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On the necessity and feasibility of revising and improving the methodology for calculating losses of petroleum products from evaporation based on the results of calculation and comparative analysis

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Abstract. The aim of the work was to analyse the regulatory framework for accounting for petroleum product losses in Ukraine. A comparative and empirical analysis of three methods for determining petroleum product losses from evaporation was carried out. Calculations were made of petrol standing losses in vertical steel tanks with a nominal volume of 1,000, 2,000 and 3,000 m^3 in different climatic zones of Ukraine. The impact of tank filling level and saturated vapour pressure on losses was assessed. A comparative analysis showed that the EPA and Konstantynov methods demonstrate a physically justified reduction in losses with an increase in the filling level, as well as high sensitivity to climatic conditions. For the VCT-3000 tank, the relative error between calculations for the middle and southern climatic zones according to the Konstantynov method is 6.9-10.6%, and according to the EPA method – 8.5-12.0%. For the VCT-2000, these figures are 5.9-9.3% (Konstantynov) and 6.9-10.5% (EPA), and for the VCT-1000, they are 6.9-10.6% and 8.5-12%, respectively. However, calculations using the standard methodology showed virtually zero sensitivity to the climate zone (relative error ~0.26%), which contradicts actual operating conditions and leads to potentially significant errors in the assessment of volatile organic compound losses. This indicates the need to revise the current Ukrainian standards, taking into account modern physicochemical evaporation models. Additionally, the influence of saturated petroleum product vapour pressure according to Reid on the amount of losses was analysed. The results of calculations for the middle and southern climatic zones showed that an increase in saturated vapour pressure from 50 kPa to 80 kPa causes an approximately 1.6-fold increase in losses for all types of tanks studied. This confirms the high sensitivity of physical and mathematical methods to the physical and chemical properties of petroleum products, in contrast to the normative approach, which does not take this parameter into account. The results obtained can be used to develop an adapted combined methodology that combines the accuracy of international standards with the simplicity of normative accounting

Keywords: petrol; standing losses; saturated vapour pressure; climate zones; tanks; regulatory document

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Introduction

The relevance of reviewing and improving the methodology for calculating petroleum product losses from evaporation is determined by factors that affect the efficiency of energy resource use, environmental safety, and economic costs. As stated in the study by G.C. Ribeiro *et al.* (2024), regular updating of regulatory documents should be considered a strategically important process that ensures the accuracy, reliability, and practical value of methods for assessing emissions from organic liquid storage tanks. This allows the document to remain an effective tool for environmental regulation, technological planning, and sustainable industrial development. Conducting a comparative analysis of existing methods is an important step in developing modern and scientifically sound standards that will optimise energy resource management in Ukraine.

International research confirms the scale of the problem. According to a study by G. You *et al.* (2024), the oil refining industry is one of the main sources of industrial emissions of volatile organic compounds (VOC). Based on the analysis of 76 samples from eight oil refineries, the authors determined that losses due to equipment leaks, storage tanks, wastewater treatment systems, and loading operations account for the majority of total emissions. In particular, emissions from storage tanks averaged 0.28 kg of VOC per tonne of refined oil, and total VOC losses at different plants ranged from 0.67 to 2.77 kg/t. Alkanes (ethane, propane, butane) and aromatic hydrocarbons (benzene, toluene) were the dominant components. This confirms that losses during storage in tanks are not only technically significant, but also have a significant environmental and regulatory dimension that needs to be taken into account in national methods for accounting and regulating losses.

A review of petrol loss calculation processes and the development of emission reduction technologies in the oil refining industry has highlighted a number of relevant issues. P. Orozco *et al*. (2023) describe the physical phenomena of petrol evaporation and their negative impact on the environment and human health. The article examines VOC emissions at various facilities (petrol stations, oil refineries), analyses standards and protocols for assessing losses in coastal reservoirs, and discusses the widespread application of these methods. It is emphasised that most studies are based on industry standards, and some of them take into account the uncertainty of measurements. In addition, the use of computational hydrodynamics methods to assess evaporation losses is described, which significantly enhances theoretical and experimental models in storage tanks. The article confirms the importance of modernising and refining national methods for calculating fuel losses during storage, aimed at reducing environmental risks, economic losses and improving regulatory control.

H. Rajabi *et al*. (2020) noted that during the storage of petroleum products in vertical tanks with floating or fixed roofs, hydrocarbons evaporate, leading to the formation of VOC in the air. These compounds are highly volatile, toxic and capable of forming a secondary pollutant such as tropospheric ozone, which has a negative impact on both human health and the environment. The study provides an overview of VOC emissions arising at various stages of oil processing and assesses the environmental impact of these emissions. An important aspect of the study was the creation of a global emissions inventory system, which provided a better understanding of the scale and sources of pollution and identified priority areas for regulating emissions and reducing environmental impact. This study was important for the development of environmental protection policies and practices, as it developed a comprehensive understanding of global VOC emissions from oil refining and helped in the search for more effective technologies to reduce these emissions. At the same time, tank losses account for a significant share of total VOC emissions at oil depots and fuel and energy complex enterprises.

Given global environmental challenges and Ukraine's international commitments to reduce industrial emissions, the issue of regulating and technically controlling VOC emissions has become particularly relevant (Law of Ukraine No. 2707-XII, 1992; Directive of the European Parliament and of the Council No. 2004/42/CE, 2004). At the same time, in order to harmonise national regulations with international standards and introduce best practices in the field of environmental protection, the regulation of industrial emissions is determined by Directive of the European Parliament and Council of the European Union No. 2010/75/EU (2010), which establishes requirements for integrated prevention and control of emissions.

In addition to the environmental impact, evaporation causes direct economic losses of fuel, which requires the implementation of effective technological solutions to minimise them. F. Beiranvand & H. Najibi (2021) emphasised the importance of reducing losses from the evaporation of volatile fuels, which is important from both an economic and environmental point of view. Evaporation leads to significant financial losses due to a reduction in fuel volume and also contributes to atmospheric pollution with harmful VOC, which can cause the formation of secondary pollutants, in particular tropospheric ozone. In addition, the accumulation of fuel vapours creates potential explosion hazards. The authors proposed an innovative approach using new mixtures of surfactants that effectively reduce evaporation, which highlights the relevance of developing and implementing technological solutions to minimise fuel losses in industry.

