compensate for the reduced useful work output.

Thus, the smaller the temperature difference between T_1 and T_2 , the lower the theoretical efficiency limit of the cycle, and the greater the proportion of energy dissipated into the environment as low-grade heat. This directly links thermodynamic limitations of heat engine cycles with environmental losses, which appear as both thermal and associated chemical environmental impacts.

Using the above temperature values $T_1 = 800$ K and $T_2 = 300$ K, the theoretical thermal efficiency of energy systems (based on the ideal Carnot cycle) is determined as follows:

$$\eta = 1 - \frac{300}{800} = 0,625.$$

Thus, even under idealized conditions with no additional losses considered, the maximum theoretical efficiency of heat-to-work conversion is limited to 62.5%. Accordingly, the fraction of energy that cannot be converted into useful work and is inevitably rejected to the environment as heat amounts to 37.5%. This portion of energy forms so-called thermodynamically determined losses, which in real systems further increase due to irreversibilities in heat transfer, combustion, and mechanical friction processes, thereby intensifying the environmental burden of energy systems.

The real efficiency of modern thermal power plants (TPPs) is approximately 35–40%, meaning that 60–65% of the fuel's supplied thermal energy is not converted into electrical energy and is dissipated into the environment as heat fluxes. This indicates significant thermodynamic limitations in energy conversion processes and inefficient use of fuel resources, as approximately 2.5–3 times more fuel must be burned to produce the same amount of electrical power compared to idealized conditions.

At an installed thermal power capacity of approximately 5387 MW, total heat losses can be estimated at around 10,004 MW, which is irreversibly released into the environment through cooling systems, flue gases, and other heat transfer pathways. Thus, a substantial portion of chemical energy is transformed into low-grade heat, generating a significant thermal load on surrounding ecosystems.

The operation of TPPs is also associated with intensive water consumption, as water serves as the main working medium in condensation systems. For steam condensation in condensers, the required cooling water flow rate is approximately 500–530 times greater than the thermal effect of cooling, reflecting the low efficiency of heat utilization at the final stages of the cycle. Actual water consumption of condensing TPPs for compensating evaporation losses is about 0.1–0.2 m³/MWh, whereas water withdrawal from natural sources reaches 2–3 m³/MWh, resulting in significant excess thermal loading of aquatic environments.

At an installed capacity of 5387 MW, this corresponds to water abstraction from natural sources in the range of 10,774–16,161 m³/h, while the technically required consumption is only 539–1077 m³/h. The difference between these values is returned to the environment in the form of heated water, leading to local temperature increases in aquatic ecosystems, disruption of their hydrobiological balance, and the development of thermal pollution effects.

From a thermodynamic standpoint, these losses can be interpreted as exergy losses, i.e., a reduction in the ability of energy to perform useful work. A significant portion of the supplied energy in TPPs is converted into low-grade heat with temperatures close to the ambient environment, which, according to the second law of thermodynamics, is practically unavailable for further useful conversion. Thus, the environmental impacts of TPP operation are directly linked to fundamental thermodynamic limitations of energy cycles, and their reduction is only possible through improving the exergy efficiency of systems and utilizing secondary heat flows.

Waste cooling water from thermal power plants is typically discharged into natural water bodies with a temperature increase of 5–10 °C above baseline levels. This thermal load causes significant changes in aquatic ecosystem functioning, including accelerated eutrophication (water “blooming”), reduced dissolved oxygen concentration, and deterioration of living conditions for aquatic organisms, including fish and microorganisms. As a result, the natural equilibrium of aquatic ecosystems is disrupted, and their self-regulation capacity is reduced.

An additional environmental impact is associated with cooling systems such as cooling towers, where partial water evaporation occurs. In this case, warm and moisture-saturated air masses are released into the atmosphere, leading to local microclimatic changes, increased humidity, and additional thermal loading of surrounding territories.

The low thermodynamic efficiency of thermal power plants directly results in excessive fuel consumption, which in turn increases emissions of greenhouse gases and pollutants, including CO₂, SO₂, NO_x, and particulate matter. Thus, thermal inefficiency of energy systems is directly correlated with intensified global warming processes and deterioration of air quality.

From the perspective of environmental energy systems, an alternative to thermal power plants is the use of renewable and low-carbon energy sources characterized by minimal environmental impact and significantly reduced emissions of harmful substances. The main directions include solar energy, wind energy, and bioenergy, which enable electricity generation without large-scale fossil fuel combustion and, consequently, without substantial thermal and chemical pollution.

