UDC 621.182-5: 504.064.2.001.18
DOI: 10.15587/1729-4061.2016.85408

IMPROVING THE EFFICIENCY OF FUEL COMBUSTION WITH REGARD TO THE UNCERTAINTY OF MEASURING OXYGEN CONCENTRATION

V. Babak
Doctor of Technical Sciences, Professor,
Corresponding Member of the NAS of Ukraine*
E-mail: vdoe@ukr.net
V. Mokiychuk
PhD, Associate Professor**
E-mail: nau_307@ukr.net
A. Zaporozhets
Junior Researcher*
E-mail: art.morco@gmail.com
O. Redko
Postgraduate Student**
E-mail: ralex_sh@mail.ru
*Department heat measurement,
diagnosis and optimization in power engineering
Institute of Engineering Thermophysics of
National academy of sciences of Ukraine
Zhelyabov str., 2 a, Kyiv, Ukraine, 03057
**Department of Information Measuring Systems
National Aviation University
Kosmonavta Komarova ave., 1, Kyiv, Ukraine, 03058

Досліджено вплив метеорологічних параметрів навколишнього середовища на процес спалювання палива в котлоагрегатах. Встановлено функціональний взаємозв'язок між температурою, абсолютним тиском, відносною вологістю і об'ємною концентрацією кисню в повітрі. Запропоновано спосіб підвищення точності вимірювання коефіцієнта надлишку повітря для зменшення втрат теплової енергії в котлоагрегатах

Ключові слова: коефіцієнт надлишку повітря, метеорологічні параметри, невизначеність вимірювання, метод Монте-Карло

Исследовано влияние метеорологических параметров окружающей среды на процесс сжигания топлива в котлоагрегатах. Установлена функциональная взаимосвязь между температурой, абсолютным давлением, относительной влажностью и объемной концентрацией кислорода в воздухе. Предложен способ повышения точности измерения коэффициента избытка воздуха для уменьшения потерь тепловой энергии в котлоагрегатах

Ключевые слова: коэффициент избытка воздуха, метеорологические параметры, неопределенность измерения, метод Монте-Карло

1. Introduction

Contemporary state of thermo-technical equipment in the post-Soviet countries is characterized by a considerable period of operation and low efficiency. In Ukraine, about 11 000 boilers of power from 0,1 Gcal/h to 1 Gcal/h have been in operation for more than 20 years, more than 6000 boiler plants function with the efficiency around 70 %. Technical condition of existing boiler units requires their immediate improvement. Maximum effect in a number of such technologies is possible to attain by the automation of the process of fuel combustion [1]. In this case, the optimization of the process of fuel combustion is directed toward the formation of stoichiometric air-fuel mixture (AFM).

In order to control the process of fuel combustion in the furnace of a boiler, the excess air ratio coefficient (EAC) is applied, which is determined by the ratio of the amount of air that enters a combustion chamber to theoretically necessary for full combustion of fuel. In practice, EAC depends on the volumetric concentrations of oxygen in air (constant, 21 %) and output gases.

Taking into account the EAC value for the process of fuel combustion, a relevant task is to increase the accuracy of measuring EAC with regard to meteorological environmental parameters.

2. Literature review and problem statement

Literary sources [2–5] present different methods for optimization of the process of fuel combustion in the industrial high power boiler units (exceeding 3,5 MW). Coal, brown coal, peat, shales, biomass, petroleum residue, other solid and liquid-fuel materials are often considered as fuel [2]. A highly effective process of fuel combustion is reached by the minimization of EAC, the boundary of which is a sharp increase of CO in the output gases (higher than 100 ppm) [3]. In this case, an amount of NO_x is also reduced, the minimum value of which is reached at EAC in the range of 0,8–0,95 [4]. Frequently in the technological processes they use heat recovery of the waste gases, which makes it possible to reduce the consumption of fuel to 30 % [5].