In accordance with the Instructions on the Procedure for Receiving, Transporting, Storing, Dispensing, and Accounting for Oil and Petroleum Products at Enterprises and Organisations in Ukraine (2008), during the storage of petroleum products, it is necessary to ensure proper accounting and control of losses. However, N.V. Liuta *et al*. (2020) noted that, unlike most developed countries, Ukraine lacks a clearly defined system for measuring, accounting for, and setting limits on petroleum product losses, particularly those resulting from evaporation during storage. The analysis of existing methods for regulating petroleum product losses showed that they do not sufficiently take into account the climatic and technological characteristics of different regions, which leads to inaccuracies in calculations and exceeding permissible losses.

The document Norms of Petroleum Product Losses During Their Reception, Storage, Dispensing, Transshipment and Transportation (2020) establishes the maximum permissible loss rates that occur during various stages of petroleum product circulation, in particular during transportation by road, rail, water and pipeline, as well as during storage. However, as noted in a study conducted by N.V. Liuta *et al*. (2020), the current methodology does not take into account a number of important factors that have a significant impact on the volume of losses, especially during the storage of petroleum products in tanks, and that it is precisely these factors ignored by the authors of the methodology that are often decisive in assessing losses from evaporation. In view of the above, the aim of this work was to justify the expediency of revising the current regulatory methodology for assessing petroleum product losses, taking into account a range of factors that actually influence the evaporation process, in order to ensure more accurate determination of such losses and improve the efficiency of their accounting and storage.

Materials and Methods

In order to identify areas for improvement in Norms of Petroleum Product Losses During Their Reception, Storage, Dispensing, Transshipment and Transportation (2020), it became necessary to conduct a scientific comparison with the methods of the United States Environmental Protection Agency (EPA) (AP-42 Chapter 7..., 2024) and Konstantynov (Lisafin & Liuta, 2018). The combined use of comparative and empirical analysis methods ensured an objective identification of differences in the approaches, parameters, calculations and regulatory aspects of these documents. Comparative analysis made it possible to compare the structure of calculation formulas, determine which factors are taken into account, and analyse the depth of scientific justification of each document.

Empirical analysis was performed based on calculations of losses for the same object (above-ground vertical cylindrical tanks (VCT) with a nominal volume of 1,000 m^3, 2,000 m^3 and 3,000 m^3) using three methods to verify the accuracy and reliability of the selected methods in practical examples. For the purpose of empirical analysis of standing losses, calculations were made for tanks with a nominal volume of 1,000 m^3 (one unit), 2,000 m^3 (one unit) and 3,000 m^3 (one unit), which were operated in the conditions of the middle and southern climatic zones. The analysis covered various tank filling levels – from minimum to maximum (Table 1), all months of the calendar year 2024, as well as the saturated vapour pressure of stored liquids in the range from 50 kPa to 80 kPa, and the geometric characteristics of the tanks. To calculate the losses of volatile fractions of petroleum products using the Konstantynov method and EPA standards, a number of initial data were taken into account. These include meteorological conditions, in particular the average monthly maximum and minimum air temperature, as well as barometric pressure on the date of calculation (Table 2).

Table 1. Main technical characteristics of the device

Nominal tank capacity, m^3	Tank diameter, m	Tank height, m	Minimum filling level, m	Maximum filling level, m
1,000	11.99	9.606	1	8
2,000	15.233	11.64	1	10
3,000	19.042	11.731	1	10.8

Source: created by authors based on V. Lisafin & N. Liuta (2018)

Table 2. Meteorological conditions in the central and southern climatic zones of Ukraine

Month	January	February	March	April	May	June	July	August	September	October	November	December
Middle zone												
Maximum air temperature, °C	5.4	1.8	4.9	11.9	17.6	20.3	22.1	22.1	17.7	11.8	8.1	8.2
Minimum air temperature, °C	0.8	-2.3	-1.5	3	7.8	10.7	12.5	11.5	8.9	6.3	4	2.9
Southern zone												
Maximum air temperature, °C	2.5	0.1	6.9	12.8	20.7	24.4	27.4	28	23	16.3	7.6	4.2
Minimum air temperature, °C	-0.1	-2.1	1.6	6.6	13.9	18.6	21.2	21.5	17.9	12.5	5	2.2

Source: created by the authors based on V.M. Lipinsky *et al*. (2003)

In addition, geographical parameters are important, in particular the geographical latitude of the reservoir location (47°37′N for the southern zone and 51°29′28″N for the middle zone). The geometric characteristics of the tank include its diameter, geometric height, and the level of liquid filling in the tank (filling height) (Table 1). The settings of the mechanical breathing valve, namely the excess pressure (2,000 Pa) and vacuum (250 Pa) at which it operates, must be taken into account. Among the physical and chemical characteristics of the petroleum product, its density (kg/m^3) and boiling point (40°C) are essential. Additionally, the review included the type and condition of the external surface of the tank (0.65), which affect the thermal regime and, accordingly, the intensity of evaporation.

Standing losses of petroleum products were calculated according to the EPA recommendations using the formula:

$$L_s = 365 \times V_V \times W_V \times K_E \times K_s, \tag{1}$$

where V_V is the volume of gas space in the tank; W_V is the vapour saturation; K_E is the gas space expansion coefficient; K_S is the saturated vapour ventilation coefficient. The vapour saturation is determined by the formula:

$$W_V = \frac{M_V \times P_{VA}}{R \times T_{LA}}, \tag{2}$$

where M_V is the molar mass of a mixture of hydrocarbon vapours; P_{VA} is the saturated vapour pressure at the average daily temperature of the surface layer of the liquid; R is the gas constant; T_{LA} is the average daily temperature of the surface layer of liquid. The average daily temperature of the surface layer of the liquid is determined by the formula:

$$T_{LA} = 0.44 \times T_{AA} + 0.56 \times T_B + 0.0079 \times \alpha \times I, \tag{3}$$

where T_{AA} is the average daily ambient temperature; T_B is the temperature of the liquid below the surface layer; α is the solar radiation absorption coefficient; I is the daily amount of solar radiation. The temperature of the liquid below the surface layer of the petroleum product is equal to:

$$T_B = T_{AA} + 6 \times \alpha - 1. \tag{4}$$

The saturated vapour pressure at the average daily temperature of the surface layer of the liquid C. de la Calle-Arroyo *et al*. (2021) recommend determining it using Antoine's formula:

$$P_{VA} = exp\left[A - \frac{B}{T_{LA}}\right], \tag{5}$$

where A and B are constant coefficients selected from reference literature depending on the type of liquid stored. The gas space expansion coefficient K_E for a known geographical location of the tank farm is determined by the following formula:

$$K_E = 0.0018[0.72 \times (T_{AX} - T_{AN}) + 0.28 \times \alpha \times I]. \tag{6}$$

