NUMERICAL SIMULATION OF PROCESSES IN THE ANNULAR COMBUSTOR OF A GAS TURBINE ENGINE

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Abstract: One of the main problems of modeling combustion in a gas turbine combustor is the account for interaction between turbulent and chemical processes. These physical and chemical processes are so complex that their detailed simulation requires use of complex mathematical models which contain a large number of parameters. Based on the results of experimental data, a periodic feature of temperature fields at the outlet of the flame tube of the gas turbine combustor was revealed. This feature consists in the absence of the expected individual temperature maxima and their pairwise association at the outlet of the flame tube. In the present work, numerical simulation of temperature fields in the gas turbine combustor was performed using the commercial package STAR-CCM+. For modeling turbulence and combustion, a k–ε model and a steady laminar flamelet (SLF) model were used. The fuel nozzle spray was modeled by the linear instability sheet atomization (LISA) model.

Keywords: gas turbine engine; combustor; flame tube; temperature fields; combustion; k–ε model; SLF; LISA

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Figure Captions

Figure 1 Schematic with the indication of the rotation direction of the turret with thermocouple combs and the location of the belts (view from the turbine side); the arrow shows the rotation direction of the turret: *1* — burner center; *2* — outer belt; *3* — central belt; *4* — inner belt; and *5* — rotating turret with thermocouple combs

Figure 2 Average temperature fields measured by thermocouples of central (*1*) and inner (*2*) belts (*a*) and central (*1*) and outer (*3*) belts (*b*): A — burner; B — upright; and C — fire tube mount

Figure 3 Schematic of the annular combustor: (*a*) longitudinal section of annular combustor; (*b*) calculation sector with two burners; *1* — air inlet to the combustor; *2* — burner device; *3* — flame tube; *4* — air outlet from the outer annular channel; *5* — temperature measuring surface; *6* — air outlet from the inner annular channel; *7* — external combustor body; *8* — outer annular channel; *9* — inner annular channel; *10* — internal combustor body; *11* — first manifold; and *12* — second manifold

Figure 4 Location of design sectors in the turbine side view: *1* — upright; *2* — upright and flame tube mount; and *3* — nozzle and swirl

Figure 5 Temperature field of the central belt at the combustor outlet: *1* — experiment [3]; *2* — 2 burners; *3* — 4 burners; *4* — 8 burners; A — burner; B — upright; and C — fire tube mount

Figure 6 Deviation of total pressure (*1*) and mass flow rate of the nozzle (*2*) from the average value: (*a*) first manifold; (*b*) second manifold; and (*c*) total flow from both manifolds

Figure 7 Temperature fields of central (*a*), outer (*b*), and inner (*c*) belts at the combustor outlet with refined fuel flow rate through different burners: *1* — experiment [3]; *2* — 2 burners; *3* — 2 burners (option 2); *4* — 4 burners; *5* — 4 burners (option 2); *6* — 8 burners; A — burner; B — upright; and C — fire tube mount

Figure 8 Calculated temperature fields of the central belt at the combustor outlet in various sector designs: *1* — 2 burners (option 2); *2* — 4 burners (option 2); and *3* — 8 burners

