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COMPARATIVE ANALYSIS OF THE EFFICIENCY OF GAS BOILERS BY EXPRESS METHOD OF MULTI-CRITERIA ASSESSMENT

Об'єктом дослідження є метод експрес-аналізу багатокритерійної оцінки, на прикладі порівняння ефективності побутових газових котлів типу АОГВ (апарат опалювальний газовий водонагрівний). На даний час на українському ринку пропонується велика кількість газових котлів українських та зарубіжних заводів-виробників, яка має незначні відмінності. Це обумовлено в першу чергу простотою конструктивного рішення газових котлів даної моделі та використанням для них однакових паливних пристроїв і блоків автоматики італійського виробництва.

Порівняння показників ефективності даного виду продукції є великою проблемою. Існуючі методики розрахунку показників ефективності та чинні нормативні документи не завжди дають коректне уявлення про якість продукції. Тому в даній роботі пропонується новий метод експрес-аналізу порівняння ефективності, який дозволяє в короткий час провести коректне порівняння показників роботи котельного обладнання без використання великої кількості розрахунків, які потребують більших затрат часу. Ця проблема вирішується вибором трьох яскравих критеріїв ефективності, а саме енергетичного, екологічного та економічного, з подальшим визначенням довірчих інтервалів кожного з показників та побудові на їх базі трикритеріальної діаграми. Даний метод дозволяє наочно бачити недоліки та переваги кожного з котлів, планувати заходи по їх модернізації та визначати їх рейтинг.

В ході дослідження використовувалися матеріали технічного звіту теплоекологічних іспитів семи газових котлів, який було проведено загальноприйнятою методикою. Аналіз отриманих результатів було проведено методом сум з подальшим ранжуванням афектів та подальшою верифікацією запропонованого експрес-методу порівняння ефективності. Отриманий якісний результат дозволяє зробити висновок, що запропонований експрес-метод більш детально та коректно, ніж інші відомі методи аналізу визначає рейтингове положення кожного котла. Це дозволить потенційному інвестору зробити правильний висновок при заміні та придбанні нового котельного обладнання. Використання методу експрес-аналізу дає змогу заводам-виробникам котельного обладнання провести реальну оцінку якості продукції та визначити шляхи по подоланню її недоліків.

Ключові слова: газовий котел, ефективність енергетичного обладнання, системний аналіз, ваговий коефіцієнт.

1. Introduction

Heat supply systems have significant potential for energy savings. The total potential of energy efficiency in Ukraine is about 45 % of the volume of consumed fuel and energy resources. The daily energy losses in Ukraine are about 3.5 million USD. All this negatively affects the national economy of the country. Reasonable and efficient energy consumption is a key factor in creating new jobs and economic growth in the country.

Energy saving in the field of natural gas consumption remains the most critical. Ukraine consumes about 40.0 billion m³ of natural gas per year, of which:

- 13.0 billion m³ consumes industry;
- 4.0 billion m³ are technical needs and losses during transportation;
- 5.0 billion m³ is spent on cooking and power generation;
- 17.8 billion m³ for heating of apartment and private houses.

At the same time, the level of unproductive gas consumption losses is from 30 to 40 %. By reducing them to

the European level, it is possible to save up to 9.0 billion m³ of natural gas per year.

About 11.0 billion m³ of gas is consumed per year for heating homes, while the potential for energy saving reaches 6.3 billion m³, of which 1.7 billion m³ are used for heating and hot water by household gas boilers. 60 % of heating boilers, which are sold in Ukraine, are occupied by imported boilers. Currently, 40 % of the market needs are covered by domestic-made boilers. One of the models, which are mass-produced and mass-sold for many years, is floor boilers of the WHGA type (water heating gas apparatus) operating on gas. Therefore, the appropriate solution for energy efficiency is ensuring the quality of boilers at the design, manufacturing and operation stages, as well as to develop recommendations for their modernization.

When choosing boiler equipment, it is desirable to be guided by objective methods of system analysis and multi-criteria evaluation of efficiency indicators. Existing benchmarking methods do not provide systemic estimates. Therefore, it is urgent to improve the methods of multi-criteria evaluation of the effectiveness of heating boilers, first of all, by technological, economic and environmental conditions.

2. The object of research and its technological audit

The *object of research* is a method of rapid analysis of multi-criteria evaluation using the example of comparing the efficiency of domestic gas water boilers of the WHGA type; they have been used for many years for heating and supplying hot water to private houses and public utility facilities.