If the geographical location of the tank farm is unknown, the gas space expansion coefficient is taken to be 0.04. The saturated vapour ventilation coefficient is equal to:

$$K_s = \frac{1}{1 + 0.053 \times P_{VA} \times H_{VO}}. \tag{7}$$

As part of calculating petroleum standing losses using Konstantynov's method, it is necessary to calculate the molar mass of petroleum vapours, the thermal conductivity coefficient of petrol at average temperature, the specific heat capacity of petrol, the density of petroleum products, the thermal conductivity coefficient of the petroleum product, the length of daylight hours, the transparency coefficient of atmospheric air, the intensity of solar radiation, the geometric characteristics of the gas space of the tank and the liquid surface in the tank, the amount of heat received from solar radiation by 1 m^2 of the wall limiting the gas space of the tank, determine the values of a number of heat transfer coefficients from graphs, simulate the temperature regime of the tank and petroleum product, the pressure of saturated vapours of the petroleum product, and the maximum and minimum partial pressures. The average mass content of petrol vapours in the gas-air mixture is calculated:

$$\sigma_m = \frac{P_{max} + P_{min}}{R(T_{gp.min} + T_{gp.max})}, \tag{8}$$

where P_{max}, P_{min} are the maximum and minimum pressure in the gas space of the tank; $T_{gp.max}$, $T_{gp.min}$ are the maximum and minimum temperature in the gas space of the tank; R is the universal gas constant. Volume of gas-air mixture released into the atmosphere:

$$\Delta V = V_{gp}\, ln\left(\frac{P_a - P_v - P_{min}}{P_a + P_n - P_{max}} \times \frac{T_{gp.max}}{T_{gp.min}}\right), \tag{9}$$

where V_{gp} is the volume of the gas space in the tank; P_a is the atmospheric pressure; P_v is the vacuum in the gas space in the tank; P_n is the excess pressure in the gas space in the tank. The saturated vapour pressure is determined using Rybakov's formula:

$$P_T = P_{S38} 10^{\frac{1,430}{T}}, \tag{10}$$

where P_{S38} is the saturated vapour pressure of petrol by Reid; T is the temperature of petroleum product vapours. Standing losses will be equal to:

$$M_{m.d.} = \Delta V \times \sigma_m. \tag{11}$$

To calculate petroleum product losses during storage in tanks, the following input parameters are used in accordance with the requirements of current regulations: the volume of petroleum products in the tank, its density at average temperature, the number of calendar days in the calculation month, as well as loss standards determined on the basis of daily product residues (Norms of Petroleum Product Losses..., 2020). The latter are formed on the basis of daily accounting data recorded in the petroleum product measurement log. These parameters are critical for ensuring the accuracy of loss calculations and further analysis of the efficiency of fuel and lubricant storage systems. Losses of petroleum products during storage in tanks are calculated:

$$M_{norm} = K \times V \times \rho, \tag{12}$$

where K is the loss rate based on the actual daily product balances according to the daily records specified in the petroleum product measurement log, %; V is the volume of petroleum product in the tank; ρ is the density of the petroleum product at average temperature. Another influential factor that must be indicated in the petrol quality certificate is the saturated vapour pressure according to Reid, which is the approximate absolute vapour pressure of the petroleum product under study at a temperature of 37.8°C. The saturated vapour pressure of a petroleum product significantly depends on temperature. To model this dependence, the Rybakov formula (10) and the Antoine formula (5) were used in the compared methods. To evaluate the discrepancies between the results obtained using different methods, the relative error (discrepancy) was calculated using the formula:

$$\delta = \frac{x_1 - x_2}{x_1}, \quad (13)$$

where x_1 is the reference (or base) value; x_2 is the comparable value.

Results

There is a global practice of constantly updating and improving regulatory documents. In particular, as noted in their study by N. Stef & A. Ashta (2023), this is the continuously updated document AP-42 Chapter 7, Section 1 – organic liquid storage tanks (2024), designed to provide scientifically sound methods for calculating VOC emissions generated during the storage of organic liquids in industrial tanks. These methods are used in environmental reporting, planning of emission control measures, and environmental assessment. First published in 1968, it was the first edition of a collection of emission factors for air pollutants prepared by the U.S. Public Health Service, revised in 1972 and republished under the auspices of the EPA. Since then, this document has been regularly updated to take into account new scientific data, technological advances, and changes in regulatory requirements.

In order to systematise and gain a deeper understanding of approaches to assessing petroleum product losses from evaporation, this study conducted a comparative analysis of three common methods: the American EPA AP-42 method (Section 7), current Ukrainian standards (2020) and the Konstantynov engineering method. Table 3 summarises the main characteristics of each approach, including the type of document, purpose of application, scope, consideration of climatic factors, level of detail of parameters, calculation methods and practical relevance. The data presented made it possible to identify differences in the structure, purpose and accuracy of these methods, which is the basis for further analysis of their effectiveness in different conditions. The results of the comparative analysis of the three methods are presented in Table 3.

