Environmental safety and toxicity indicators of gas and fuel oil boilers

Kuat Baubekov [1], Hasan Alimov [2], Munira Azimova [2], Nargiza Kurbanova [2], Raxmatillo Karimov [2,3,a)], Matlybaxon Xodjialimova [2], Husniddin Abdikhalilov [2]

[1] *Seifullin Kazakh Agrotechnical Research University, Astana, Kazakhstan*
[2] *Tashkent state technical university named after Islam Karimov, Tashkent, Uzbekistan*
[3] *Almalyk State Technical Institute, Almalyk, Uzbekistan*

[a)] *Corresponding author: rahmatillo05.03.1982@gmail.com*

Abstract. This article presents the results of a study on the impact of secondary and tertiary air proportions and their ratios on the formation of nitrogen oxides and carcinogenic PAHs during the combustion of gas and fuel oil. Indicators of total and partial toxicity of combustion products under various conditions of conventional and staged combustion of gas and fuel oil were determined, and a comprehensive analysis was performed. The research showed that the total toxicity of gas combustion decreased by 51%, while the toxicity of nitrogen oxides alone was reduced by approximately 59%. At the same time, the toxicity of soot increased by 1.8 times, and that of benzo(a)pyrene by about 2 times (due to their low initial concentrations), which led to a 10% increase in overall toxicity. Thus, it was concluded that the tested three-stage gas combustion regime can be recommended for use.

INTRODUCTION

The development of scientific foundations for in-furnace methods to reduce the toxicity of combustion products of gas and fuel oil has been carried out without consideration of the actual condition of the boiler, without optimizing fuel combustion modes, or improving the efficiency of the main equipment. Moreover, these studies have often been one-sided, based on traditionally declared components of incomplete combustion (usually CO) and nitrogen oxides. Meanwhile, emissions of another unregulated group of carcinogenic substances and soot — which increase several times during fuel oil combustion, and especially during its co-combustion with gas — have been unfairly neglected. Furthermore, even traditional methods of gas and fuel oil combustion are not sufficiently studied, although their toxicity in operating boilers significantly depends not only on the main parameters .characteristics of fuel-air mixture, design and operating parameters, but also on the elemental condition and wear of the equipment, poor adjustment of combustion modes, which can also influence the ratio of incomplete combustion components to NOx. This explains the significant variation in the effectiveness of in-furnace methods for reducing combustion toxicity reported in the literature [1-5].

The developed boiler retrofit schemes [1-3] made it possible to separately study the influence of the proportion of secondary and tertiary air and their ratio on the formation of nitrogen oxides and carcinogenic PAHs during the combustion of gas and fuel oil. Consequently, this allowed for a deeper understanding of the mechanisms of interdependence in the formation of emissions from various harmful substance groups, the formation of which depends on the excess air ratio in the combustion zone and other operating conditions, often in mutually opposite ways [4-6].

Boiler modernization projects for TGM-94 units at the Nevinnomysskaya GRES, the Krasnodar CHP plant, and TGM-104 boilers at the Mary GRES for staged combustion of gas and fuel oil were carried out by Kharkiv Central Design Bureau “Energoprogress” of LLC “Kotloturboprom” (Kharkiv, Ukraine) [1-3, 7-11].

Various burner configurations for TGM-94 gas-fuel oil boilers were tested, allowing air to be supplied in two-, three-, or four-stage modes (Fig.1), which led to a significant improvement in environmental performance and compliance with emission limits for controlled pollutants, while maintaining the same levels of uncontrolled sulfur oxide emissions. At the same time, high environmental, reliability, and techno-economic performance was ensured for the boiler during both separate and combined staged combustion of gas and fuel oil across the entire load range [5-7, 12-16].