3. Environmental Pollution from Internal Combustion Engine Emissions

The fuel combustion temperature in internal combustion engines of various types ranges from 1800 to 2500 °C, which theoretically enables high thermal efficiency values of about 80–85%. However, under real operating conditions, a significant portion of heat is removed with exhaust gases, which leave the cylinder at temperatures of 500–700 °C, and additional losses occur due to friction and cooling systems. As a result, the actual efficiency of modern internal combustion engines is only 30–55% [4].

The main source of environmental pollution during engine operation is exhaust gases. As of March 19, 2024, there were 13.16 million motor vehicles in Ukraine, of which approximately 9.8 million were passenger cars, with an average vehicle age of 16.1 years [5]. Such a structure of the vehicle fleet represents an additional factor of increased environmental pressure.

During gasoline combustion in engines with outdated fuel injection systems, emission levels of pollutants can be significantly higher compared to modern engines. According to generalized emission factors for low Euro-class vehicles provided in the EMEP/EEA guidebook [6], elevated emissions of CO, unburned hydrocarbons (HC), nitrogen oxides (NO_x), and particulate matter are typical, reflecting incomplete

combustion processes and the absence of effective exhaust gas after-treatment systems. Even modern vehicles equipped with emission control technologies remain a significant source of air pollutants.

On a global scale, the transport sector is one of the key contributors to greenhouse gas emissions. In the European Union, road transport accounts for approximately 35% of CO₂ emissions and about 20% of total greenhouse gas emissions, while in the United States this share reaches around 30%. For Ukraine, transport-related greenhouse gas emissions are estimated at 8–12% of the total national emissions [7]. Forecasts indicate that by 2026, global CO₂ emissions from internal combustion engines may increase by 25–44%, intensifying greenhouse effect risks and climate change processes. According to the United Nations, an increase of approximately 9% in global greenhouse gas emissions has been recorded over the last decade [7].

The European Union is actively implementing transport decarbonization policies aimed at significantly reducing greenhouse gas emissions from road transport by 2050 (by up to 60% compared to 1990 levels). A key technological measure is the widespread use of three-way catalytic converters, which simultaneously reduce CO, NO_x, and hydrocarbon emissions under stoichiometric air-fuel mixture conditions [8].

In addition to structural improvements of engines and exhaust gas treatment systems, an important approach to reducing environmental impact is the use of alternative fuels. Biofuels derived from renewable biomass sources and secondary organic resources represent a promising solution. In particular, biodiesel produced from vegetable oils and fat-containing waste is considered an effective alternative to conventional diesel fuel [9].

A promising feedstock is technical chicken fat obtained from fat-rich waste of poultry processing plants, including feathers, blood, offal, and meat-fat residues [10–11]. The cost of such raw material is approximately three times lower compared to vegetable oils, which increases its economic feasibility.

Biodiesel has several environmental advantages compared to conventional fuels: it is a renewable energy source, contains lower levels of sulfur and polycyclic aromatic hydrocarbons, and contributes to a reduction in total pollutant emissions. Additionally, it reduces the impact on the greenhouse effect, since during combustion it releases approximately the same amount of CO₂ that was absorbed by plants during growth, thereby partially closing the natural carbon cycle [9].

DISCUSSION OF RESULTS

Based on the performed analysis of the thermodynamic efficiency of thermotechnical equipment and the environmental impact of vehicles with internal combustion engines, a set of technical and organizational measures aimed at reducing emissions and improving energy efficiency can be formulated.

The primary direction is the improvement of the thermodynamic efficiency of thermal energy systems through the modernization of main equipment. In particular, the implementation of high-efficiency heat exchangers, the enhancement of burner systems, the optimization of combustion processes, and the use of advanced thermal insulation materials enable the reduction of heat losses and, consequently, a decrease in fuel consumption.

An important role is played by the introduction of waste heat recovery systems, including regenerative cycles and cogeneration units, which increase the overall fuel energy utilization efficiency and reduce the level of thermal pollution of the environment. Special attention should also be given to improving water cooling systems, in particular through the implementation of closed-loop or low-water consumption cycles, which reduce the thermal load on natural water bodies.

For internal combustion engines, a key direction is the reduction of exhaust gas toxicity through the implementation of modern after-treatment systems, including three-way catalytic converters, particulate filters, and selective catalytic reduction systems for nitrogen oxides. Additional benefits are achieved by maintaining an optimal stoichiometric air-fuel ratio and applying electronic engine control systems to regulate the combustion process.