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References

1. Lefebvre, A. H. 1983. *Gas turbine combustion*. West Lafayette, IN: Purdue University. 531 p.
2. Vyunov, S. A., and Yu. I. Gusev. 1989. *Konstruktsiya i proektirovanie aviatsionnykh gazoturbinnykh dvigateley* [Construction and design of aviation gas turbine engines]. Moscow: Mashinostroenie. 368 p.
3. Tropin, Ya. V., and S. A. Rashkovskiy. 2024. The specific features of temperature fields in the combustion chamber of a gas turbine engine. *Goren. Vzryv (Mosk.) — Combustion and Explosion* 17(2):25–34. doi: 10.30826/CE24170204.
4. Krylov, B. A., I. I. Onishchik, and A. A. Yun. 2009. Modelirovanie protsessov teplo- i massoobmena v model'nykh kamerakh sgoraniya [Modeling of heat and mass transfer processes in model combustion chambers]. *Aerospace MAI J.* 16(1):3.
5. Uryga-Bugajska, I., D. Borman, M. Pourkashanian, *et al.* 2011. Theoretical investigation of the performance of alternative aviation fuels in an aero-engine combustion chamber. *P. I. Mech. Eng. G — J. Aer.* 225(8):874–885.
6. Vafin, I. I., and B. G. Mingazov. 2013. Modelirovanie protsessa smesheniya v kamerakh sgoraniya [Modeling of mixing process in combustion chambers]. *Problems and Prospects of Development of Aviation, Ground Transportation and Power Engineering Conference (International) Proceedings*. 395–398.
7. Livebardon, T., S. Moreau, T. Poinsot, and É. Bouty. 2015. Numerical investigation of combustion noise generation in a full annular combustion chamber. *21st AIAA/CEAS Aeroacoustics Conference*. 2971.
8. Sipatov, A. M., K. A. Shilov, A. D. Nugumanov, and T. V. Abramchuk. 2016. Chislennaya dovodka poley temperatury gazov na vykhode iz kamery sgoraniya gazoturbinnoy ustanovki [Numerical simulation for fine-tuning the gas temperature fields at the outlet of the gas turbine combustion chamber]. *Vestnik Permskogo natsional'nogo issledovatel'skogo politekhnicheskogo universiteta. Aerokosmicheskaya tekhnika* [Bulletin of the Perm National Research Polytechnic University] 46:40–55. doi: 10.15593/2224-9982/2016.46.02.
9. Mark, C. P., and A. Selwyn. 2016. Design and analysis of annular combustion chamber of a low bypass turbofan engine in a jet trainer aircraft. *Propulsion Power Research* 5(2):97–107.
10. Agulnik, A. B., I. I. Onishchik, and A. D. Yarmash. 2017. Protsess smesheniya i neravnomernost' polya temperatur gaza na vykhode iz kamery sgoraniya GTD [Mixing process and nonuniformity of the gas temperature field at the outlet of the combustion chamber of a GTE]. *Nasosy. Turbiny. Sistemy* [Pumps. Turbines. Systems] 2(23): 30–38.
11. Tao, W., J. Wang, R. Mao, X. Wang, C. Zhang, and Y. Lin. 2019. Generation and migration of hot streaks within an LPP combustor. *Turbo Expo: Turbomachinery Technical Conference and Exposition*. Phoenix, AZ: American Society of Mechanical Engineers. 4A:GT2019-90601. 9 p. doi: 10.1115/GT2019-90601.
12. Bertini, D., L. Mazzei, A. Andreini, and B. Facchini. 2019. Multiphysics numerical investigation of an aeronautical lean burn combustor. *Turbo Expo: Turbomachinery Technical Conference and Exposition*. Phoenix, AZ: American Society of Mechanical Engineers. 5B:GT2019-91437. 15 p. doi: 10.1115/GT2019-91437.
13. Reddy, S. S., and M. K. Reddy. 2019. Design of annular combustion chamber for a micro turbofan engine. *Int. J. Mechanical Production Engineering Research Development* 9(6):747–754.
14. Evseev, S. A., D. V. Kozel, and I. F. Kravchenko. 2020. Povyshenie tochnosti rascheta polya temperatur gaza na vykhode iz kamery sgoraniya GTD metodom trekhmernogo komp'yuternogo modelirovaniya [Increasing the accuracy of calculation of the gas temperature field at the outlet of the combustion chamber of the GTD by three-dimensional computer modeling]. *Aviatsionno-kosmicheskaya tekhnika i tekhnologiya* [Aviation and Space Engineering and Technology] 5:74–82. doi: 10.32620/aktt.2020.5.10.
15. Moreno-Pacheco, L. A., F. Sánchez-López, J. G. Barbosa-Saldaña, *et al.* 2024. Design and numerical analysis of an annular combustion chamber. *Fluids* 9(7):161. doi: 10.3390/fluids9070161.
16. Krylov, B. A., A. A. Manuilov, and S. A. Fedorov. 2010. Osnovnye printsipy vybora modeley turbulentnosti, ispol'zuemykh pri raschete poley skorostey i temperaturnogo sostoyaniya sistemy okhlazhdeniya stenok zharovoy truby osnovnoy kamery sgoraniya gazoturbinnogo dvigatelya [Basic principles of turbulence models selection used in the calculation of velocity fields and temperature state of the cooling system of the flame tube walls of the main combustion chamber of a gas turbine engine]. *Aerospace MAI J.* 17(5):15.
17. OST 1.01134-86. 1986. Kamery sgoraniya osnovnykh gazoturbinnykh dvigateley. Metody opredeleniya polya temperatury gaza na vykhode iz osnovnoy KS pri avtonomnykh ispytaniyakh [Combustion chambers of main gas turbine engines. Methods for determining the gas temperature field at the main compressor station outlet during autonomous tests]. Moscow. 16 p.
18. Marchukov, E. Yu., I. I. Onishchik, B. B. Rutovskiy, *et al.* 2004. *Ispytaniya i obespechenie nadezhnosti aviatsionnykh dvigateley i energeticheskikh ustanovok* [Testing and ensuring the reliability of aircraft engines and power plants]. Moscow: MAI Publishing House. 334 p.
19. STAR-CCM+ v16.06 © 2020 Siemens PLM Software.
20. Han, Z., S. Parish, P. V. Farrell, and R. D. Reitz. 1997. Modeling atomization processes of pressure-swirl hollow-cone fuel sprays. *Atomization Spray.* 7(6):663–684.
21. Schmidt, D. P., I. Nouar, P. Senecal, *et al.* 1999. Pressure-swirl atomization in the near field. *SAE Transactions*. SAE Technical Paper 108(3).
22. Senecal, P. K., K. Richards, E. Pomraning, *et al.* 2007. A new parallel cut-cell Cartesian CFD code for rapid grid generation applied to in-cylinder diesel engine simulations. SAE Technical Paper No. 2007-01-0159.