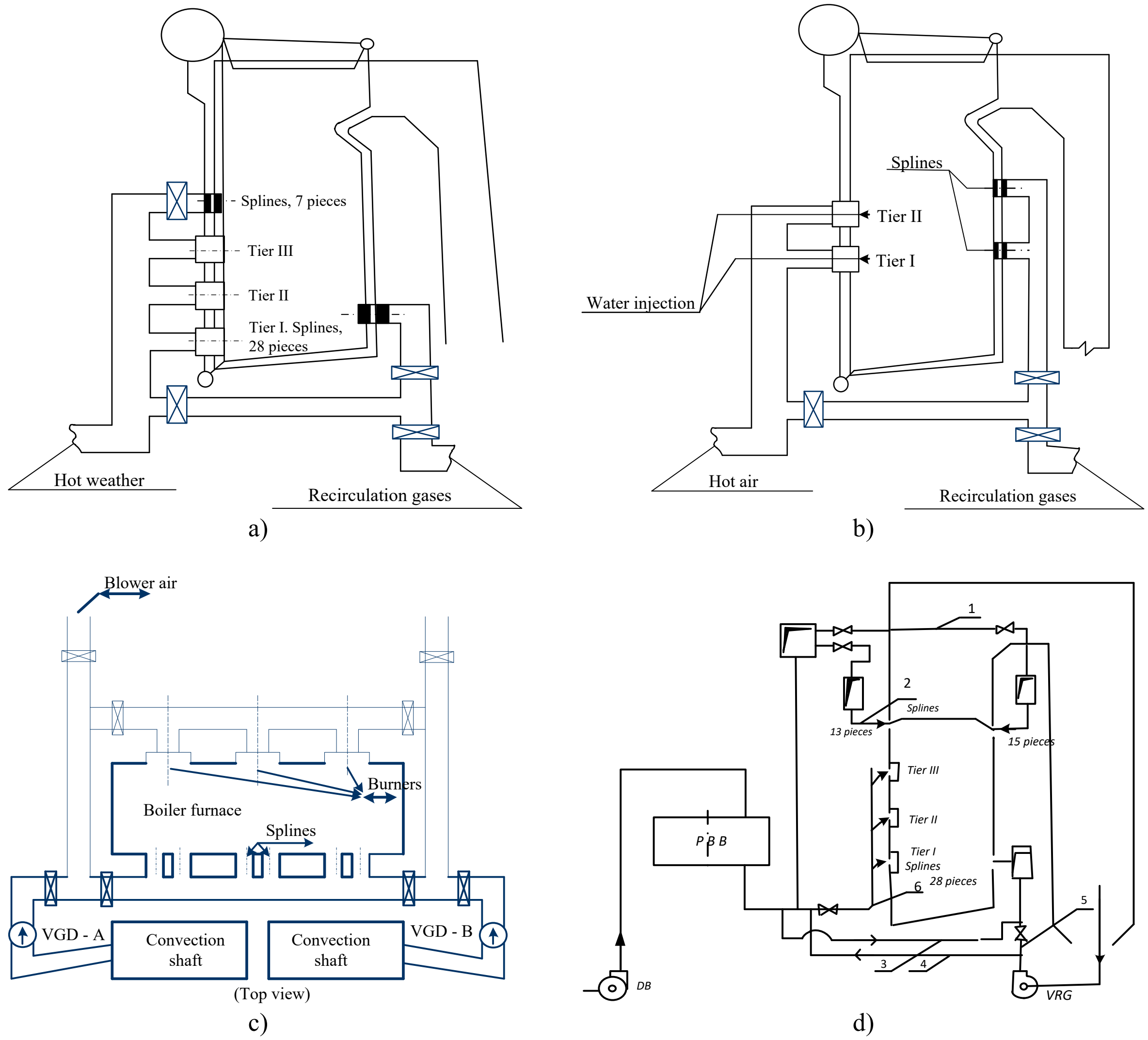

FIGURE 1. Modernization Schemes of TGM-94 Boilers: Unit №6 at Tashkent TPP (a), Units №8 and 11 at Nevinnomysskaya TPP (b), TGM-104 Unit №3 at Mary GRES (c), and TGM-94 Unit №9 at Krasnodar CHP (d)

The interrelation between the emissions of two antagonistic groups of harmful substances - NOx concentration, soot, and benzo(a)pyrene - was also traced using a unified methodology on operating boilers (for both conventional and unconventional methods), and a correlation between them was established [17-21].