To provide for a highly effective combustion of fuel, different types of the systems are used: biodiesel plant as a part of cogeneration system [6], a two-level intelligent control system of the process of fuel combustion in steam boilers and steam generators [7], a system of active carburetion for the water-heating boilers with capacity of up to 600 MW [8], a multilevel system of recirculation of gases in steam generators [9].

Many examined methods and systems regard EAC as the informative parameter. Paper [10] proposed a method for increasing the accuracy of its measurement based on the assumption about inconstancy of the gas concentration in the air. The importance of predicting gas concentrations, which form part of atmospheric air, is given emphasis in article [11]. Paper [12] presents studies of the influence of pollutants in air on changes in the synoptic and meteorological parameters of medium.

In practice, for determining EAC, a so-called "oxygen" formula is used, which with complete fuel combustion takes the following form:

$$\alpha = \frac{21}{21-[O_2]_{out}}, \tag{1}$$

where 21 is the volumetric concentration of oxygen (VCO) in air, %, $[O_2]_{out}$ is the VCO in the flue gases, %.

The quantity of VCO is considered to be constant at any climatic changes and phenomena, in the mountains and in the plains. However, long-term climate and physical observations [13] refute this assertion, which necessitates conducting research in this field.

3. The aim and tasks of the study

The research we conducted set the goal of determining peculiarities of change in VCO in the air depending on meteorological environmental parameters, which will make it possible to increase the accuracy of determining EAC and, consequently, to increase efficiency of the fuel combustion in boiler units.

To achieve this aim, the following tasks were set:

– to determine functional interrelation between the current meteorological parameters (temperature, humidity, pressure) and VCO in the air;

– to explore daily/seasonal dynamics of the change in current VCO by direct (with the aid of a gas analyzing instrument) and indirect (based on meteorological parameters) methods;

– to carry out a metrological assessment of the obtained results;

– to propose a functional dependence of EAC on the current VCO in the air and to estimate the accuracy of its measurement.

4. Methods and equipment for research into the influence of meteorological parameters on the change in oxygen concentration in the air

4. 1. Methods of determining volumetric concentration of oxygen in the air

An analytical value of the partial density of oxygen (E, g/m^3) is directly proportional to atmospheric pressure (P, hPa) minus the partial pressure of water vapor (e, hPa) and it is inversely proportional to the temperature of air (T, K):

$$E = 23{,}15 \cdot 10^3 \cdot \frac{P-e}{R \cdot T}, \tag{2}$$

where R is the specific gas constant for dry air, J/kg·K; 23,15 is the mass concentration of oxygen in dry air, %.

Calculation of the partial pressure of water vapor is determined by formula:

$$e = \varphi \cdot p_{vap}, \tag{3}$$

where ϕ is the humidity of air, %; p_{vap} is the quantity, which can be determined according to recommendations of the Guide to Meteorological Instruments and Methods of Observation (Switzerland):

$$p_{vap}(P, T') = f(P) \cdot r(T'), \tag{4}$$

$$f(P) = 1{,}0016 + 3{,}15 \cdot 10^{-6} \cdot P - 0{,}074 \cdot P^{-1}, \tag{5}$$

$$r(T') = 6{,}112 \cdot e^{\frac{17{,}62 \cdot T'}{243{,}2+T'}}, \tag{6}$$

where T' is the temperature of air in the Celsius degrees, °C.

Transition to the volumetric concentration of oxygen occurs by the following ratio:

$$[O_2] = \frac{6{,}236 \cdot E \cdot T}{P' \cdot M_{O_2}}, \tag{7}$$

where $[O_2]$ is the volumetric concentration of oxygen in the air, %; P' is the atmospheric pressure, mm Hg; M_{O2} is the molar mass of oxygen, g/mol.