Table 3. Results of a comparative analysis of methods for calculating petroleum product losses due to evaporation from tanks

Criterion	AP-42 Chapter 7	Ukrainian standards	Konstantynov's methodology
Document type	Methodology for calculating VOC emissions	Regulatory document on loss accounting	Calculated engineering methodology
Main purpose	Environmental control of emissions	Regulation of permissible losses	Technical and economic accounting of losses
Developing organisation	U.S. EPA	Ministry of Economy of Ukraine	Transnefteprodukt Research Institute, USSR
Types of tanks	All types: fixed, floating, domed roofs	Mainly fixed roofs, some underground reservoirs	Vertical and horizontal steel tanks
Type of petroleum products	Organic liquids	Petrol, diesel fuel, fuel oil, kerosene, etc.	Petrol, diesel fuel, fuel oil
Climatic factors	The following must be taken into account: ambient temperature, temperature difference, wind	Autumn-winter and spring-summer periods are taken into account	Temperature of the surrounding environment, temperature difference, weather conditions (sunny, cloudy) are taken into account
Product parameters	Saturated vapour pressure, molar mass, density	Density, fuel type	Molar mass of vapours, thermal conductivity coefficient, specific heat capacity, density, thermal conductivity coefficient, saturated vapour pressure
Type of losses	Evaporation losses	Losses during storage, filling, draining, transportation	Evaporation losses
Calculation approach	Physical and chemical modelling of processes	Regulatory coefficients based on statistics	Semi-empirical formulas with corrections
Calculation methods	Analytical formulas + software (TANKS)	Tables and coefficients	Formulas with corrections (K_1, K_2, etc.)
Ease of application	High accuracy, requires software	The simplest option, easy to apply	Requires technical training, complex calculations, and software
Current relevance	Applicable in the United States, used globally	In Ukraine since 2020	Used in part in practice as an engineering basis in the post-Soviet space
Documentation purpose	Reporting emissions to environmental protection agencies	Accountancy, technological accounting	Project documentation, internal calculations of enterprises

Source: developed by the authors based on a comparison of V. Lisafin & N. Liuta (2018), Norms of Petroleum Product Losses During Their Reception, Storage, Dispensing, Transshipment and Transportation (2020), AP-42 Chapter 7, Section 1 – organic liquid storage tanks (2024)

Table 3 summarises the differences between the three approaches to estimating VOC losses during petroleum product storage. The EPA methodology is highly accurate due to physical and chemical modelling and the use of specialised software (e.g. TANKS), which makes it suitable for environmental monitoring and international reporting. At the same time, Ukrainian standards are mainly focused on accounting and technological accounting of losses, are based on tabulated coefficients and are the easiest to implement in practice, although they are less accurate. Konstantynov's methodology, developed back in the Soviet period, remains relevant as an engineering basis due to semi-empirical formulas adapted to the real conditions of tank operation, but requires a high level of technical training and complex calculations. Comparative calculations were performed using the above-mentioned methodologies and standards. Table 4 presents the results of comparative calculations of evaporation losses from tanks with a nominal volume of 3,000 m^3, located in different climatic zones and for tank filling levels from a minimum of 1 m to a maximum of 10.8 m.

Table 4. Results of calculations of petrol losses due to evaporation during storage in an VCT-3000 tank at different filling levels

Level of petrol filling, m	The volume of petrol in the tank, m^3	Annual losses (Konstantynov method), kg/year		Annual losses (EPA method), kg/year		Calculation results based on storage loss rates according to Resolution of the Cabinet of Ministers of Ukraine No. 686 (2020)	
		Middle zone	Southern zone	Middle zone	Southern zone	Middle zone	Southern zone
10.8	3,076	5,261	6,502	5,962	7,644	8,272	8,315
9	2,566	12,254	14,697	13,954	17,476	6,892	6,929
8	2,278	16,005	18,954	18,214	22,567	6,127	6,159
7	1,994	19,689	23,061	22,373	27,457	5,361	5,389
6	1,709	23,292	27,021	26,420	32,143	4,595	4,619
5	1,424	26,789	30,812	30,319	36,594	3,829	3,849
4	1,139	30,127	34,387	34,010	40,739	3,063	3,080
3	854	33,205	37,638	37,361	44,423	2,298	2,310
2	570	35,759	40,280	40,046	47,246	1,532	1,540
1	285	36,775	41,188	40,812	47,672	766	770

Source: developed by the authors based on calculations

Analysis of the data in Table 4 revealed significant discrepancies in the results of calculating annual petrol losses depending on the methodology used. The EPA methodology showed the highest loss values, which clearly correlate with changes in climatic conditions: losses in the southern zone consistently exceeded the corresponding indicators for the middle zone. A similar trend, albeit with lower absolute values (by 20-30%), is recorded by the Konstantynov methodology. On the other hand, the standard method approved by Resolution of the Cabinet of Ministers of Ukraine No. 686 (2020) shows the opposite trend – as the tank filling level decreases, losses also decrease. This contradicts the physical nature of evaporation losses, which, as a rule, increase as the volume of fuel decreases due to an increase in the gas space above the liquid surface. The normative losses according to Resolution of the Cabinet of Ministers of Ukraine No. 686 (2020) are the smallest, and in the central and southern zones they differ insignificantly (less than 1%), which may indicate the limited sensitivity of this methodology to climatic factors. Table 5 presents the results of comparative calculations of evaporation losses from tanks with a nominal volume of 2,000 m^3 located in different climatic zones and for tank filling levels from a minimum of 1 m to a maximum of 10 m.

Table 5. Results of calculations of petrol losses due to evaporation during storage in an VCT-2000 tank at different filling levels

Level of petrol filling, m	The volume of petrol in the tank, m^3	Annual losses (Konstantynov method), kg/year		Annual losses (EPA method), kg/year		Calculation results based on storage loss rates according to Resolution of the Cabinet of Ministers of Ukraine No. 686 (2020)	
		Middle zone	Southern zone	Middle zone	Southern zone	Middle zone	Southern zone
10	1,823	4,664	5,628	5,084	6,274	4,933	4,959
9	1,640	6,842	8,153	7,464	9,114	4,440	4,463
8	1,458	8,958	10,558	9,768	11,816	3,947	3,967
7	1,276	11,019	12,865	12,008	14,401	3,453	3,471
6	1,094	13,023	15,076	14,177	16,872	2,960	2,975
5	911	14,955	17,182	16,261	19,217	2,467	2,480
4	729	16,791	19,159	18,230	21,401	1,973	1,984
3	547	18,474	20,946	20,019	23,352	1,480	1,488
2	365	19,860	22,383	2,146	24,871	987	992
1	182	20,394	22,844	21,921	25,193	493	496