These data, considered from the perspective of total and partial toxicity for each combustion mode, provide an objective environmental understanding of existing gas and fuel oil combustion regimes, and help guide the implementation of in-furnace measures. Indicators of total and partial toxicity of combustion products under various modes of conventional and staged combustion of gas and fuel oil were determined and comprehensively analyzed. The results of these studies are as follows (Table 1) [22-26]:

- The toxicity of natural gas combustion products during conventional single-stage combustion is determined by nitrogen oxides toxicity by 95.6-99.25%. The developed and tested three-stage gas combustion mode was superior to an unoptimized combustion mode in all environmental parameters, including a 28% reduction in total toxicity. Total toxicity decreased by 51%, and the toxicity of nitrogen oxides alone was reduced by approximately 59%. At the same time, the toxicity of soot increased 1.8 times, and benzo(a)pyrene about 2 times (due to their initially low concentrations), which led to a 10% increase in total toxicity. Thus, the tested three-stage gas combustion mode can be recommended for practical use;

TABLE 1. Environmental safety under various modes of gas and fuel oil combustion in TGM-94 boilers of different GRES, expressed through indicators of total and specific toxicity of combustion products

Object of study (boiler type, number of burners per stage), type and method of fuel combustion	Main operational and environmental combustion parameters									Patents** №
	α_1	$\delta_{gen.} \cong \delta_1 + \delta_2$	α_{yx}	NO_x, ìã/ì^3	Indicators of total and specific toxicity (in %)					
					T^{Σ}	T_{SO_2}	T_{NO_2}	T_C	$T_{C_{20}H_{12}}$	
1. Navoi GRES (TGM-94, 21 TKZ burners on 3 stages), hydrogen sulfide-containing natural gas ($H_2S = 0.08\%$):										1208412
Single-stage combustion	1,00	0	1,4	510	6276 (100%)	220 (3,51%)	6000 (95,6%)	15* (0,24%)	41 (0,65%)	
Two-stage combustion	0,82-0,89	0,22-0,36	1,4	255	3295 (100%)	220 (6,7%)	3000 (91,0%)	19* (0,58%)	56 (1,7%)	
2. Tashkent GRES (TGM-94, 21 TKZ burners on 3 stages), natural gas:										1346907
Single-stage combustion	1,00	0	1,4	608	7207 (100%)	0	7153 (99,25%)	12* (0,17%)	42* (0,58%)	
Two-stage combustion ("vertical")	0,75	0,25	1,4	225	3087 (100%)	0	3000 (97,2 %)	20* (0,63%)	67* (2,17%)	
Two-stage combustion (“horizontally”)	0,85	0,15	1,4	735	8707 (100%)	0	8647 (99,3 %)	13* (0,15%)	43* (0,55%)	
Three-stage combustion	0,67-0,73	0,27-0,33	1,4	266	3193 (100%)	0	3129 (98%)	17* (0,5%)	47* (1,5%)	
3. Nevinnomysskaya GRES (TGM-94, 6 HFTs burners in 2 tiers), Stavropol natural gas:										1346907
Single-stage combustion	1,0	0	1,4	364	4510 (100%)	-	4282 (95,0%)	18 (0,34%)	210 (4,66%)	
The same, unadjusted mode	1,0	0	1,4	210	3078 (100%)	-	2471 (80,3%)	57 (1,8%)	550 (17,9%)	
Three-stage combustion	0,69	0,31	1,4	150	2208 (100%)	-	1765 (79,9%)	33 (1,5%)	410 (18,6%)	
4. Nevinnomysskaya GRES (TGM-94, 6 HFT burners in 2 tiers), high-sulfur fuel oil ($S^p = 3.5\%$):										1398553
Single-stage combustion	1,0	0	1,4	412	14501 (100%)	8740 (60,3%)	5304 (36,6%)	327 (2,26%)	130 (0,84%)	
The same, unoptimized mode	1,0	0	1,4	315	14263 (100%)	8740 (61,3%)	3706 (26,0%)	1467 (10,3%)	350 (2,4%)	
Three-stage combustion	0,78	0,22	1,4	231	12365 (100%)	8740 (70,7%)	2718 (22,0%)	727 (5,9%)	180 (1,4%)	
5. Nevinnomysskaya GRES (TGM-94, 6 HFT burners in 2 tiers), co-combustion of gas and high-sulfur fuel oil										1346907, 1398553
Single-stage combustion	1,0	0	1,4	350	8875 (100%)	4370 (49,2%)	4118 (46,4%)	107 (1,25%)	280 (3,15%)	
The same, unadjusted mode	1,0	0	1,4	262	11815 (100%)	4370 (37,0%)	3082 (26,1%)	2333 (19,7%)	2030 (17,2%)	
Two-stage combustion (“vertically”)	0,69	0,31	1,4	190	8162 (100%)	4370 (53,5%)	2235 (27,4%)	107 (1,3%)	1450 (17,8%)	
Three-stage combustion	0,69	0,31	1,4	196	7906 (100%)	4370 (55,3%)	2306 (29,2%)	200 (2,5%)	1030 (13,0%)	
6. Tashkent GRES (TGM-94, 21 TKZ burners on 3 tiers), sulfur-containing fuel oil ($S^p = 2.0\%$):										1346907, 1398553
Single-stage combustion	1,0	0	1,4	505	11824 (100%)	5400 (45,7%)	5941 (50,2%)	333* (2,82%)	150* (1,28%)	
Three-stage combustion	0,87-0,89	0,13	1,4	260	10310 (100%)	5400 (57,5%)	3060 (32,6%)	733* (7,8%)	200* (2,1%)	