The final analytical representation of functional dependence of the volumetric concentration of oxygen in the air on meteorological parameters takes the form [10]:

$$[O_2](P, T', \varphi) = 20{,}957 \cdot \left(1 - \frac{e(P, T', \varphi)}{P}\right). \tag{8}$$

4. 2. Equipment for investigating daily/seasonal dynamics of the change in the volumetric concentration of oxygen in the air

To determine the current VCO in the air by direct method, we used the portable gas analyzer OKSI-5M with absolute error of determining the oxygen concentration Δ_{O2}=±0,1 %.

To determine VCO in the air indirectly, we used a set of tools of measurement instruments, consisting of two meteorological psychometric thermometers TM4-1 (Δ_T=±0,2 °C, Δ_ϕ=±3 %) and the barometer-aneroid BAMM-1 (Δ_P=±20 hPa).

5. Results of research into the change in the volumetric concentration of oxygen in the air

To conduct experimental studies to determine the current volumetric concentration of oxygen in the air by direct (with the aid of a gas analyzer) and indirect (based on the meteorological data on temperature, absolute pressure and relative humidity) methods, we selected a locality in the territory of the city of Lubny, Poltava Region (Ukraine), with the following geographical coordinates: latitude – 50,013°, longitude – 32,991°.

Moderate-cold climate predominates in the territory of the city of Lubny. According to the Koppen classification, climate in the territory of the city corresponds to the level Dfb (moderately cold climate with uniform humidification). Based on the statistical data between 1982 and 2012, average annual temperature in the city of Lubny is 8 °C. The average annual rainfall is 628 mm.

An experiment to determine the current VCO in the air by direct and indirect methods lasted for 8 months: from August 2015 to March 2016. Parallel measurements were taken 3 times per day around 09:00, 15:00 and 20:00 local time at any weather phenomena (rain, snow, gusty wind, etc.) in a special protected housing at the local meteorological station. Totally it was obtained 475 sets of measurements.

Fig. 1 demonstrates results of direct measurements of VCO in the air in the course of entire experiment.

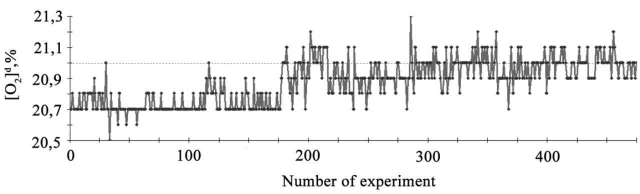

Fig. 1. Volumetric concentration of oxygen, measured by the gas analyzer OKSI-5N

In the course of conducting the experiment, in parallel with measuring the volumetric concentration of oxygen in the air using the gas analyzer OKSI-5M, we measured basic meteorological parameters – temperature, humidity and pressure (Fig. 2–4).

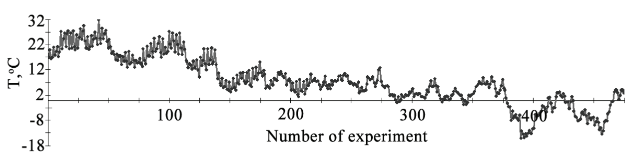

Fig. 2. Measured values of air temperature during experimental period

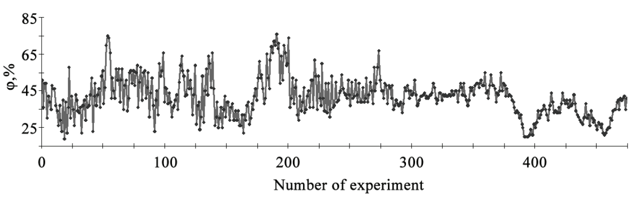

Fig. 3. Measured values of relative air humidity during experimental period

Fig. 4. Measured values of atmospheric pressure during experimental period

Based on the received data, taking into account dependence (8), we obtained theoretical dependence of the change in the volumetric concentration of oxygen in the air over entire course of the experiment (Fig. 5).