At the first stage, let's analyze and compare technical, environmental and economic indicators of models of domestic WHGA-type boilers designed for heating houses with a total area of about 100 m², their characteristic features, which the manufacturing plants declare are:

- atmospheric burners;
- possibility of use in gravitational heating systems, without connecting to the mains;
- reduced water circulation in the heating system;
- efficiency – about 90 %, which is achieved by expanding the heat exchange area and a small amount of water in the boiler;
- painting with anticorrosive enamels;
- silent work and low cost.

The negative features of these models of boilers include:

- outdated technological solution to build a boiler;
- limited service life;
- short warranty period;
- sensitive response and impact on the boiler operation changes in the discharge in the chimney;
- decrease in productivity to a complete stop of the boiler operation under reduced gas pressure, and the like.

For research, water boilers with a thermal capacity of about 12.0 kW [1] were provided:

- Ukrainian production, trademarks – ATEM «Zhytomyr 3» KCF 012 CH; ATON AOFBM-12 EM; Danko Danko 12-CP; Termobar KC-Г-12,5;
- Russian production – ДS LEMAKS Premium 12,5; Siberia 2210-012 perf. 3 Siberia 11 and MIMAKS KCF-12,5.

The investigated boilers are certified in Ukraine and declare an efficiency of 81÷93 % with complete combustion of fuel. The boilers are equipped with automatic ignition and protection systems, ensuring their operation without permanent attendants.

According to the research program, the technical documentation for each boiler was reviewed. Regime-adjustment studies and complex – warm-heat tests were carried out on two main modes of operation of boilers with a minimum and maximum heat load at a vacuum of 3.5; 7.0 and 15.0 Pa, respectively. All the boilers were carried out on three main balance sheet experiments after determining the optimal coefficients of excess air with the lowest emissions of toxic components.

Operational tests were carried out at optimal values of the air excess factor, while the gas consumption and other necessary parameters were recorded. When conducting routine and balance tests, gas analysis and measurements of the temperature of combustion products were carried out in the flue duct behind the boiler (Fig. 1).

During the work, the conditions for reliable and economical operation of the boilers were found, the efficiency factors and other technical and economic indicators of the equipment operation were determined. Experiments to determine the content of nitrogen oxides and carbon

in the combustion products, the influence of regime factors on the efficiency and the amount of emissions are conducted. When determining the gross boiler efficiency, the reverse balance method was used [2]. Measurements of the composition of the exhaust gases, their temperature and air temperature before the burner were carried out by a computer gas analyzer without interruption throughout the test. Recording of gas meter readings and other instruments was carried out every 10 minutes. Measurements and calculations of CO, NO_x and other pollutants were carried out according to [3–5]. The thermal characteristics of the thermal insulation of the boiler elements were determined by analyzing the results obtained from thermograms (measurements with a thermal imager) and in hard-to-reach places with a pyrometer.

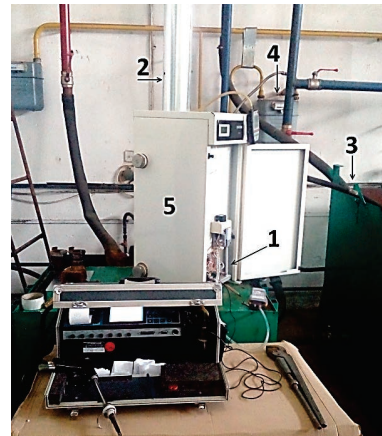


Fig. 1. Diagram of measurements of the parameters of the boiler:
1 – air temperature and pressure; 2 – temperature, rarefaction and chemical composition of flue gases; 3 – flow rate and temperature of the coolant in the direct and return pipelines; 4 – flow, temperature and pressure of natural gas; 5 – boiler body temperature

The maximum achieved heat output for each of the boilers was about 12 kW. The efficiency at the maximum achieved load was from 81 to 93.4 %, which is primarily due to the one-way flow of the coolant, using only the convective type of heat transfer and other operating characteristics of the equipment. The atmospheric low-pressure burners installed in the boilers operated reliably in research ranges of loads and air excess factors. Based on the carried out tests, calculations of the operation of boilers, certain economic, environmental and energy efficiency indicators, and proposed measures aimed at improving the efficiency and reliability of boilers operation is developed. The obtained data is illustrated by the summary Table 1, in which the color points of scores for each criterion for each boiler.

Table 1 clearly shows that all the studied models have almost identical indicators. All manufacturers' passport data of the boiler declare efficiency of at least 90 %.

However, the calculations carried out show that only boilers of the ATEM brand have this indicator at the level of 90–92 %, depending on the mode and conditions of operation.

The greatest heat output during full-scale tests was shown by the boiler produced by ATEM, the worst efficiency of the MIMAKS boiler.