- The total toxicity of combustion products from high-sulfur fuel oil is about 2.0-3.2 times higher than that of gas. The toxicity is distributed as follows: nitrogen oxides — 36.6%, sulfur oxides — 60.3%, soot — 2.26%, benzo(a)pyrene — 0.84%. Under unoptimized combustion conditions, the total toxicity remains at about the same level (within ~1%). However, the redistribution of toxicity changes as follows: a 30% reduction due to incomplete combustion is fully offset by an increase in soot toxicity by 4.5 times and benzo(a)pyrene by ~3 times, while the toxicity of uncontrolled sulfur oxides remains unchanged. Despite the impressive ~49% reduction in the partial toxicity of nitrogen oxides and the achievement of emission limit values (ELVs) through three-stage fuel oil combustion, the total toxicity compared to the optimized conventional combustion mode was reduced by only ~15%;

-The worst-case scenario occurs during co-combustion of gas and high-sulfur fuel oil: under optimized combustion modes with conventional single-stage combustion, the toxicity distribution is as follows: nitrogen oxides — 46.4%, sulfur oxides — 49.2%, soot — 1.25%, benzo(a)pyrene — 3.15%. Under unoptimized conditions with excess air coefficients of 1.06-1.08, total combustion toxicity increases by 33%. Here, a 25% reduction in toxicity due to incomplete combustion is more than offset (by 8%) by a 22-fold increase in soot toxicity and a ~7-fold increase in benzo(a)pyrene, while the toxicity of uncontrolled sulfur oxides remains unchanged. The three-stage gas and fuel oil combustion mode was superior to the unoptimized mode in all environmental parameters, including a 33.1% reduction in total toxicity, a 49.3% decrease in benzo(a)pyrene toxicity, and an 87% reduction in soot toxicity. However, compared to the optimized conventional fuel oil combustion mode, the total toxicity was reduced by only ~11%, although the partial toxicity of nitrogen oxides decreased by ~44%. Still, an increase in soot toxicity by 1.87 times and benzo(a)pyrene by ~3.68 times led to an increase in total toxicity by 13.9%.

The obtained experimental data allow for the application of correlation dependencies to other fuels and thermal power stations as well [27-36].

Of course, it is not possible to establish a correlation between the concentrations of antagonistic groups of toxic substances for the full range of equipment wear states and their associated unoptimized combustion modes of gas and fuel oil. However, the data obtained in this study are reliable within the limits of the achieved measurement accuracy [37-43].

In Kazakhstan, since July 1, 2008, newly constructed and reconstructed enterprises are subject to fairly strict specific emission standards for nitrogen oxides into the atmosphere. As shown by the studies conducted, it will be difficult to meet these standards using only in-furnace methods — even when burning an environmentally clean fuel like natural gas — without the development of a new generation of boilers. However, in practice, we are still unable to obtain the necessary funding to continue this line of work [41-45].

CONCLUSION

The developed boiler modernization schemes made it possible to separately study the influence of the proportion of secondary and tertiary air, as well as their ratio, on the formation of nitrogen oxides and carcinogenic PAHs during the combustion of gas and fuel oil. This, in turn, enabled a more comprehensive understanding of the mechanisms linking the formation of the experimental data obtained make it possible to apply correlation dependencies at thermal power plants (TPPs).