Fig. 5. Indirect values of the volumetric concentration of oxygen during experimental period

Experimental studies were conducted over a wide range of meteorological parameters; in this case, maximum and minimum values of temperature, absolute pressure and relative humidity comprised, respectively: T_{max}=31,8 °C; T_{min}=–15,1 °C; P_{max}=1046 hPa; P_{min}=990 hPa; ϕ_{max}=86 %; ϕ_{min}=29 %.

The observed minimum of VCO in the air by the direct measurement reached 20,5 %, the maximum – 21,3 %; minimum value of VCO in the air by the indirect measurement reached 20,5 %, the maximum – 21,0 %.

6. Discussion of results of research into the volumetric concentration of oxygen in the air

To compare accuracy of the two methods of determining VCO, we performed calculation of measurement uncertainty using the MathCAD programming software.

Direct method of measuring the volumetric concentration of oxygen

The gas analyzer OKSI-5N in the mode of determining has a scale value of 0,1 %. Its absolute error of measurement (according to specifications) is also 0,1 %.

Experimental measurements were one-time and they were obtained at the different levels of output quantity. The array of the obtained values of VCO was divided into 95 groups of 5 values. An uncertainty of the A type is regarded as the median estimation of the mean-square deviations of the obtained groups, which comprised 0,024 %.

An uncertainty of the B type of the direct method of measurements for the uniform law of distribution of probabilities of random variables is:

$$\hat{u}_B = \frac{\Delta_{O_2}}{\sqrt{3}} = 0{,}058\,\%. \qquad (10)$$

The estimation of summary standard uncertainty is equal to:

$$\hat{u}_c = \sqrt{u_A^2 + u_B^2} = 0{,}063\,\%. \qquad (11)$$

The estimation of the extended expanded uncertainty of the direct method of measurements at the confidence coefficient 95 % is calculated according to [14]:

$$\hat{U}_1 = t_P(\hat{v}_{eff}) \cdot \hat{u}_c =$$
$$= t_{0,95}\left(f_{eff} \cdot \left[1 + \frac{\hat{u}_A^2}{\hat{u}_B^2} \right]^2 \right) \cdot \hat{u}_c = 0{,}104\,\%, \qquad (12)$$

where $t_P(\hat{v}_{eff})$ is the Student's coefficient for probability P and the number of degrees of freedom $f_{eff} = n_i - 1$, n_i is the number of measurements, carried out when assessing the i-th contribution of uncertainty.

Indirect method of measuring the volumetric concentration of oxygen.

Conducting the evaluation of the extended expanded uncertainty of the proposed indirect method of the measurement of VCO by a classic method is impossible since the analytical representation of the model of measurement takes the form of complex nonlinear functional dependence on three input values. When differentiating function (8), we have the not simplified polynomials of partial derivatives, which complicates subsequent calculations, including determining the correlation coefficients of input quantities. Therefore, to solve this problem, we propose to estimate the extended expanded uncertainty of the indirect method of measurement by using imitation simulation according to the Monte-Carlo method [15].

By the calculated values of VCO, based on the measurements of meteorological parameters, we isolated the sets of values of input values corresponding to 20 levels of output quantity. The values of each input quantity from the chosen sets were accepted as the estimation of mathematical expectation for the generation of arrays of random numbers. As an estimation of mean-square deviation (MSD), we accepted the ratio of absolute instrument error and coefficient, which connects MSD of the Gauss' law with its boundaries with (k=1,96 at P=95 %). A quantity of iterations of the generation of arrays of random input variables is equal to 10^5.

According to data on the generated arrays of input random quantities, we obtained 20 arrays of output random quantity. Mathematical expectations of the simulated array of the VCO values differ in the fifth sign after comma from those calculated by formula (8) by the VCO value (Table 1), respectively.

A hypothesis on the normality of the law of distribution of the simulated output quantity is confirmed by the statistical criterion Pearson's χ-square. The distribution of probabilities of the simulated VCO value is represented in Fig. 6 in the form of histogram.