Table 1

Summary list of the main indicators of boilers

No.	Parameter name and unit	Boiler						
		ATON АОГБМ-12 EM	LEMAKS Premium 12,5	ATEM Zhytomyr 3 КЦГО12СН	Siberia 2210012 perf. 3	Danko Danko-12 CP	Termobar КС-Т-12,5 ДS	MIMAKS КСТ-12,5
1	Performance, %	88.31–81.33	81.2–75.5	92.18–90.82	86.7–74.0	86.3–73.81	88.2–84.0	84.6–72.05
		3	5	1	4	4	2	6
2	Fuel utilization factor, m ³ /Gcal	162.36	161.28	147.60	159.69	154.80	164.88	163.08
		5	4	1	3	2	7	6
3	Metal capacity, kg/kW	3.6	4.4	3.92	4.4	4.3	3.64	3.7
		1	6	4	6	5	2	3
4	Reduced cost, USD/kW	6.24	5.67	5.15	6.33	4.22	4.66	3.27
		6	5	4	7	2	3	1
5	Sum	15	20	10	20	15	14	16
	Assessed score	3	5	1	5	3	2	4

Thermal imaging studies of heat losses through the boiler body showed that in all boilers there is a local overheating of the body, which exceeds permissible standards. Most of the overheating is noted in the Danko and MIMAKS boilers up to 120 °C in other boiler data, the temperature of the hull, in some areas ranges from 50 to 70 °C.

It is important to note that all boilers, with the exception of the boiler of the MIMAKS trademark, are equipped with the same atmospheric burners with the automatic control and safety unit of the Italian company SIT. Thus, the costs and conditions of combustion of natural gas in them differ only because of the design features of the combustion chamber, the boiler aerodynamics and the convective heat exchanger.

Aerodynamic parameters of compared boilers showed a general tendency to decrease in efficiency from an increase in the aerodynamic resistance of the chimney. Conducted field tests showed that the boiler of the ATON brand was least susceptible to these changes in various operating modes, which is explained by its constructive solution. The worst efficiency when changing the aerodynamic mode of operation is in the boilers Siberia, Danko and MIMAKS.

All boilers have the same technological scheme, design and overall dimensions, and therefore the metal capacity of the boilers is about 4 kg/kW, although at the boiler АОГБМ-12 EM of ATON it is better than this indicator – 3.6 kg/kW.

An important environmental indicator is the temperature of flue gases, emissions of CO and nitrogen oxides, as well as reduction of carbon (CO₂).

According to these indicators, the emission of harmful substances is the most, at different modes, found in the ATON boiler, and the worst indicators in the LEMAKS, Siberia and MIMAKS boilers.

The present cost of the boilers in US dollars/kW varies from 3 to 6 US dollars per kilowatt. The boilers of the Siberia trademark have the highest value, while the lowest cost of the boiler of the MIMAKS trademark is obviously explained by the use of a simple burner, without electronic ignition, and a control and safety unit of its own production.

The obtained data allow an expert assessment of the investigated boilers by quality indicators. When analyzing the operation of boilers, it is also necessary to take into account heat losses that are not subject to an exact analytical solution, however they affect the overall efficiency indicators of the heat generation system.

These include:

- a change in the temperature of the feed water by 1 °C leads to an increase or decrease in the total heat consumption produced by the boiler by 1 %;
 - with an increase in heat output of the boiler, the specific losses to the environment q_5 decrease, and the specific losses with exhaust gases q_2 , chemical q_3 and mechanical q_4 do not increase significantly. At first, the q_5 loss reduction causes more $q_2+q_3+q_4$ losses and the boiler efficiency increases, but then $q_2+q_3+q_4$ losses grow faster than the q_5 reduction and the efficiency starts to decrease;
 - if know the dependence of the boiler efficiency on heat load, it is possible to establish the loss of fuel during the boiler underload in the mode of reduced gas pressure and rational mode of its operation;
 - heat loss by heated surfaces into the environment can be significant. For example, a wall with a temperature of 150 °C at an ambient temperature of 25 °C per 1920 kkal/hour is lost from 1 m². As a result of heat losses, the parameters of the coolant are reduced;
 - an excess of 0.2 % increase in the coefficient of excess air increases the heat loss with exhaust gases by 1–2 %, the efficiency of the boiler is reduced by 2 %, the loss of fuel increases by 2.5–3 %;
 - violation of the thermal insulation of the boiler by 30 % or more leads to excess heat loss by 1–2 %;
 - an increase in the volume of products of combustion of fuel by 80–90 % due to their dilution with air, increases the heat loss from chemical incomplete combustion of fuel by 2 times;
 - the deviation of CO₂ in the exhaust gases from the optimal value by 1 % increases the fuel consumption of the boiler by 0.6 %;
 - the presence of scale on the inner surface of the boiler with a thickness of 1.0 mm increases fuel consumption by 2 %;
 - deviation of the boiler load from the optimum by 10 % in the downward direction leads to fuel waste by 0.2 %, and in the upward direction – by 0.5 %.
- It is clearly seen that the evaluation of effectiveness is a multicriteria task.

