# STUDY OF STEAM ADDITION TO REDUCE CLEAN EMISSIONS FROM COMBUSTION OF GASEOUS FUEL IN A LOW-POWER ATMOSPHERIC BURNER

M. A. Mukhina, E. P. Kopyev, I. S. Sadkin, and E. Yu. Shadrin

S. S. Kutateladze Institute of Thermophysics of the Siberian Branch of the Russian Academy of Sciences, 1 Lavrentiev Ave., Novosibirsk 630090, Russian Federation

**Abstract:** The efficiency of steam addition is studied in relation to the problem of reducing nitrogen and carbon oxide emissions for low-power atmospheric burners using the example of gaseous fuel combustion. Thermal and environmental characteristics of gaseous fuel combustion are experimentally determined when it is supplied to the base of a high-speed jet of superheated steam as a method of low-emission combustion. During the experiment, the completeness of fuel combustion, gas analysis of exhaust gases, and average temperature along the flame symmetry axis are measured. The results demonstrate that the supply of superheated steam can significantly reduce the concentration of harmful substances in combustion products (NOx and CO by 1.6 and 1.8 times) compared to blowing heated air, while maintaining high completeness of fuel combustion due to the reaction of hydrocarbon fuel with steam.

**Keywords:** steam dilution method; superheated steam; NOx; gaseous fuel; emission reduction

**DOI:** 10.30826/CE24170302 **EDN:** TDHUBD

## Figure Captions

**Figure 1** Diagram of the experimental setup: *1* — gas line; *2* — water supply; *3* — steam; *4* — data line; and *5* — control line

**Figure 2** Diagram of the burner device

**Figure 3** Maps of oxygen (*a*) and carbon monoxide (*b*) content in combustion products: left column — heated air supply; and right column — superheated steam supply

**Figure 4** Photographs of the flame of the burner device at various operating parameters (see the table)

**Figure 5** Profiles of the average flame temperature along the vertical axis of the burner nozzle for modes when supplying a jet of heated air at constant atomizer flow rate (*a*) and at constant fuel consumption (*b*): *1* — A10P8; *2* — A10P9; *3* — A10P10; *4* — A10P11; *5* — A8P9; and *6* — A10P9

**Figure 6** Profiles of the average flame temperature along the vertical axis of the burner nozzle for modes when supplying a jet of superheated water steam at constant atomizer flow rate (*a*) and at constant fuel consumption (*b*): *1* — S8P8; *2* — S8P9; *3* — S8P10; *4* — S8P11; *5* — S6P9; *6* — S8P9; and *7* — S10P9

**Figure 7** Maps of the content of nitrogen oxides in combustion products: (*a*) heated air supply; and (*b*) superheated steam supply

**Figure 8** Concentration profiles of gas components in the flame along the vertical axis of the burner nozzle for modes when supplying a jet of heated air: *1* — A8P9; *2* — A10P8; *3* — A10P9; *4* — A10P10; and *5* — A10P11

**Figure 9** Concentration profiles of gas components in the flame along the vertical axis of the burner nozzle for modes when supplying a jet of superheated water steam: *1* — S6P9; *2* — S8P8; *3* — S8P9; *4* — S8P10; *5* — S8P11; and *6* — S10P9

## Table Caption

Operating modes of the burner device for studying flame characteristics

## References

1. World Energy Outlook. 2022. International Energy Agency. Available at: https://www.iea.org/reports/world-energy-outlook-2022 (accessed April 4, 2023).
2. Kosoi, A. S., Y. A. Zeigarnik, O. S. Popel', M. V. Sinkevich, S. P. Filippov, and V. Y. Shterenberg. 2018. The conceptual process arrangement of a steam–gas power plant with fully capturing carbon dioxide from combustion products. *Therm. Eng.* 65:597–605. doi: 10.1134/S0040601518090045.
3. Barma, M. C., R. Saidur, S. M. A. Rahman, A. Allouhi, B. A. Akash, and S. M. Sait. 2017. A review on boilers energy use, energy savings, and emissions reductions. *Renew. Sust. Energ. Rev.* 79:970–983. doi: 10.1016/J.RSER.2017.05.187.