Source: developed by the authors based on calculations

Analysis of the table showed that petrol losses based on the EPA methodology significantly exceed similar indicators based on the Konstantynov methodology and the normative methodology of Resolution of the Cabinet of Ministers of Ukraine No. 686 (2020). At a filling level of 10 m in the average climate zone, losses according to the EPA are approximately 9% higher than according to Konstantynov methodology and 3% higher than according to the standards. At the same time, Konstantynov methodology exceeds the standard losses by 5%. In the southern zone, the difference between the EPA and the Resolution is even more pronounced, amounting to 26.6%, and between the EPA and Konstantynov – 11.5%. There is also a significant difference between climatic zones: losses according to the EPA in the southern zone are 23.4% higher than in the average zone, while according to Konstantynov, this difference is about 20.7%, and according to the Resolution, only 0.5%, which confirmed the low sensitivity of the standard methodology to climatic factors. Table 6 presents the results of comparative calculations of evaporation losses from tanks with a nominal volume of 1,000 m^3 located in different climatic zones and for tank filling levels from a minimum of 1 m to a maximum of 8 m.

Table 6. Results of calculations of petrol losses due to evaporation during storage in an VCT-1000 tank at different filling levels

Level of petrol filling, m	The volume of petrol in the tank, m^3	Annual losses (Konstantynov method), kg/year		Annual losses (EPA method), kg/year		Calculation results based on storage loss rates according to Resolution of the Cabinet of Ministers of Ukraine No. 686 (2020)	
		Middle zone	Southern zone	Middle zone	Southern zone	Middle zone	Middle zone
8	903	4,472	5,530	4,935.7	6,283	2,432	2,445
7	790	6,491	7,906	7,174.7	9,021	2,128	2,139
6	678	8,409	10,115	9,296	11,562	1,824	1,834
5	565	10,240	12,183	11,312	13,934	1,520	1,528
4	452	11,973	14,107	13,209	16,127	1,216	1,223
3	339	13,572	15,852	14,945	18,093	912	916.9
2	226	14,938	17,301	16,400	19,678	608	611
1	113	15,670	17,982	17,099	20,281	304	306

Source: developed by the authors based on calculations

A comparative analysis of the results presented in Table 6 showed significant differences between the three methods of calculating petrol losses from evaporation. The EPA method gives values that are on average 9-10.5% higher than the Konstantynov method, which indicates its increased sensitivity to temperature and climatic factors, while the standard method showed significantly lower results – the largest deviations were observed at the minimum filling level (1 m), where the calculated losses according to the standards are only about 2% of the values obtained using engineering methods. Thus, the data in this table confirm the trends identified in the previous comparative tables: the standard approach provides simplicity of calculations, but is significantly inferior in accuracy, while the EPA and Konstantynov methods are more suitable for a reliable assessment of losses during the storage of petroleum products.

A comprehensive analysis of the data in Tables 4-6 showed that the two methods (EPA and Konstantynov) demonstrate a reduction in losses with an increase in the tank filling level, while the standard method approved by Resolution of the Cabinet of Ministers of Ukraine No. 686 (2020) shows the opposite trend. This is because the Konstantynov and EPA methodologies are based on the physical and chemical principles of liquid evaporation and take into account variable parameters, such as gas space volume, temperature and saturated vapour pressure. According to these approaches, an increase in the tank filling level is accompanied by a decrease in the volume of the vapour-gas phase, which leads to a reduction in VOC losses. In contrast, the regulatory methodology uses a simplified relationship, according to which losses are determined in proportion to the volume of petroleum products stored. This approach does not reflect the actual evaporation processes and leads to the opposite dynamics – an increase in calculated losses with an increase in the filling level. Table 7 presents a comparative calculation of the relative errors in determining petroleum product losses for tanks located in different regions of Ukraine using three methods in order to establish whether it is acceptable to ignore the geographical location of tanks with a nominal volume of 1,000 m^3, 2,000 m^3 and 3,000 m^3 when determining the rate of petroleum product losses during storage in them.

Table 7. Relative errors in determining petrol losses from evaporation during storage in tanks, caused by differences in climate zones

Level of petrol filling, m	The volume of petrol in the tank, m^3	Relative error caused by differences in climate zones, %		
		Results obtained using Konsantynov method	Results obtained using the EPA method	Results obtained using the standard method
VCT-3000				
10.8	3,076	10.6	12.4	0.262856
9	2,563	9.1	11.2	0.263364
8	2,278	8.4	10.7	0.262912
7	1,994	7.9	10.2	0.263258
6	1,709	7.4	9.8	0.263726
5	1,424	7.0	9.4	0.263076
4	1,139	6.6	9.0	0.263723
3	854	6.3	8.6	0.262638
2	570	5.9	8.2	0.260468
1	285	5.7	7.8	0.266979
VCT-2000				
10	1,823	9.4	10.5	0.258785
9	1,640	8.7	10.0	0.25946
8	1,458	8.2	9.5	0.259038
7	1,276	7.7	9.1	0.259943
6	1,094	7.3	8.7	0.25946
5	911	6.9	8.3	0.258785
4	729	6.6	8.0	0.260305
3	547	6.3	7.7	0.25946
2	365	6.0	84.1	0.257771
1	182	5.7	6.9	0.262839
VCT-1000				
8	903	10.6	12.0	0.264491
7	790	9.8	11.4	0.262443
6	678	9.2	10.9	0.262438
5	565	8.7	10.4	0.262433
4	452	8.2	9.9	0.262446
3	339	7.7	9.5	0.262438
2	226	7.3	9.1	0.262424
1	113	6.9	8.5	0.262467