Summation of points in Table 1 shows that the ATEM boiler has the best performance, the worst characteristics in Siberia and LEMAKS boilers, which scored 20 points each.

To determine the direction of further search for optimal solutions for comparing the investigated boilers, one can use evaluation methods based on the mathematical statistics apparatus.

3. The aim and objectives of research

The aim of research is development and test of a rapid method for system analysis of multi-criteria evaluation, with a specific example of determining the effectiveness of gas water boilers from seven manufacturing plants.

To achieve this aim it is necessary to perform the following tasks:

1. To carry out a detailed analysis of seven gas boilers on the Ukrainian market and, on the basis of the made measurements, calculate the efficiency, specific fuel consumption and emissions of harmful substances into the atmosphere.
2. To compare technological, environmental and economic indicators of boilers using well-known methods of mathematical statistics and methods of mathematical modeling and verify the rapid method for the analysis of multi-criteria evaluation.

4. Research of existing solutions of the problem

The concept of efficiency plays an important role in evaluating virtually any project. The theory and methods of optimization have been widely used to solve many problems in various fields of human activity. The properties and methods for finding optimal solutions to such problems are well studied both from theoretical and applied points of view [6, 7], but they do not consider the possibility of multi-criteria evaluation using the graph-analytical method. The work [8] is devoted to the analysis and planning of decisions in the economy; however, the question of combining and comparing economic indicators with technological and environmental ones remains unresolved. A multi-criteria evaluation of measures to optimize the consumption of heat energy is proposed in [9], but environmental problems are ignored. With all the importance in everyday practice, the concept of efficiency becomes quite a difficult and poorly formalized task.

One of such methods is the functioning environment analysis (FEA) [10, 11]. FEA technology considers a complex object characterized by many input and output parameters. This technology is based on the fundamental principles of mathematical economics and actively uses modern achievements in the field of systems analysis and operations research [12].

FEA technology is a mathematical model that does not require the task of constants, the choice of distribution functions and other characteristics. However, the interpretation and analysis of the simulation results using the FEA technology presents a certain complexity, since it is practically impossible to imagine the behavior of an object in the multidimensional space of input and output parameters [13]. In addition, the standard analysis of the FEA technology, usually gives two ways to improve efficiency.

The method of multi-criteria analysis (MCI) is a mathematical tool of a systematic approach to complex decision-making problems [14]. Formation of the structure of the decision-making model in the MCI is quite a laborious process. However, as a result, it is possible to get a de-

tailed idea of how the factors influencing the decisions and ratings that reflect the importance of the factors interact [15]. MCI does not have a means to validate data. This is an important drawback, which partially limits the possibilities of applying the method. MCI may be overly time consuming to make simple decisions because a large number of comparisons are required to collect data [16]. There are specialized software products For computer support of MCI.

Thus, the results of the analysis of literary sources allow to conclude that all existing methods have certain disadvantages and require the development of new rapid methods for quick analysis and evaluation of criteria for making strategic decisions.

5. Methods of research

The decision-making process in various fields of activity is in many respects similar. Application of the system analysis methodology when comparing the main indicators of boiler equipment allows developing measures to improve the efficiency of its use indicators. The main areas of application of the system methodology are the assessment of heat engineering (technological), economic and environmental efficiency of equipment and making decisions on further modernization and optimization of the design of boilers.

To do this, use the method of comparison – the most common method of system analysis.

As can be seen from Table 1, the sum method was originally used, based on summing the values of certain indicators for each boiler. According to the results of a comparative comprehensive assessment, it is possible to decide which of the boilers should be considered the best for a number of specific features. Ranking indicators in descending order, the rating of WHGA-type boilers was established. The disadvantages of this method include the fact that the total of all indicators, the low results of individual indicators are covered by the high results of other indicators. In order to obtain an objective assessment, it is necessary to exclude those indicators that are most likely to affect the final result.