An evaluation of the extended expanded uncertainty of VCO measured by indirect method according to the results of simulation by the Monte Carlo method is the interval of scope with confidence coefficient P=95 % (10). The values of estimation of the extended expanded uncertainty for the sets of input quantities are presented in Table 1.

$$\hat{U}_2 = \frac{(O_2)_{m_{1-\frac{1-P}{2}}} - (O_2)_{m_{\frac{1-P}{2}}}}{2}, \qquad (13)$$

where $f(O_2)_{m_q}$ is the value of q-quantile of the function of distribution of the density of probabilities of the VCO value being simulated.

Fig. 7–9 demonstrate diagrams, which reflect dependence of the change in the extended expanded uncertainty of output quantity (P, T, ϕ) with an increase of MSD of one input physical quantity by 2, 3 and 4 times, respectively. We examined the sets of values of the input quantities that correspond to the minimum, mean and maximum levels of output quantity.

Table 1

Calculated and simulated by the Monte Carlo method values of VCO

Number of measurement	VCO values, calculated by (8)	Mathematical expectation of the simulated VCO	VCO uncertainty
0	20,71503	20,71498	0,01288
35	20,69303	20,69298	0,02079
70	20,76964	20,76961	0,01162
105	20,67201	20,67198	0,02150
130	20,77282	20,77281	0,00960
140	20,86138	20,86136	0,00815
172	20,84103	20,84102	0,00710
204	20,85621	20,85620	0,00662
236	20,85598	20,85597	0,00687
268	20,85677	20,85677	0,00658
270	20,84035	20,84032	0,00683
295	20,87586	20,87586	0,00475
320	20,88221	20,88221	0,00492
345	20,90193	20,90193	0,00367
370	20,87519	20,87517	0,00495
375	20,85319	20,85318	0,00580
400	20,93778	20,93778	0,00168
425	20,88545	20,88546	0,00453
450	20,93647	20,93647	0,00183
474	20,87782	20,87781	0,00494

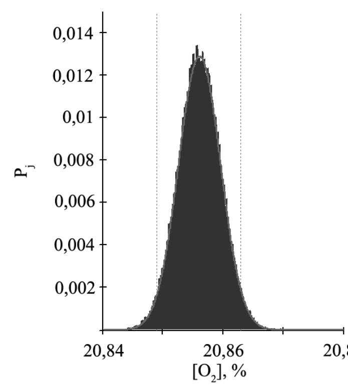

Fig. 6. Distribution of probabilities of the simulated VCO value that corresponds to the 236th set of input quantities

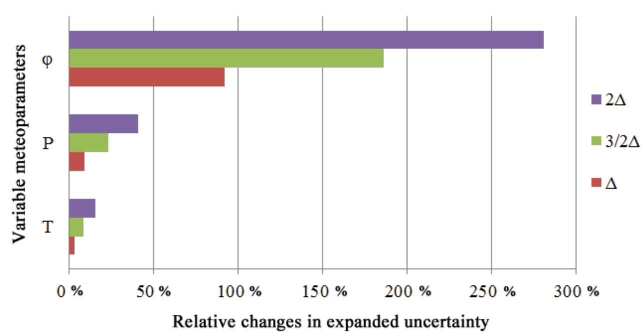

Fig. 7. Relative changes in the extended expanded uncertainty of minimum VCO value (for the set of measurements No. 105) on the change in MSD of measuring input quantities

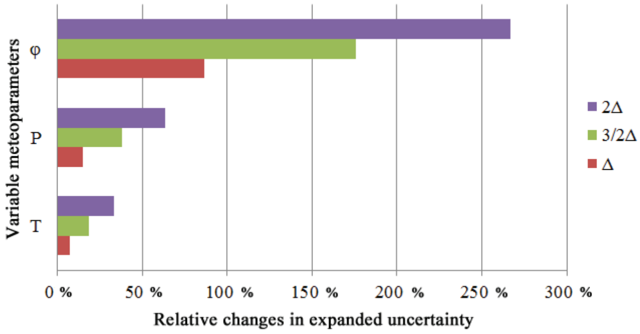

Fig. 8. Relative changes in the extended expanded uncertainty of mean value of VCO (for the set of measurements No. 270) on the change in MSD of measuring input quantities