23. Strokach, E. A., and I. N. Borovik. 2016. Chislennoe modelirovanie protsessa raspylivaniya kerosina tsentrobezhnoy forsunkoy [Numerical simulation of kerosene dispersion process by the centrifugal atomizer]. *Vestnik Moskovskogo gosudarstvennogo tekhnicheskogo universiteta im. N. E. Baumana. Ser. Mashinostroenie* [Herald of the Bauman Moscow State Technical University. Ser. Mechanical Engineering]. 3:37–54. doi: 10.18698/0236-3941-2016-3-37-54.
24. Shih, T. H., W. W. Liou, A. Shabbir, Z. Yang, and J. Zhu. 1995. A new k-ε eddy viscosity model for high Reynolds number turbulent flows. *Comput. Fluids* 24(3):227–238.
25. Wilcox, D. C. 1998. *Turbulence modeling for CFD*. 3rd ed. La Cañada, CA: DCW Industries. 536 p.
26. Peters, N. 1984. Laminar diffusion flamelet models in non-premixed turbulent combustion. *Prog. Energ. Combust.* 10(3):319–339.
27. Honnet, S., K. Seshadri, U. Niemann, and N. Peters. 2009. A surrogate fuel for kerosene. *P. Combust. Inst.* 32:485–492.
28. Inozemtsev, A. A., M. A. Nikhamkin, and V. L. Sandratskiy. 2008. Osnovy konstruirovaniya aviatsionnykh dvigateley i energeticheskikh ustanovok [Fundamentals of design of aircraft engines and power plants]. Moscow: Mashinostroenie. Vol. 2. 366 p.
29. Leont'ev, M. K. 2008. *Atlas detaley i uzlov dvukhkonturnogo turboreaktivnogo dvigatelya AL-31F* [Atlas of parts and assemblies of the AL-31F twin-circuit turbojet engine]. Moscow: MAI. 20 p.
30. Idelchik, I. E. 1992. *Spravochnik po gidravlicheskim soprotivleniyam* [Reference book on hydraulic resistances]. Ed. M. O. Shteinberg. 3rd ed. Moscow: Mashinostroenie. 672 p.

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