In order to obtain an objective assessment at the second stage of the study, the method of scoring was used, which is based on assigning ordinal values to boilers in accordance with the specified numerical categories. The scoring method consists in summing up the scores assigned to each indicator. The higher the score, the lower the score. The lower the score, the higher the rating of the object. The disadvantages of this method include the fact that, in fact, the difference in efficiency can be very significant, or, conversely, purely nominal, which can vary significantly and distort the assessment. The need to apply the scoring method arose due to the fact that it is necessary to compare the effectiveness of seven boilers by four indicators.

This disadvantage is eliminated by using the interpolation method in the range of 1–7 points.

At the third stage of the study, the 3E grapho-analytical method was used for a multi-criteria evaluation of decision-making efficiency [17, 18]. It is based on a multi-criteria method of system analysis, which includes a wide range of mathematical and statistical methods and can be used for any calculations for making decisions in any field of

activity. Multi-criteria analysis requires combining three different types of information in a single method that can be applied in practice. This method has practically no analogues and is based on making pair comparisons. Application of the «3E» method is completely independent of the sphere of activity in which a strategic decision is made. Therefore, the «3E» method is universal, and its application allows you to organize a decision support system.

The proposed method allows to obtain a graphic image of the result of a comparative analysis of the efficiency of WHGA-type boilers and with a high degree of probability to determine the rating of the products of manufacturers.

The analysis is based on three main criteria, namely, energy, environmental and economic. The results of the express analysis are graphically represented in the form of the area of allowable values in the triangular diagram «3E triangle» from the initial letters of the words.

An important factor in the calculations using the new «3E» method of rapid analysis is the identification of a confidence interval. Based on the expert assessment, it is proposed to assign the limits of confidence intervals, with a given reliability, for each criterion weight coefficient KE , which are dimensionless values expressed as a percentage. The intersection of the boundaries of the minimum values of weight coefficients forms confidence field (shaded area) of the 3E diagram, in which the ranks of WHGA-type boilers are defined, which are discussed in the next section of this paper.

An equilateral triangle is used to find the relationship between the weight indicators of equipment efficiency, diagonals in any level. From the vertices of the triangle lay the values obtained by calculation or in-situ measurement. The obtained benchmarks for the indicators of each boiler are combined, and at the intersection of the diagonals of the resulting small triangle, the basic rating of the boiler is obtained for three weights.

Formulas for calculating the weight coefficients are given in Table 2.

The confidence interval of the KE_1 energy index is taken from 70 % to 100 % and the well-known formulas for calculating the efficiency of the boiler [2] are used to calculate it.

Actual values of the carbon dioxide content CO_2 are taken as the weighting ecological index KE_2 , which is calculated for each of the boilers in accordance with the current methods [3–5]. CO_2 is selected as the main component, as it reflects the quality of the combustion of natural gas. This is justified by the fact that the maximum CO_2 content in the analysis of the fuel is directly proportional to the fuel component and inversely proportional to the amount of harmful emissions and ballast gases in the combustion products. On this basis, CO_2 values fully reflect the environmental efficiency of fuel combustion. The confidence interval of the ecological coefficient KE_2 is proposed to be taken in the value from 5 % to 10 %.

The confidence interval of the economic index KE_3 takes values from 60 to 100 % and for its calculation the well-known formulas for calculating the fuel utilization factor (CFU) [2] are used. The calculated data on the consumption of natural gas for the production of 1.0 Gcal of heat were converted into reference fuel. Then, using the [19] method and the [20] instruction, the interpolation method (Fig. 2) was used to recalculate the values for determining heat production by the corresponding fuel consumption in the range from 60 to 100 % of possible values in accordance with the heat generation efficiency. After that, the CFU was determined in percent using the results obtained from the calculations. To build a confidence field «3E triangle» the resulting values of instrumentation need to be postponed in the reverse order.

The choice of the optimal variant of the boiler can be carried out using the attractiveness index, which is calculated by summing up the weighting indexes of the KE . Comparison and determination of deviations for each boiler from the target value of the standard is obtained by multiplying the values of the weighting indexes, as a result of which a proportionality index is obtained.

Thus, the proposed system for assessing the effectiveness allows determining the generalized integral indicators of each boiler, on the basis of which it is possible to judge their effectiveness with a sufficient degree of objectivity. The results of the integrated assessment, as well as a graphic illustration of the effectiveness, make it possible to identify the functioning deficiencies and develop measures to focus efforts on eliminating the deficiencies (Fig. 3, 4).

As can be seen from Fig. 3, 4, the boilers of the trademarks Lemax and MIMAKS are characterized by high fuel consumption and low efficiency, the best efficiency has the boiler company ATEM. The best environmental efficiency in case of negative pressure behind the boiler is $\Delta P=3.5$ Pa at the rated power in the boilers of the ATEM and MIMAKS trademarks, the worst in the Данко, ATON and Termobar boilers.