Source: developed by the authors based on calculations

An analysis of the impact of climate zone and conditions on the results of petrol loss calculations also demonstrates a significant dependence of the results obtained using the physical and mathematical methods of Konstantynov and the EPA. For the VCT-3000 tank, the relative error between calculations for the middle and southern climate zones according to Konstantynov's method ranges from 6.9% to 10.6%, and according to the EPA method – from 8.5% to 12.0%, depending on the filling level. For the VCT-2000 tank, the relative error between calculations for the middle and southern climate zones according to Konstantynov method ranges from 5.9% to 9.3%, and according to the EPA method – from 6.9% to 10.5%, depending on the filling level. At the same time, for the VCT-1000 tank, the corresponding errors range from 6.9 to 10.6% and 8.5 to 12%. This indicates the high sensitivity of these methods to temperature factors that affect the intensity of evaporation. However, within the regulatory methodology in accordance with Resolution of the Cabinet of Ministers of Ukraine No. 686 (2020), the discrepancy between climate zones for all tanks is statistically insignificant – the relative error is approximately 0.26%, which indicates the actual indifference of the regulatory approach to the influence of climatic parameters. However, such a generalised assessment does not reflect the actual operating conditions of tanks in different regions and may lead to significant deviations from actual VOC losses. The results of comparative calculations of petroleum product losses, characterised by different saturated vapour pressure values according to Reid, are presented in the relevant tables. Table 8 shows the results of the study for the average storage zone.

Table 8. Results of research into the effect of saturated petroleum product vapour pressure on evaporation losses during storage (middle zone)

Pressure of saturated petrol vapours according to Reid, Pa	Losses of petroleum products from the tank VCT-1000, kg				Losses of petroleum products from the tank VCT-2000, kg				Losses of petroleum products from the tank VCT-3000, kg			
	Standard methodology		Methodology of Konstantynov		Standard methodology		Methodology of Konstantynov		Standard methodology		Methodology of Konstantynov	
	Filling level, m											
	1	8	1	8	1	10	1	10	1	10	1	10
50,000	304	2,432	12,160	3,415	493	4,935	20,394	4,664	766	7,658	28,695	6,495
60,000			14,461	4,102			24,211	5,590			34,021	7,759
70,000			16,795	4,823			28,036	6,549			39,307	9,048
80,000			19,168	5,586			31,870	7,548			44,548	10,369

Source: developed by the authors based on calculations

Analysing the data in Table 8, it should be noted that, according to Konstantynov's methodology, there is a clear dependence of the amount of petroleum product losses on the pressure of saturated petrol vapours: as the pressure increases, the losses increase significantly. In particular, when the saturated vapour pressure increases from 50 to 80 kPa, the calculated losses increase: for the VCT-1000 tank (H_{min} = 1 m) – from 12,160 kg to 19,168 kg, which is +57.6%, for the VCT-2000 tank (H_{min} = 1 m) – from 20,394 kg to 31,870 kg (+56.3%), for the VCT-3000 tank (H_{min} = 1 m) – from 28,695 kg to 44,548 kg (+55.3%). For all tank volumes and minimum fill level conditions, there is a steady increase in losses within the range of 55-58% when moving from the minimum to the maximum pressure considered. Analysis of the results for the maximum filling level (H_{max}) of the tanks also demonstrates a clear dependence of the amount of petroleum product losses on the saturated vapour pressure according to Konstantinov's method. With an increase in saturated vapour pressure from 50 kPa to 80 kPa, losses increase in all types of tanks: for the VCT-1000 tank from 3,415 kg to 5,586 kg, which is +63.6%, for the VCT-2000 tank, from 4,664 kg to 7,548 kg (+61.8%) for the VCT-3000 tank, from 6,495 kg to 10,369 kg (+59.6%). Thus, at maximum filling level, the increase in losses when the saturated vapour pressure of petrol increases by 30 kPa ranges from 59% to 64%, which is slightly higher than in the case of minimum filling level. This indicates the stable nature of the effect of saturated vapour pressure on the intensity of evaporation, even with a reduced volume of the vapour-gas phase. The standard method demonstrates complete insensitivity to this parameter: the loss values remain constant for each level of petroleum product filling, regardless of changes in saturated vapour pressure. Table 9 shows the results of a study of the effect of saturated vapour pressure according to Reid on petroleum product losses for the southern storage zone.

Table 9. Results of research into the effect of saturated petroleum product vapour pressure on evaporation losses during storage (southern zone)

Pressure of saturated petrol vapours according to Reid, Pa	Losses of petroleum products from the tank VCT-1000, kg				Losses of petroleum products from the tank VCT-2000, kg				Losses of petroleum products from the tank VCT-3000, kg			
	Standard methodology		Methodology of Konstantynov		Standard methodology		Methodology of Konstantynov		Standard methodology		Methodology of Konstantynov	
	Filling level, m											
	1	8	1	8	1	10	1	10	1	10	1	10
50,000	306	2,444	13,801	4,127	495	4,960	22,844	5,628	770	7,699	32,094	7,815
60,000			16,531	5,030			27,219	6,820			38,092	9,407
70,000			19,343	6,014			31,626	8,093			44,030	11,066
80,000			22,260	7,110			36,076	9,477			49,899	12,815

Source: developed by the authors based on calculations

Analysis of the results obtained using Konstantynov's method for the minimum tank filling level (H_{min}) in the southern climate zone also demonstrates an increase in petroleum product losses with an increase in saturated petrol vapour pressure for the VCT-1000 tank from 13,801 kg (at 50 kPa) to 22,260 kg (at 80 kPa), which is +61.3%, for the VCT-2000 tank from 22,844 kg to 36,076 kg (+57.9%), for the VCT-3000 tank from 32,094 kg to 49,899 kg (+55.5%). In all cases, there is an increase in losses within the range of 55-61%, which is consistent with the results obtained for the average climate zone. For the maximum filling level (H_{max}), there is also a significant increase in losses, namely for the VCT-1000 from 4,127 kg to 7,110 kg, which is +72.2%, for VCT-2000 from 5,628 kg to 9,477 kg (+68.3%), for VCT-3000 from 7,815 kg to 12,815 kg (+64.0%). The increase in losses at maximum filling levels ranges from 64% to 72%, which is due to the influence of higher temperatures in the southern climate zone, which contribute to more intense evaporation. As in the previous case (Table 7), the standard methodology remains insensitive to changes in saturated vapour pressure, demonstrating fixed loss values regardless of the physical and chemical characteristics of the fuel. As shown in Tables 8 and 9, a change in the saturated vapour pressure of petroleum products according to

Reid from 50 to 80 kPa causes an increase in the calculated values of petroleum product losses from small breaths by approximately 1.6 times for all tanks studied.