A significant environmental potential lies in the gradual substitution of conventional fossil fuels with alternative energy carriers. The use of biofuels derived from plant-based feedstocks or organic waste materials (including fat-containing residues from the agro-industrial sector) makes it possible to reduce total greenhouse gas emissions and partially close the carbon cycle.

A separate strategic direction is the development of renewable energy sources such as solar, wind, and bioenergy, which enable electricity generation without large-scale fossil fuel combustion and, consequently, without significant emissions of pollutants and thermal discharges.

The comprehensive implementation of the above measures allows for simultaneous reduction of anthropogenic environmental impact, improvement of energy efficiency in heat supply and transport systems, and ensuring sustainable development of industrial and energy enterprises.

CONCLUSIONS

1. The operation of thermal power plants is accompanied by significant thermodynamic energy losses, which are dissipated into the environment in the form of low-grade heat. This leads to thermal pollution of water bodies and atmospheric air, deterioration of ecosystem conditions, and indirectly intensifies the greenhouse effect due to the need for additional fuel consumption to generate the required electrical power.

2. Fundamental limitations of thermodynamic cycles determine a low fraction of useful energy conversion, resulting in increased resource consumption and considerable environmental losses. From the perspective of sustainable energy development, the most promising approach is the integration of renewable energy sources into a balanced energy system with energy storage facilities, which reduces dependence on fossil fuels.

3. Internal combustion engines are a significant source of atmospheric pollution by carbon oxides, nitrogen oxides, hydrocarbons, and particulate matter. Their environmental impact can be reduced through the improvement of emission standards, the development of advanced exhaust gas after-treatment systems, and the use of alternative fuels, particularly biodiesel.

4. The application of energy-efficient heat exchanger designs, environmentally safe materials, and automated purification systems for process media contributes to reducing energy losses and anthropogenic pressure on the environment. This ensures higher overall energy efficiency of industrial systems and aligns with the principles of sustainable industrial development.

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Шинкарик М.М., Кравець О.І. Енергетичні втрати та екологічні наслідки роботи теплотехнічних систем

Розглянуто термодинамічні причини формування екологічного навантаження, пов'язаного з функціонуванням теплових електростанцій та двигунів внутрішнього згоряння. Мета дослідження полягає в комплексному оцінюванні енергетичних втрат теплотехнічних систем і визначенні їхнього впливу на довкілля з позицій другого закону термодинаміки та сучасних екологічних вимог. Методика реалізації базується на аналітичному дослідженні термічного коефіцієнта корисної дії енергетичних установок, оцінюванні ексергетичних втрат у процесах перетворення енергії, аналізі

нормативних емісійних показників стандартів Еуго-2–Еуго-6, а також використанні статистичних даних щодо енергетичного сектору та автомобільного транспорту.

Результати дослідження показали, що реальний коефіцієнт корисної дії теплових електростанцій перебуває в межах 35–40 %, що зумовлює втрати до 60–65 % первинної енергії палива у вигляді низькопотенційної теплоти, яка відводиться у навколишнє середовище. Це спричиняє теплове забруднення водних об'єктів і атмосферного повітря, а також додаткове споживання природних ресурсів. Встановлено, що теплова потужність, яка розсіюється у докільля за наявних генерувальних потужностей, перевищує 10 ГВт, тоді як водоспоживання систем охолодження залишається екологічно значущим чинником впливу.

Для двигунів внутрішнього згоряння підтверджено суттєве скорочення питомих викидів за рахунок послідовного впровадження стандартів Еуго, однак транспортний сектор і надалі залишається вагомим джерелом викидів CO₂, NO_x, незгорілих вуглеводнів та твердих частинок. Показано прямий взаємозв'язок між енергетичною неефективністю та зростанням техногенного навантаження на докільля. Висновки свідчать, що ключовими напрямками мінімізації негативного впливу є підвищення енергоефективності теплотехнічного обладнання, утилізація вторинної теплоти, модернізація систем очищення викидів, розвиток відновлюваної енергетики та впровадження альтернативних палив, зокрема біопалива.

Ключові слова: термодинамічний аналіз, теплові електростанції, двигуни внутрішнього згоряння, енергетичні втрати, ексергія, теплове забруднення, викиди шкідливих речовин.

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