The calculation of the weights for the construction of «3E triangle»

Name	Formula for calculation	Confidence interval
Weight power index KE_1	$KE_1 = 100 - \sum q_i$, %, where q_i – heat losses, %	70–100 %
Weight ecological index KE_2	$KE_2 = \frac{(CO_2 + CO + CH_4 + \sum n \cdot C_n H_m) \cdot 100}{(CO_2 + CO + CH_4 + \sum n \cdot C_n H_m + N_2 + 79 \cdot V^0)}$ %, where $C_n H_m$ – hydrocarbons included in the composition of the gas, for example, methane CH_4 ($n=1, m=4$), ethane $C_2 H_6$ ($n=2, m=6$), etc.; V^0 – theoretical volume of dry air required for complete combustion of fuel, m^3/kg	5–10 %
Weight economic index KE_3	$KE_3 = \left(1 - \frac{B}{Q_i}\right)$ %, where B – the total fuel consumption for the boiler unit, kg/h ; Q_i – specific heat of combustion, $Gcal/kg$	60–100 %
Attractiveness index I^p	$I^p = KE_1 + KE_2 + KE_3$	Integrated quantitative quality score
Proportionality index I^a	$I^a = KE_1 \cdot KE_2 \cdot KE_3$	Integrated rate of deviation from the standard

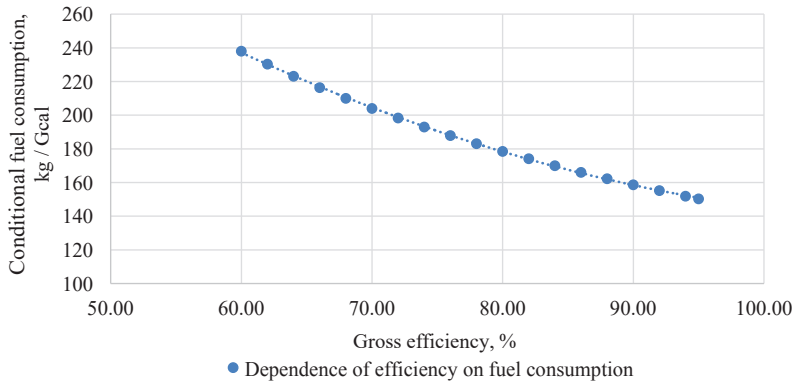


Fig. 2. Correlation field of theoretical data pairs according to the Instruction [20]

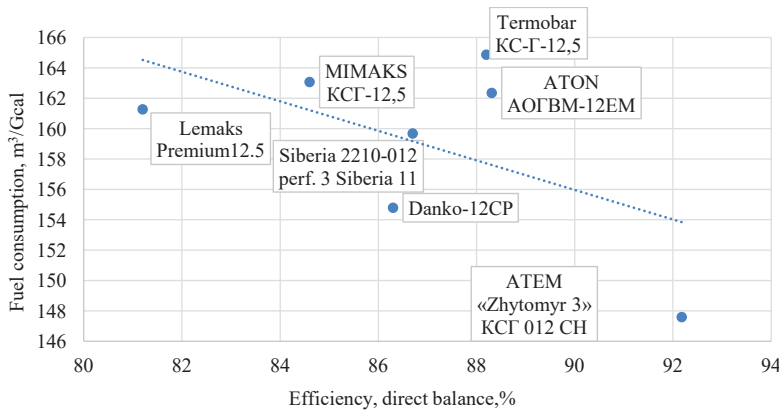


Fig. 3. Correlation field according to calculations of efficiency and fuel utilization factor

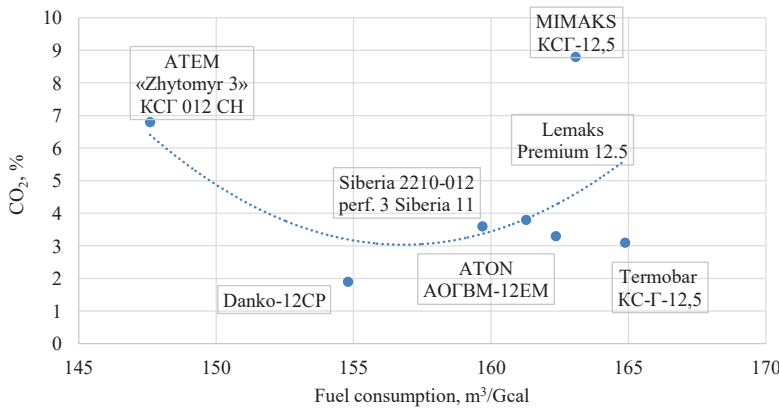


Fig. 4. Correlation field of data pairs: fuel utilization factor, m³/Gcal and CO₂, % at vacuum pressure behind the boiler $\Delta P=3.5$ Pa at nominal power

6. Research results

The study was conducted according to the traditional method and the subsequent testing of the «3E» method. As a result of solving the $N=7$ optimization problems of nonlinear mathematical programming by the FEA method, it was concluded that all the data of the seven boilers are effective ($h=1$).

