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Design, numerical analysis and experimental studies of model high-speed propane combustion chamber

Vladimir A. Sabelnikov[1, 2], Vladimir V. Vlasenko[1], Mikhail A. Ivankin[1], Sergey S.Molev[1], Alexey A. Nikolayev[1], Vadim A. Talyzin[1], Alexander F. Chevagin[1]

Abstract

The report is devoted to preparation of "fire" experiments in TsAGI T-131 wind tunnel, aimed at creation of an experimental database for validation of physical models and software. Design of model high-speed combustion chamber with optical windows is presented. Simple geometry with symmetric expanding duct without combustion stabilizers is chosen. Flow regime at the entrance: $M = 2.5$, T_t = 2100 K, P_t = 10 atm. Gaseous fuel is injected from the walls. Preliminary 2D URANS calculations were used for the choice of fuel injection scheme. For the chosen flow regime, stabilization of combustion was not obtained for pure propane fuel. Addition of small portion of hydrogen allowed to stabilize the flame. Stable combustion in asymmetric subsonic mode is obtained at the equivalence ratio *ER*=0.67 with addition of 15% H_2. Supersonic combustion regime is realized at *ER*=0.33 with addition of 30% H_2.

Keywords: *high-speed combustor, experiment, calculation, validation*

In 2017, the scientific laboratory "Studies and development of physical models and numerical technologies for description of different combustion regimes in aircraft engines" was created in Propulsion department of TsAGI under the support of Russian Ministry of education and science. Goals of the laboratory are the development and validation of physically-grounded models for various combustion regimes in air-breathing engines, as well as the creation of special software for use in the cycle of aerodynamic design for new aircraft engines.

The first activity direction of the laboratory's activity is the improvement of existing and the development of new physical and mathematical models of turbulent combustion, oriented to calculations in the framework of RANS and LES approaches, as well as implementation of these models into high-performance computer programs. Now the laboratory is working under numerical models of high-speed combustors and of the propulsion device with resonator and rotating detonation.

The second activity direction of the laboratory is the "fire" aerodynamic experiments in TsAGI T-131 facility, specially prepared to get new domestic experimental database on the flows in high-speed combustors. The database will be intended for validation of physical models and software. For this purpose, an experimental model of a dual-mode combustion chamber (a chamber with supersonic flow at the entrance, where a subsonic or supersonic combustion regime is realized in dependence on the incoming flow parameters) has been designed and will be manufactured in TsAGI.

In designing the combustion chamber, the experience of studying the model hydrogen-fueled chamber of similar geometry has been used, which was studied at ONERA-LAERTE test rig in the framework of the LAPCAT-II European project [1]. In those experiments, a symmetrical combustion chamber with three expansion compartments was considered (with the inclination angle of 1° on each side, then 3° on each side and, finally, 1° on each side) without special devices for stabilization of supersonic combustion. The chamber was made of copper alloy; its inner surface was covered with

[1] *Central Aerohydrodynamic Institute named after N.E.Zhukovsky (TsAGI), 140185, 1, Zhukovsky street, Zhukovsky, Moscow region, Russia, vlasenko.vv@yandex.ru*

[2] *ONERA – French Aerospace Lab, Chemin de la Hunière - BP 80100, FR-91123 PALAISEAU cedex, vladimir.sabelnikov@onera.fr*

a heat-protective material based on zirconium. Flow regimes with stagnation parameters P_t = 0.4 MPa, T_t = 1356…1712 K and the inflow Mach number M = 2 were considered. The fuel (hydrogen, hydrocarbons) was injected from the walls perpendicular to the flow. In the ONERA experiments, both subsonic combustion with the pseudoshock formation and different regimes of supersonic combustion were obtained. Flow structure was determined by the interaction of fuel jets with boundary layers on the chamber walls and shock-wave structures in the duct.

In 2017, the project of TsAGI model chamber have been developed and prepared for production. The geometry of model combustor is chosen to be as simple as possible, without special devices for the flame stabilization – see Fig.1. The chamber has rectangular constant-width cross-sections and includes two parts with constant height H, separated by the part with continuous expansion of duct. The experiments are performed in connected-pipe regime, and the incoming air is heated by kerosene fired heater. The following flow regime at the combustor entrance is chosen: M = 2.5, total temperature T_t = 2100 K, total pressure P_t = 10 atm. Gaseous fuel (pure propane or propane-hydrogen mixture), is injected from upper and lower walls, perpendicular to the flow.

The chamber is made of stainless heat-resistant steel. There is no active cooling of the walls. On the side walls of the chamber, 4 pairs of optical windows, made of quartz glass with a thickness of 5 cm, are installed (Fig.2).