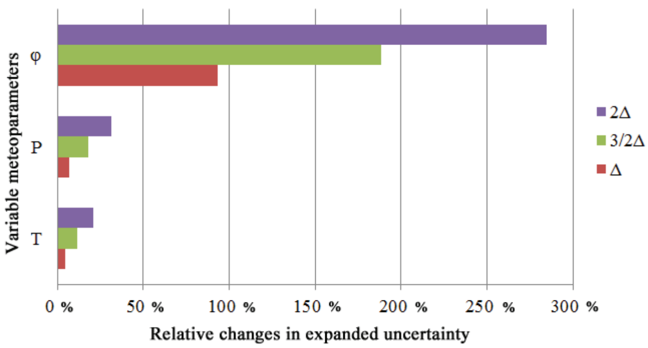

Fig. 9. Relative changes in the extended expanded uncertainty of maximum value of VCO (for the set of measurements No. 400) on the change in MSD of measuring input quantities

Based on the received data of research into the nature of change in the extended expanded uncertainty of VCO in the air on the MSD of meteorological parameters, it follows that relative air humidity is the most influencing input physical quantity. In this case, the effect of temperature and of atmospheric air pressure on the estimation of the extended expanded uncertainty of VCO at the mean level is less than that at the minimum and maximum levels.

Fig. 10 demonstrates dependence of the extended expanded uncertainty on the VCO value, calculated by the indirect method.

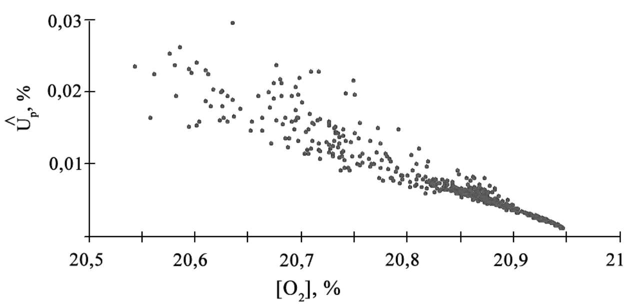

Fig. 10. Dependence of uncertainty on the indirect measurement of VCO

It follows from Fig. 10 that the proposed dependence has specific character, which is represented by the spread of estimation of the measurement uncertainty of VCO over the entire range. A variable set of values of input quantities that corresponds to the narrow range of output quantity might be one of the probable reasons for this behavior of dependence.

A comparison of numerical results of uncertainties of the VCO values measured by the direct (0,104 %) and indirect (≤0,03 %) methods reveals that the former can be applied in practice for the calculation of VCO with a better accuracy.

Taking into account the data represented above on the instability of VCO in the air, it is relevant to consider daily/seasonal change in the meteorological parameters of medium and operating conditions of a boiler unit when executing control and managing the process of fuel combustion. The experiment performed in the work attests to the fact that VCO in the air (21 %) accepted as the constant cannot be used for the technological and ecological calculations of thermo-technical equipment performance. Thus, to increase the accuracy of EAC measurement, formula (1) must be transformed as follows:

$$\alpha=\frac{[O_2]}{[O_2]-[O_2]_{out}}=1+\frac{[O_2]_{out}}{20{,}957\cdot\left(1-\dfrac{e(P,T',\varphi)}{P}\right)-[O_2]_{out}}. \quad (14)$$

Represented below is the two-parameter dependence of correction (absolute methodical error in the measurement of EAC):

$$\Delta\alpha([O_2],[O_2]_{out})=\frac{[O_2]_{out}\cdot(21-[O_2])}{([O_2]-[O_2]_{out})\cdot(21-[O_2]_{out})}. \quad (15)$$

It is shown based on theoretical calculations that the application of the proposed method of EAC measurement, taking into account the current VCO in the air, makes it possible to considerably reduce methodological error of the measurement (to 1,2 of the absolute value of EAC quantity (at $[O_2]$=20,5 %, $[O_2]_{out}$=18 %)).