To rank this set of criteria by importance, MAI was used to determine the rating of boilers.

To compare the efficiency of the boilers that were investigated and determine the optimal indicators, a correlation and regression analysis of the reference table was carried out according to the Instruction [20] presented in Fig. 2 and data obtained by measuring (Fig. 3).

Having 19 pairs of data from the Instruction [20], let's establish the form of the connection between the data and build a correlation field (a dotted graph connected in descending order by straight lines) and obtain a regression line that can be described by a polynomial.

In this case, it is possible to see a simple dependency, which can be easily described by a function. In this case, the correlation coefficient for the field of values according to the Instructions: $r_1=0.99$. Thus, the theoretical indicator of the gross boiler efficiency depends on the quantitative change in the reference fuel consumption by 99 %.

Let's build a correlation field according to the measurements and calculations made on existing boilers (Table 3).

Table 3

Key estimates for the evaluation of the investigated boilers

Boiler	Efficiency, direct balance, %	Fuel utilization factor, m³/Gcal	CO ₂ , % at negative pressure behind the boiler $\Delta P=3.5$ Pa at nominal power
ATON AOFBM-12EM	88.31	162.36	3.3
ДС LEMAKS Premium 12.5	81.2	161.28	3.8
ATEM «Zhytomyr 3» KCF 012 CH	92.18	147.6	6.8
Siberia 2210-012 perf. 3 Siberia 11	86.7	159.69	3.6
Danko Danko-12CP	86.3	154.8	1.9
Termobar KC-Г-12,5	88.2	164.88	3.1
MIMAKS KCF-12,5	84.6	163.08	8.8

Correlation coefficient for the field of values according to measurements and calculations of boiler efficiency and fuel consumption ratio: $r_1=-0.55$. At the same time, the inverse proportionality remains, but the dependence is only 55 %. This is significantly different from the data shown in Fig. 2. Thus, 45 % has the influence of other factors on efficiency.

Let's conduct a correlation-regression analysis of fuel consumption and CO₂ content (Fig. 4). As can be seen from Fig. 4, the most approximate to the ideal dependence of fuel consumption on the efficiency of boilers LEMAKS, MIMAKS and SIBERIA. The boilers of the trademarks ATON, DANKO, Termobar and ATEM fall out of the correlation field.

The correlation coefficient for the field values of the fuel consumption ratio and CO₂ content: $r_1 = -0.14$. Thus, the relationship between these indicators is almost absent, while it makes it difficult to select such an approximating function, its value was quite close to the values according to measurements and calculations.

To obtain a generalized comprehensive assessment of the effectiveness of this work, the nonparametric method of multidimensional analysis is used, which combines the scoring method and the method of multidimensional comparisons. This method is quite simple to use, but at the same time, the estimates obtained as a result of its application adequately reflect the system of the study and provide useful and important information about the objects under study. The essence of the proposed methodology for integrated assessment of the effectiveness of boilers is in comparing the actual efficiency with the benchmark indicators, and the efficiency of the boilers having the worst values.

Approbation using the «3E» method provides a more realistic picture, which is based on three anchor efficiency indicators. So, on the basis of the adopted confidence intervals and the construction of a confidence field, it becomes possible to graphically display the rating of boilers (Fig. 5).

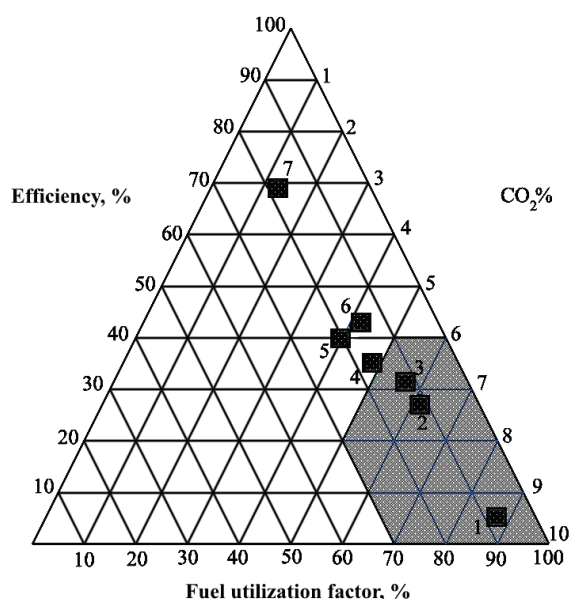


Fig. 5. «3E» diagram of the boiler criteria for the evaluation of efficiency, fuel utilization and carbon dioxide: 1 – ATEM; 2 – Termobar; 3 – ATON; 4 – Siberia; 5 – Lemaks; 6 – Danko; 7 – MIMAKS