Discussion

Continuous updating and revision of the document is a necessary and systematic process aimed at ensuring its scientific validity, technical relevance, and compliance with current environmental requirements, as noted by G. Xing *et al*. (2023). The EPA regularly reviews the document, taking into account both scientific advances and practical changes (AP-42 Chapter 7..., 2024). In particular, updates are prompted by the emergence of new experimental data, refinement of the physicochemical properties of liquids, development of evaporation models, and the need to consider factors such as temperature, solar radiation, and air flows. An additional reason is the introduction of modern storage technologies: the modernisation of tanks, the improvement of seals, the use of inert gases and vapour recovery systems require a review of emission factors. Changes in climatic conditions also play an important role, in particular the rise in average temperatures and the emergence of extreme weather events that alter evaporation dynamics. The EPA also continuously verifies the accuracy of methodologies, updates calculation factors and adapts approaches to modern monitoring tools. Finally, an important source of change is feedback from users: industrialists, scientists, environmentalists and the public, which contributes to the openness and relevance of the document.

The study by H. Yang *et al.* (2024) provided important empirical data on VOC emissions from tanks with internal floating roofs, allowing for a deeper understanding of the main factors affecting petroleum product losses through evaporation. The authors pointed to the significant influence of parameters such as temperature, wind speed, tank design and sealing quality, confirming the need to take these factors into account when developing loss calculation methods. In particular, the use of secondary sealing and pontoons significantly reduces VOC emissions, indicating the advisability of introducing more detailed and comprehensive correction factors into the calculation models. In addition, the identified negative correlation between the height of the liquid in the tank and the intensity of emissions emphasises the need to take into account variable operating conditions, which are often ignored in traditional methods. The use of infrared imaging as a tool for rapid and accurate detection of leak sources demonstrates the promise of implementing the latest technological monitoring tools to improve the accuracy of loss estimates. Overall, the results of the study indicate the need to revise existing approaches to calculating petroleum product losses, taking into account multifactorial influences, which will improve the accuracy of forecasts and enable the development of effective measures to minimise environmental and economic losses.

I.M. Babić (2023) investigated methods for reducing evaporation losses in oil and petroleum product storage tanks using the example of a warehouse in Požega (Serbia). The paper analyses the impact of tank design features and operating conditions on evaporation levels and proposes measures to optimise storage in order to minimise VOC losses. The results of the study highlight the importance of applying technological and organisational measures to reduce the environmental and economic impact of evaporation losses from tanks. The article by X. Kong *et al.* (2025) is devoted to the numerical modelling of evaporation and oil vapour emission processes during the loading of oil into railway tankers using the Volume of Fluid method. The study covers a wide range of aspects, including the impact of ambient temperature, wind speed, tank geometry and fill level on VOC emissions. The modelling was carried out taking into account various scenarios, allowing the effectiveness of different emission reduction measures to be assessed.

The results of a study by M.R. Raazi Tabari *et al.* (2020) confirmed the importance of considering ambient temperature, wind speed, and tank design features when assessing VOC losses. The authors found that the highest emission rates were observed in the summer, particularly in July, when air temperature and wind speed reached their maximum values, indicating a significant influence of meteorological factors on evaporation intensity. In addition, a comparison of tanks with external and internal floating roofs showed that the former account for more than 98% of total VOC emissions, while the latter account for only 2%, demonstrating the significant role of tank design in determining losses.

C. Wu *et al.* (2022) combined numerical modelling and aerodynamic experiments to study the spread of oil vapours after spillage from tanks, focusing on the relationship between the evaporation of petroleum products from tanks and the level of fire safety. The authors showed that under certain conditions – in particular, high fire barriers, windward position of tanks and multiple spill sources – vapour concentrations can reach or exceed the lower explosive limit. Thus, the paper demonstrates for the first time the practical relationship between evaporation intensity and explosion risk, which is important for the development of effective fire safety measures in tank farms.

Another issue was investigated by M. Farzaneh-Gord *et al.* (2011), who analysed how the absorption capacity of the paint coating of crude oil storage tanks affects their temperature and, accordingly, losses in tropical climates. It turned out that when the absorption coefficient increases to 90%, annual losses increase to 200%. Similar conclusions were obtained in the publication by N.V. Liuta *et al.* (2020), which studied this problem in Ukraine. According to their data, if the solar radiation absorption coefficient of a reservoir increases from 0.3 to 0.9, this leads to an increase in petroleum product losses by approximately 40%. Thus, the results of independent studies conducted in different climatic zones indicate the need and expediency of taking into account the geographical location of reservoirs when determining the volume of losses during storage.

In their study, S.V. Boichenko & N.H. Kalmykova (2020) conducted a systematic cause-and-effect analysis of the process of petrol evaporation from horizontal tanks using an Ishikawa diagram, which makes it possible to clearly identify the factors causing losses. The authors draw attention to the significant influence of the physical and chemical characteristics of fuel (volatility, saturated vapour pressure), ambient temperature, tank design features and operating modes on the intensity of evaporation. It has been established that the main causes include technological "breathing" losses during filling and emptying, losses due to the capillary effect in the gaps of the seals, as well as insufficient sealing and organisational shortcomings in product accounting. In addition, the economic (reduced fuel quality, shorter engine life), environmental (pollution of the atmosphere with toxic hydrocarbons) and technical consequences of such losses were assessed. The authors consider a combined approach to be the most effective measure: the introduction of both methods for accurate leak accounting (quantitative determination of losses) and organisational and technical measures for sealing and monitoring the condition of tanks. Thus, the results of S.V. Boichenko & N.H. Kalmykova (2020) emphasise the expediency of updating the methods for calculating petroleum product losses due to the need to integrate a multifactorial approach that includes the design, operational, and chemical-physical properties of fuel.