The conducted research allows us to considerably enlarge the understanding of the effect of meteorological parameters on the gas composition of medium. The discovered functional interrelations make it possible to qualitatively increase the efficiency of fuel combustion due to an increase in the accuracy of measurement of EAC. However, the elimination of methodological error when determining EAC requires additional equipment in the form of an oxygen sensor, or a set of temperature sensors, pressure and humidity sensors, which will be introduced to the analytical block of a gas analyzing device. This may lead to additional financial expenditures.

Results of the conducted research can be used not only in the field of thermal-power engineering for the quality control over fuel materials combustion, but also:

– in medicine – for the creation of microclimatic zones with the assigned gas composition of the environment;

– in agriculture – to control growth of agricultural crops;

– in ecology when compiling climatic maps, as well as other areas.

We plan to conduct further experimental studies on the dynamics of change in VCO in the air in other climatic zones. The functional interrelations we received might be used as well for measuring the volumetric concentrations of nitrogen and carbon dioxide in the environment.

7. Conclusions

1. Based on basic gas laws and the Mendeleyev-Klapeyron equation, we received function of dependence of VCO in the air on temperature, absolute pressure and relative humidity of the environment in the form $[O_2]=f(T, P, \phi)$.

2. It was established that VCO in the air depending on day or night and season can vary in the range of 0,1...0,6 %. These results are confirmed both by direct and indirect measurement of VCO.

3. An estimation of the extended expanded uncertainty of the direct method of measurement at confidence coefficient 95 % is 0,104 %. To evaluate the extended expanded uncertainty of the indirect method of measurement, we carried out imitation simulation, which consisted in a sequential increase in the instrumental errors of measuring tools. It was revealed as a result that the largest influence on the extended expanded uncertainty of measuring VCO by the indirect method is exerted by an increase in the instrumental error of hygrometer. In this case, a quantity of the extended expanded uncertainty of the indirect method of measurement did not exceed 0,03 %. A comparison of the uncertainties of VCO measurement by indirect (≤0,03 %) and direct (0,104 %) methods reflects the possibility of applying the former in the course of technological and ecological calculations of functioning of thermo-technical equipment.

4. We proposed a method for measuring EAC, which is based on the calculation of the current VCO in the air, which makes it possible to exclude a methodological error in the measurement. It is shown that the quantity of determining EAC, according to the proposed method, may amount to 1,2 of absolute value of the quantity. In this case, its value may grow depending on VCO in the air and output gases.