REFERENCES

1. R.Yusupaliyev, N.Musashayxova, A.Kuchkarov. *Methods of Purification of Polluted Water from Ammonia Compounds at Nitrogen Fertilizer Plants*. E3S Web of Conferences, 563, **03085**, (2024). https://doi.org/10.1051/e3sconf/202456303085

2. R.Yusupaliev, N.Kurbanova, M.Azimova, N.Musashaikhova, A.Kuchkarov. *Establishing a Water-chemical Regime and Increasing the Efficiency of Combustion of a Mixture of Fuel Oil and Gas in a DE 25-14 GM Boiler: A Case Study of the Kokand Distillery*. AIP Conference Proceedings, 2552, **030026**, (2022), https://doi.org/10.1063/5.0130471

3. R.Yusupaliev, B.Yunusov, M.Azimova. *The composition of natural waters of some source rivers of the republic of Uzbekistan, used in the thermal power engineering and the results of the experimental researches at preliminary and ion exchange treatment of water*. E3S Web of Conferences, 139, **01083**, (2019), https://doi.org/10.1051/e3sconf/201913901083

4. S.M.Turabdzhanov, J.M.Tangirov, P.M.Matyakubova, N.S.Amirkhulov, S.S.Khabibullaev. *Methods of providing metrological supply when pumping water into wells in oil fields.* AIP Conference Proceedings, 3045(1), **030073**, (2024), https://doi.org/10.1063/5.0197355

5. M.Azimova, N.Kurbanova, D.Rakhmatov. *Large-scale environmental benefits of biogas technology*. AIP Conference Proceedings, 3152(1), **060007**, (2024), https://doi.org/10.1063/5.0218937

6. M.Jalilov, M.Azimova, A.Jalilova. *On a new technology of preparation of hot drinking water*. Energetika Proceedings of Cis Higher Education Institutions and Power Engineering Associations, **60(5)**, (2017), pp.484-492. https://doi.org/10.21122/1029-7448-2017-60-5-484-492

7. M.Sadullaev, E.Usmanov, R.Karimov, D.Xushvaktov, D.Xalmanov, Y.Shoyimov, D.Khimmataliev. *Mathematical Models and Calculation of Elements of Developed Schemes of Contactless Devices*. AIP Conference Proceedings, 3331(1), **040043**, (2025), https://doi.org/10.1063/5.0305748

8. E.Yuldashev, M.Yuldasheva, A.Togayev, J.Abdullayev, R.Karimov. *Energy efficiency research of conveyor transport*. AIP Conference Proceedings, 3331(1), **040030**, (2025), https://doi.org/10.1063/5.0305742

9. A.Nuraliyev, I.Jalolov, M.Peysenov, A.Adxamov, S.Rismukhamedov, R.Karimov. *Improving and Increasing the Efficiency of the Industrial Gas Waste Cleaning Electrical Filter Device*. AIP Conference Proceedings, 3331(1), **040040**, (2025), https://doi.org/10.1063/5.0305751

10. M.Sadullaev, E.Usmanov, R.Karimov, D.Xushvaktov, N.Tairova, A.Yusubaliev. *Development of Contactless Device Schemes for Automatic Control of the Power of a Capacitor Battery*. AIP Conference Proceedings, 3331(1), **040042**, (2025), https://doi.org/10.1063/5.0305879

11. M.Sadullaev, E.Usmanov, R.Karimov, D.Xushvaktov, N.Tairova, A.Yusubaliev. *Review of Literature Sources and Internet Materials on Contactless Devices for Reactive Power Compensation*. AIP Conference Proceedings, 3331(1), **040041**, (2025), https://doi.org/10.1063/5.0305878

12. M.Sadullaev, M.Bobojanov, R.Karimov, D.Xushvaktov, Y.Shoyimov, H.Achilov. *Experimental Studies of Contactless Devices for Controlling the Power of Capacitor Batteries*. AIP Conference Proceedings, 3331(1), **040044**, (2025), https://doi.org/10.1063/5.0307195

13. E.Usmanov, M.Bobojanov, R.Karimov, D.Xalmanov, N.Tairova, S.Torayev. *Contactless Switching Devices Using Nonlinear Circuits*. AIP Conference Proceedings, 3331(1), **040031**, (2025), https://doi.org/10.1063/5.0305744

14. K.Abidov, A.Alimov, M.Gafurova. *Transients in Devices of Control Systems With Excitation Winding*. AIP Conference Proceedings, 3331(1), **040033**, (2025), https://doi.org/10.1063/5.0305756

15. K.Abidov, E.Abduraimov, M.Gafurova. *Possibility of Applying Methods of Analysis and Synthesis of Linear Electrical Circuits to Some Nonlinear Circuits*. AIP Conference Proceedings, 3331(1), **040034**, (2025), https://doi.org/10.1063/5.0305757