Let's analyze the data using the author's multicriteria method «3E» to determine which of the analyzed boilers meet the specified criteria. To do this, within a triangle diagram, let's construct a field of confidence values, which is determined using the algorithm described in Section 5 and Table 2. Fig. 5 shows the result of the use of express analysis «3E», according to which in the field of confidence intervals there are three boiler units of manufacturers ATEM, Termobar and ATON. Thus, using a multi-criteria analysis, the optimal values of the indicators for each of the boilers were determined, and the affecting of the boiler units was carried out in a short time.

It is clearly seen that only three of the boilers, namely, boilers 1 – ATEM, 2 – Termobar, 3 – ATON, meet the standards of quality and efficiency, the worst indicators

at the boiler 7 – MIMAKS, the other three boilers also do not meet modern requirements.

7. SWOT analysis of research results

Strengths. The «3E» method makes it possible to carry out multi-criteria analysis of complex systems and equipment with high accuracy, in a short time, usually impossible using standard statistical approaches and methods of mathematical modeling. Thus, this method is an important tool for energy management of enterprises for making strategic decisions.

Weaknesses. The result of the express analysis affects the exact construction of the boundaries of the confidence interval.

Opportunities. The proposed rapid analysis can be applied in other industries. Application of the «3E» method is completely independent of the sphere of activity in which the decision is made. The results of testing the «3E» method indicate the feasibility of its further use.

The variability and flexibility of this method is achieved by the ability to change the main criterion indicators, as well as the field of optimal values. In multi-criteria analysis, each of the efficiency criteria acquires a specific quantitative value, which allows using the results of calculations in the decision-making process. Further development of the «3E» method requires testing at the enterprises of medium and large businesses, state institutions, in the defense industry in order to improve and unify the algorithms for creating the field of optimal values to make the right decision. This approach can be used as a marketing research tool for solving the problem of promoting a new product or service on the market and determining its competitiveness.

Threats. In some cases, with limited access to reliable information about the products of a production or service, an error may occur when determining the boundaries of the field of optimal values.

8. Conclusions

1. When conducting a technology audit based on field experiments and subsequent calculations using the method of reverse and direct balance, quantitative indicators of seven hot water WHGA-type boilers were found. According to them, a high energy indicator, namely, the efficiency of the direct balance of the ATEM boiler is 92.18 %, the lowest efficiency = 81.2 % of the LEMAKS boiler, and the other five boilers also do not meet regulatory requirements. According to the economic criterion, namely the fuel utilization factor, the best indicator was obtained by the boiler company ATEM, CFU=147.6 m³/Gcal, the worst figure, by the same criterion, at the boiler of the company Termobar, CFU=164.88 m³/Gcal. According to the environmental criterion, the best indicator is at the boiler of the MIMAKS company (CO₂=8.8 %), the worst at the boiler of the Danko company (CO₂=1.9 %). Based on this, the conclusion is drawn that a comparative analysis of efficiency requires additional research and the development of new methods of multi-criteria evaluation.

2. Analysis of the efficiency of boilers by the method of sums and the ranking of affects show that the boiler of ATEM is in the first place, the boilers of the firms LEMAKS and Siberia share fifth place. The correlation-regressive method of comparing the indicators of efficiency,

fuel consumption and CO₂ content in flue gases shows that the boilers of the trademarks LEMAKS and MIMAKS are characterized by high fuel consumption and low efficiency. The best efficiency has a boiler company ATEM. The best environmental efficiency at nominal capacity in the boilers has ATEM and MIMAKS brandi, the worst in Danko, ATON and Termobar boilers. The results obtained by these two methods coincide with the results of the technology audit, therefore the complex relationship between efficiency indicators cannot be fully correctly determined using known methods of analysis. The results obtained by testing the «3E» method make it possible to obtain a more realistic and correct assessment of the effectiveness. The express method «3E» demonstrated that only boilers of the ATEM, Termobar and ATON trademarks meet all modern requirements for all efficiency criteria.

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