References

1. Volikov, A. N. Povyshenie jeffektivnosti szhiganija topliva v kotloagregatah [Text] / A. N. Volikov, O. N. Novikov, A. N. Okat'ev // Jenergonadzor-inform. – 2010. – Issue 1 (43). – P. 54–57.
2. Kouprianov, V. I. Optimization of excess air for the improvement of environmental performance of a 150 MW boiler fired with Thai lignite [Text] / V. I. Kouprianov, V. Tanetsakunvatana // Applied Energy. – 2003. – Vol. 74, Issue 3-4. – P. 445–453. doi: 10.1016/s0306-2619(02)00199-x
3. Kouprianov, V. I. Applications of a cost-based method of excess air optimization for the improvement of thermal efficiency and environmental performance of steam boilers [Text] / V. I. Kuprianov // Renewable and Sustainable Energy Reviews. – 2005. – Vol. 9, Issue 5. – P. 474–498. doi: 10.1016/j.rser.2004.05.006
4. Houshfar, E. Effect of excess air ratio and temperature on NOx emission from grate combustion of biomass in the staged air combustion scenario [Text] / E. Houshfar, O. Skreiberg, T. Lovas, D. Todorovic, L. Sorum // Energy & Fuels. – 2011. – Vol. 25, Issue 10. – P. 4643–4654. doi: 10.1021/ef200714d
5. Ning, F.-H. Method for designing and calculating a boiler flue gas waste heat recovery system and its applications [Text] / F.-H. Ning, K. Wang, H-Q. Zhang, K. Cheng // Journal of Engineering for Thermal Energy and Power. – 2015. – Issue 5. – P. 745–749.
6. Chajkovs'ka, Je. Je. The development of energy-saving operation technology of the biodiesel plant as a part of the cogeneration system [Text] / Je. Je. Chajkovs'ka // Eastern-European Journal of Enterprise Technologies. – 2016. – Vol. 1, Issue 8 (79). – P. 4–10. doi: 10.15587/1729-4061.2016.59479
7. Liu, X. J. An energy saving control for combined cycle power plant by supervisory predictive scheme [Text] / X. J. Liu, G. L. Hou, C. Yin // Proceedings of the European Control Conference. – Greece, 2007. – P. 2991–2998.
8. Ma, L. Effect of the separated overfire air location on the combustion optimization and NOx reduction of a 600 MWe FW down-fired utility boiler with a novel combustion system [Text] / L. Ma, Q. Fang, P. Tan, C. Zhang, G. Chen, D. Lv et. al. // Applied Energy. – 2016. – Vol. 180. – P. 104–115. doi: 10.1016/j.apenergy.2016.07.102
9. Luo, W. Exergy-based control strategy selection for flue gas recycle in oxy-fuel combustion plant [Text] / W. Luo, Q. Wang, J, Guo, Z. Liu, C. Zheng // Fuel. – 2015. – Vol. 161. – P. 87–96. doi: 10.1016/j.fuel.2015.08.036
10. Babak, V. P. Pidvyshhennja tochnosti vymirjuvannja koeficijenta nadlyshku povitrja v kotloagregatah iz zastosuvannjam gazoanalizatoriv elektrohimichnogo typu [Text] / V. P. Babak, A. O. Zaporozhets, O. O. Redko // Promyslova teplotehnika. – 2015. – Vol. 37, Issue 1. – P. 82–96.
11. Klanova, J. Assessing the Influence of Meteorological Parameters on the Performance of Polyurethane Foam-Based Passive Air Samplers [Text] / J. Klanova, P. Eupr, J. Kohoutek, T. Harner // Environmental Science & Technology. – 2007. – Vol. 42, Issue 2. – P. 550–555. doi: 10.1021/es072098o
12. Katsoulis, B. D. The relationship between synoptic, mesoscale and microscale meteorological parameters during poor air quality events in Athens, Greece [Text] / B. D. Katsoulis // Science of The Total Environment. – 1996. – Vol. 181, Issue 1. – P. 13–24. doi: 10.1016/0048-9697(95)04953-3
13. Ovcharova, V. F. Metodika rascheta kolichestva kisloroda v atmosfernom vozduhe na osnove meteorologicheskih parametrov s cel'ju prognozirovanija meteopaticheskih jeffektov atmosfery [Text]: metod. rekom. / V. F. Ovcharova. – Moscow: MZ SSSR, 1983. – 13 p.
14. Zaharov, I. P. Analiz chislennyh metodov ocenivanija neopredelennosti v izmerenijah [Text] / I. P. Zaharov // Vestnik Nacional'nogo tehnicheskogo universiteta Har'kovskij politehnicheskij institut. – 2006. – Vol. 40. – P. 96–100.
15. Pereira, E. J. da S. Methodology of risk analysis by Monte Carlo Method applied to power generation with renewable energy [Text] / E. J. da S. Pereira, J. T. Pinho, M. A. B. Galhardo, W. N. Macedo // Renewable Energy. – 2014. – Vol. 69. – P. 347–355. doi: 10.1016/j.renene.2014.03.054