16. O.Ishnazarov, N.Khamudkhanova, K.Kholbutayeva, K.Abidov. *Energy Efficiency Optimization in Irrigation Pump Installations*. AIP Conference Proceedings, 3331(1), **040036**, (2025), https://doi.org/10.1063/5.0305844

17. K.Abidov, A.Alimov, N.Khamudkhanova, M.Gafurova. *Determination of the Permissible Number of Pumping Units Supplied From the Transformer of the Amu-Zang-I Substation, Selection of the Power of Static Capacitors*. AIP Conference Proceedings, 3331(1), **040029**, (2025), https://doi.org/10.1063/5.0305754

18. F.Akbarov, R.Kabulov, A.Alimov, E.Abduraimov, D.Nasirova. *Dependence of Output Parameters of Photovoltaic Module Based on CIGS Solar Cells on External Temperatures*. AIP Conference Parameters, 3331(1), **040046**, (2025), https://doi.org/10.1063/5.0305885

19. A.Alimov, K.Abidov, E.Abduraimov, F.Akbarov, H.Muminov. *Generalized Model of Nonlinear Inductance and its.* AIP Conference *Parameters*, 3331(1), **040035**, (2025), https://doi.org/10.1063/5.0305883

20. E.Abduraimov, M.Peysenov, N.Tairova. *Development of Contactless Device for Maintaining the Rated Voltage of Power Supply Systems*. AIP Conference Proceedings, 2552, **040012**, (2022). https://doi.org/10.1063/5.0116235

21. E.Abduraimov. *Automatic control of reactive power compensation using a solid state voltage relays*. Journal of Physics Conference Series, 2373(7), **072009**, (2022). DOI 10.1088/1742-6596/2373/7/072009

22. E.Abduraimov, D.Khalmanov. *Invention of a contactless voltage relay with an adjustable reset ratio*. Journal of Physics Conference Series, 2373(7), **072010**, (2022). DOI 10.1088/1742-6596/2373/7/072010

23. E.Abduraimov, D.Khalmanov, B.Nurmatov, M.Peysenov, N.Toirova. *Analysis of dynamic circuits of contactless switching devices*. Journal of Physics Conference Series, 2094(2), **022072**, (2021). DOI 10.1088/1742-6596/2094/2/022072

24. Y.Adilov, A.Nuraliyev, M.Abdullayev, S.Matkarimov. *Dynamic Performance Model of a Hybrid Power System*. AIP Conference Proceedings, 3331(1), **040038**, (2025). https://doi.org/10.1063/5.0305909

25. Y.Adilov, M.Khabibullaev. *Application of fiber-optic measuring current transformer in control and relay protection systems of belt conveyor drives*. IOP Conference Series Earth and Environmental Science, 614(1), **012022**, (2020), doi:10.1088/1755-1315/614/1/012022

26. S.Amirov, A.Sulliev, U.Mukhtorov. *Resonance sensors of motion parameters*. AIP Conference Proceedings, 3256(1), 050028, (2025). https://doi.org/10.1063/5.0267548

27. K.Turdibekov, A.Sulliev, O.Iskandarova, J.Boboqulov. *Experimental and statistical methods for studying the modes of electric power systems under conditions of uncertainty*. E3S Web of Conferences, 452, **04002**, (2023), https://doi.org/10.1051/e3sconf/202345204002

28. S.Kasimov, A.Sulliev, A.Eshkabilov. *Optimising Pulse Combustion Systems for Enhanced Efficiency and Sustainability in Thermal Power Engineering*. E3S Web of Conferences, 449, **06006**, (2023), https://doi.org/10.1051/e3sconf/202344906006

29. S.Amirov, A.Sulliev, S.Sharapov. *Study on differential transformer displacement sensors*. E3S Web of Conferences, 434, **02011**, (2023), https://doi.org/10.1051/e3sconf/202343402011

30. S.Amirov, A.Sulliev, K.Turdibekov. *Investigation of biparametric resonance sensors with distributed parameters*. E3S Web of Conferences, 377, **01002**, (2023), https://doi.org/10.1051/e3sconf/202337701002

31. M.Yakubov, A.Sulliev, A.Sanbetova. *Modern methods of evaluation of metrological indicators of channels for measurement and processing of diagnostic values of traction power supply*. IOP Conference Series Earth and Environmental Science, 1142(1), **012010**, (2023), doi:10.1088/1755-1315/1142/1/012010