One of the compelling arguments in favour of improving calculation approaches for determining petroleum product losses is the work of A. Ahmed Alwaise *et al.* (2023), which analyses the impact of the physical properties of petroleum products on the volume of losses in vertical tanks. The authors focused on the specific gravity and volatility of products such as kerosene and gas oil, investigating changes in losses when the density (0.750-0.820 t/m^3) of samples in a volume of 1,000 m^3 varied. It was found that losses can fluctuate up to 5 m^3 per 1,000 m^3 when physical properties change. In view of this, the researchers recommend periodically checking the physical and chemical parameters of products to update the methods for calculating losses, which will reduce the discrepancies between theoretical estimates and actual values. In the context of improving existing methods, this study highlights the need to introduce correction factors or update input parameters in accordance with the actual properties of petroleum products, which will avoid systematic errors in loss calculations.

In developing the topic of the impact of operating parameters on petroleum product losses, it is also worth paying attention to the work of S. Andalucia (2023), which conducted multi-variant calculations of petroleum product losses from evaporation in two fixed-roof tanks at the SA Field PT X Prabumulih facility. The author analyses the impact of parameters such as petroleum product temperature, ambient temperature and gas space volume in the tank, establishing that an increase in free space directly correlates with an increase in oil evaporation. The economic consequences of these losses are also assessed: large volumes of losses lead to significant financial losses for the enterprise. Thus, the results of these studies also confirm the need and expediency of revising the current regulatory methodology, taking into account a complex of factors that actually influence the evaporation process. N. Kapilan *et al.* (2025) investigated the loss of petroleum products through evaporation from tanks under laboratory conditions, simulating different evaporation surface areas and petroleum product temperatures. The results confirmed that petroleum product losses increase with time, surface area and temperature.

Scientific research and practical experience in calculating petroleum product losses during storage in vertical tanks indicate an objective need for a systematic update of current regulatory approaches. The summary shows that the accuracy of loss assessment significantly depends on taking into account a wide range of factors: temperature regime, wind speed, saturated vapour pressure, gas space volume, tank design characteristics, sealing efficiency, etc. Ignoring these parameters in simplified regulatory methods leads to significant discrepancies with the results of physical and mathematical models and experimental observations. Particular attention should be paid to the introduction of correction factors, regular updating of input parameters in accordance with actual operating conditions, and the use of modern monitoring tools. In addition, the results of the analysis confirm the advisability of harmonising the regulatory framework with international standards. This will ensure high accuracy of calculations, compliance with environmental requirements, and increase the efficiency of VOC loss management. In this context, the development of an integrated methodology that combines scientific validity, adaptability to real operating conditions, and compliance with modern international approaches is particularly relevant.

Conclusions

In summary, a systematic review of the current regulatory framework in Ukraine regarding the accounting of petroleum product losses during storage in vertical tanks is required. The analysis revealed a number of limitations in the current Ukrainian regulatory framework. This methodology does not take into account a number of important factors, including the design features of tanks, climatic conditions, the properties of stored products, the degree of tank filling, the level of sealing, etc. A comparative analysis of the results obtained using different methodologies revealed significant discrepancies. Calculations showed that physical and mathematical methods (Konstantynov and EPA) are highly dependent on climatic conditions: for VCT-1000, VCT-2000 and VCT-3000 tanks, the relative error between the northern and southern climatic zones ranges from 5.9% to 12%. In contrast, the standard method practically does not take climatic differences into account (error of about 0.26%), which can lead to inaccuracies in the assessment of VOC losses in different regions.

A comparative analysis of the results obtained using different methods revealed significant discrepancies. In particular, two methods (EPA and Konstantynov), which are based on the physical and chemical principles of liquid evaporation and take into account variable parameters (gas space volume, temperature, saturated vapour pressure), show a decrease in losses with an increase in the tank filling level. In contrast, the standard method uses a simplified relationship, where losses are proportional to the volume of petroleum products stored, which leads to the opposite trend – an increase in losses with an increase in the filling level. It has also been established that an increase in the saturated vapour pressure of petroleum products from 50 to 80 kPa increases the calculated losses by almost 1.6 times for all tanks studied. Further research will focus on developing a scientifically sound, technologically adapted and environmentally oriented methodology for determining and standardising petroleum product losses during storage in tanks.

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Conflict of Interest

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Анотація. Метою роботи було проаналізувати нормативну базу обліку втрат нафтопродуктів в Україні. Здійснено компаративний і емпіричний аналіз трьох методик визначення втрат нафтопродуктів від випаровування. Виконано розрахунки втрат бензину від «малих дихань» у вертикальних сталевих резервуарах номінальним об'ємом 1 000, 2 000 та 3 000 м^3 у різних кліматичних зонах України. Проведено оцінку впливу рівня заповнення резервуара та тиску насичених парів на втрати. Порівняльний аналіз виявив, що методики EPA та Константинова демонструють фізично обґрунтоване зменшення втрат при підвищенні рівня наливу, а також високу чутливість до кліматичних умов. Для резервуара РВС-3000 відносна похибка між розрахунками для середньої та південної кліматичних зон за методикою Константинова становить 6,9-10,6 %, а за методикою EPA – 8,5-12,0 %. Для РВС-2000 ці показники становлять 5,9-9,3 % (Константинова) та 6,9-10,5 % (EPA), а для РВС-1000 – 6,9-10,6 % і 8,5-12 % відповідно. Натомість розрахунки за нормативною методикою показали практично нульову чутливість до кліматичної зони (відносна похибка ~0,26 %), що суперечить реальним умовам експлуатації й призводить до потенційно значних похибок в оцінці втрат летких органічних сполук. Це свідчить про необхідність перегляду чинних українських норм з урахуванням сучасних фізико-хімічних моделей випаровування. Додатково проаналізовано вплив тиску насичених парів нафтопродукту за Рейдом на величину втрат. Результати розрахунків для середньої та південної кліматичних зон показали, що зростання тиску насичених парів від 50 кПа до 80 кПа спричиняє збільшення втрат приблизно в 1,6 рази для всіх досліджуваних типів резервуарів. Це підтверджує високу чутливість фізико-математичних методик до фізико-хімічних властивостей нафтопродуктів, на відміну від нормативного підходу, який не враховує цей параметр. Отримані результати можуть бути використані для розробки адаптованої комбінованої методики, що поєднує точність міжнародних стандартів із простотою нормативного обліку

Ключові слова: бензин; малі дихання; тиск насичених парів; кліматичні зони; резервуари; нормативний документ