4. Al-Qurashi, K., A. D. Lueking, and A. L. Boehman. 2011. The deconvolution of the thermal, dilution, and chemical effects of exhaust gas recirculation (EGR) on the reactivity of engine and flame soot. *Combust. Flame* 158:1696–1704. doi: 10.1016/j.combustflame.2011.02.006.
5. Li, S., Y. Zhang, X. Qiu, B. Li, and H. Zhang. 2014. Effects of inert dilution and preheating temperature on lean flammability limit of syngas. *Energ. Fuel.* 28:3442–3452. doi: 10.1021/ef500187s.
6. Pugh, D. G., P. J. Bowen, R. Marsh, *et al.* 2017. Dissociative influence of $H_2O$ vapour/spray on lean blowoff and NOx reduction for heavily carbonaceous syngas swirling flames. *Combust. Flame* 177:37–48. doi: 10.1016/j.combustflame.2016.11.010.
7. Zhang, P., Y. Shao, J. Niu, X. Zeng, X. Zheng, and C. Wu. 2022. Effect of low-nitrogen combustion system with flue gas circulation technology on the performance of NOx emission in waste-to-energy power plant. *Chem. Eng. Process.* 175:108910. doi: 10.1016/J.CEP.2022.108910.
8. Li, A., Z. Zheng, and T. Peng. 2020. Effect of water injection on the knock, combustion, and emissions of a direct injection gasoline engine. *Fuel* 268:117376. doi: 10.1016/j.fuel.2020.117376.
9. Le Cong, T., and P. Dagaut. 2009. Experimental and detailed modeling study of the effect of water vapor on the kinetics of combustion of hydrogen and natural gas, impact on NOx. *Energ. Fuel.* 23:725–34. doi: 10.1021/ef800832q.
10. Boushaki, T., Y. Dhué, L. Selle, B. Ferret, and T. Poinsot. 2012. Effects of hydrogen and steam addition on laminar burning velocity of methane–air premixed flame: Experimental and numerical analysis. *Int. J. Hydrogen Energ.* 37:9412–9422. doi: 10.1016/j.ijhydene.2012.03.037.
11. Albin, E., H. Nawroth, S. Göke, Y. D'Angelo, and C. O. Paschereit. 2013. Experimental investigation of burning velocities of ultra-wet methane–air–steam mixtures. *Fuel Process Technol.* 107:27–35. doi: 10.1016/j.fuproc.2012.06.027.
12. Zou, C., Y. Song, G. Li, S. Cao, Y. He, and C. Zheng. 2014. The chemical mechanism of steam's effect on the temperature in methane oxy-steam combustion. *Int. J. Heat Mass Tran.* 75:12–18. doi: 10.1016/j.ijheatmasstransfer.2014.03.051.
13. Honzawa, T., R. Kai, M. Seino, *et al.* 2020. Numerical and experimental investigations on turbulent combustion fields generated by large-scale submerged combustion vaporizer burners with water spray equipment. *J. Nat. Gas Sci. Eng.* 76:103158. doi: 10.1016/j.jngse.2020.103158.
14. Matynia, A., J. L. Delfau, L. Pillier, and C. Vovelle. 2009. Comparative study of the influence of $CO_2$ and $H_2O$ on the chemical structure of lean and rich methane–air flames at atmospheric pressure. *Combust. Explo. Shock Waves* 45:635–645. doi: 10.1007/s10573-009-0078-5.
15. Cui, G., Z. Dong, S. Wang, X. Xing, T. Shan, and Z. Li. 2020. Effect of the water on the flame characteristics of methane hydrate combustion. *Appl. Energ.* 259:114205. doi: 10.1016/j.apenergy.2019.114205.
16. Anufriev, I. S., E. P. Kopyev, I. S. Sadkin, and M. A. Mukhina. 2021. NOx reduction by steam injection method during liquid fuel and waste burning. *Process Saf. Environ.* 152:240–248. doi: 10.1016/j.psep.2021.06.016.
17. Kopyev, E. P., I. S. Anufriev, I. S. Sadkin, E. Y. Shadrin, and A. V. Minakov. 2022. Experimental study of kerosene combustion with steam injection in laboratory burner. *J. Eng. Thermophys.* 31(4):589–602. doi: 10.1134/S1810232822040063.
18. USU "Krupnomasshtabnyy termogidrodinamicheskiy stend dlya issledovaniya teplovykh i gazodinamicheskikh kharakteristik energoustanovok" [Unique research facility USU "Large-scale thermo-hydrodynamic setup for studying the thermal and gas-dynamic characteristics of power plants"]. Available at: `http://ckp-rf.ru/usu/73570/` (accessed August 27, 2024).
19. Anufriev, I. S., and E. P. Kopyev. 2019. Diesel fuel combustion by spraying in a superheated steam jet. *Fuel Process. Technol.* 192:154–169. doi: 10.1016/j.fuproc.2019.04.027.
20. Anufriev, I. S., D. V. Krasinsky, E. Y. Shadrin, E. P. Kopyev, and O. V. Sharypov. 2019. Investigation of the structure of the gas flow from the nozzle of a spray-type burner. *Thermophys. Aeromech.* 26:657–672. doi: 10.1134/S0869864319050044.

*Received May 14, 2024*

## Contributors

**Mukhina Maria A.** (b. 1998) — research engineer, S. S. Katuteladze Institute of Thermophysics of the Siberian Branch of the Russian Academy of Sciences, 1 Lavrentiev Ave., Novosibirsk 630090, Russian Federation; mary-andr@yandex.ru

**Kopyev Evgeny P.** (b. 1991) — Candidate of Science in technology, head of laboratory, S. S. Katuteladze Institute of Thermophysics of the Siberian Branch of the Russian Academy of Sciences, 1 Lavrentiev Ave., Novosibirsk 630090, Russian Federation; kopyeve@itp.nsc.ru

**Sadkin Ivan S.** (b. 1998) — research engineer, S. S. Katuteladze Institute of Thermophysics of the Siberian Branch of the Russian Academy of Sciences, 1 Lavrentiev Ave., Novosibirsk 630090, Russian Federation; sadkinvanya@mail.ru

**Shadrin Evgeniy Yu.** (b. 1992) — Candidate of Science in physics and mathematics, junior research scientist, S. S. Katuteladze Institute of Thermophysics of the Siberian Branch of the Russian Academy of Sciences, 1 Lavrentiev Ave., Novosibirsk 630090, Russian Federation; evgen_zavita@mail.ru