32. K.Turdibekov, A.Sulliev, I.Qurbanov, S.Samatov, A.Sanbetova. *Voltage Symmetration in High Speed Transport Power Supply Systems*. AIP Conference Proceedings, 2432, **030084**, (2022), https://doi.org/10.1063/5.0089958

33. K.Turdibekov, M.Yakubov, A.Sulliev, A.Sanbetova. *Mathematical Models of Asymmetric Modes in High-Speed Traffic*. Lecture Notes in Networks and Systems, **247**, (2022), pp.1051-1058. DOI:10.1007/978-3-030-80946-1_95

34. S.K.Shah, L.Safarov, A.Sanbetova, and etc. *Investigation on composite phase change materials for energy-saving buildings*. E3S Web of Conferences, 563, **01003**, (2024), https://doi.org/10.1051/e3sconf/202456301003

35. A.Sanbetova, A.Mukhammadiev, A.Rakhmatov, Z.Beknazarova. *Study on cultivation of environmentally friendly seed potatoes based on electrical technology*. E3S Web of Conferences, 377, **03001**, (2023), https://doi.org/10.1051/e3sconf/202337703001

36. J.Safarov, A.Khujakulov, Sh.Sultanova, U.Khujakulov. S.Verma. *Research on energy efficient kinetics of drying raw material*. E3S Web of Conferences, 216, **01093**, (2020). https://doi.org/10.1051/e3sconf/202021601093

37. J.Safarov, Sh.Sultanova, G.Dadayev, Sh.Zulponov. *Influence of the structure of coolant flows on the temperature profile by phases in a water heating dryer*. IOP Conf. Series: Materials Science and Engineering, 1029(1), **012019**, (2021). doi:10.1088/1757-899X/1029/1/012019

38. Sh.Sultanova, A.Artikov, Z.Masharipova, A.Tarawade, J.Safarov. *Results of experiments conducted in a helio water heating convective drying plant*. IOP Conf. Series: Earth and Environmental Science, 868(1), **012045**, (2021). doi:10.1088/1755-1315/868/1/012045

39. Sh.Sultanova, J.Safarov, A.Usenov, D.Samandarov, T.Azimov. *Ultrasonic extraction and determination of flavonoids*. AIP Conference Proceedings, 2507, **050005**, (2023). https://doi.org/10.1063/5.0110524

40. M.Mirsadov, B.Fayzullayev, I.Abdullabekov, A.Kupriyanova, D.Kurbanbayeva, U.Boqijonov. *The mutual influence of electromagnetic and mechanical processes in dynamic modes of inertial vibrating electric drives*. IOP Conference Series Materials Science and Engineering, 862(6), **062081**, (2020). doi:10.1088/1757-899X/862/6/062081

41. I.Abdullabekov, M.Mirsaidov, F.Tuychiev, R.Dusmatov. *Frequency converter – asynchronous motor – pump pressure piping system mechanical specifications*. AIP Conference Proceedings, 3152, **040007** (2024). https://doi.org/10.1063/5.0218880

42. I.Abdullabekov, M.Mirsaidov, Sh.Umarov, M.Tulyaganov, S.Oripov. *Optimizing energy efficiency in water pumping stations: A case study of the Chilonzor water distribution facility*. AIP Conference Proceedings, 3331, **030107**, (2025). https://doi.org/10.1063/5.0305780

43. M.Bobojanov, F.Tuychiev, N.Rashidov, A.Haqberdiyev, I.Abdullabekov. *Dynamic simulation of a three-phase induction motor using Matlab Simulink*. AIP Conference Proceedings, 3331, **040012**, (2025). https://doi.org/10.1063/5.0305750

44. M.Tulyaganov, Sh.Umarov, I.Abdullabekov, Sh.Adilova. *Optimization of modes of an asynchronous electric drive taken into account thermal transient processes*. AIP Conference Proceedings, 3331, **030084**, (2025). https://doi.org/10.1063/5.0305786

45. Sh.Umarov, Kh.Sapaev, I.Abdullabekov. *The Implicit Formulas of Numerical Integration Digital Models of Nonlinear Transformers*. AIP Conference Proceedings, 3331, **030105**, (2025), https://doi.org/10.1063/5.0305793