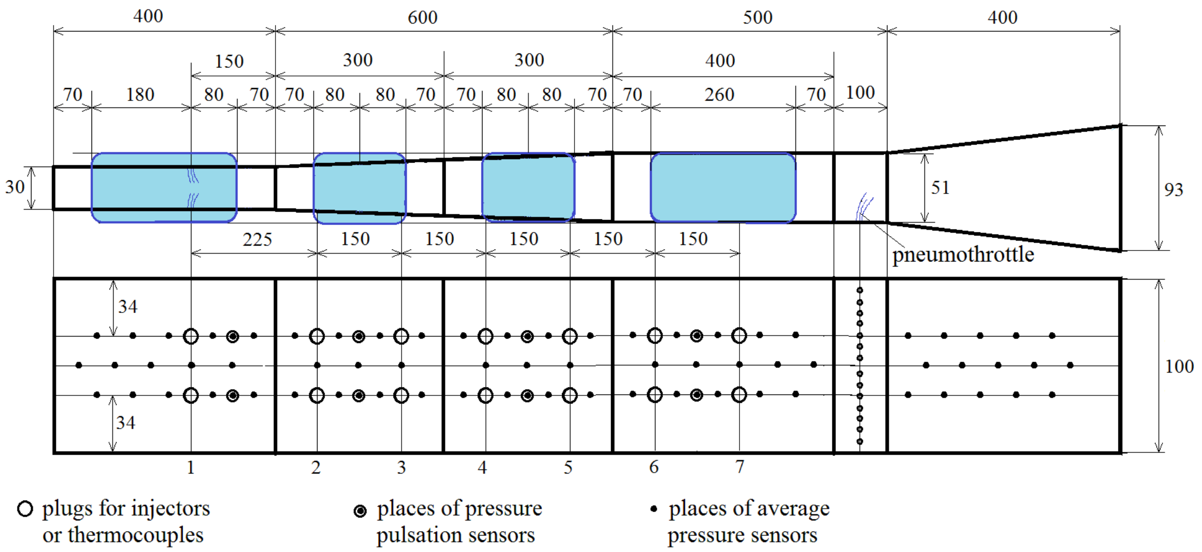

Fig 1. Geometry of the model chamber and places of measurements

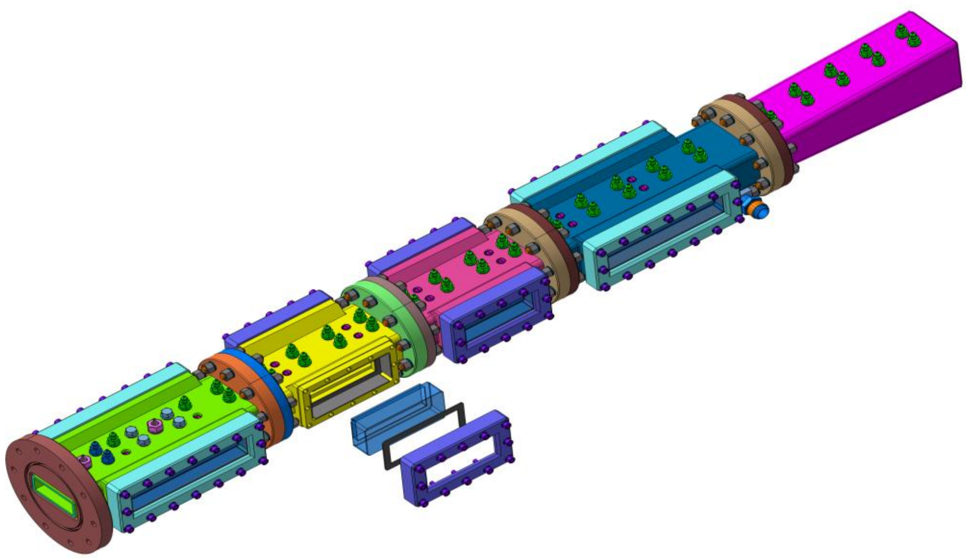

Fig 2. Total view of the model chamber with optical windows

A wide range of measurements is prepared with the aim to visualize the physical structure of the flow: high-speed schlieren-video filming; visualization of the excited OH radicals radiation (chemiluminescence); measurements of the wall temperature by thermocouples installed inside the walls of the chamber and on its outer surface; registration of time-averaged static pressure distributions along the walls.

Prior to experiments, preliminary parametrical 2D calculations have been performed to determine the possible working regimes. Calculations were performed on the basis of unsteady Reynolds equations for multi-component gas. Modification of the *q-ω* differential model of turbulence with a transition function (as in the SST model) [2] was used. Combustion was simulated using the reduced kinetic scheme, allowing to take into account reactions that proceed in combustion of both hydrogen and hydrocarbons. For parametrical calculations, the method of 2.5D approximation, which had been developed in TsAGI [3], was used. This method allows to take into account the flow replacement by boundary layers, growing at the duct side walls. Successful validation of 2.5D method is described in [4].

Initially, calculations with pure propane fuel have been performed. But it has been found that the selected flow conditions do not provide the propane self-ignition in the chamber. An attempt has been made to use a pneumothrottle to initiate combustion. Within short time interval, compressed air was supplied into the duct from the bottom wall, leading to the duct choking and to the self-ignition of fuel in the arising separations of boundary layer. This method of ignition is successfully practiced in TsAGI [5]. But in this task, when the throttle was turned off, the flameout occurred. To ensure stable combustion, it has been decided to add some amount of hydrogen to propane.

As a result of numerical calculations, fuel supply schemes have been found that provide stabilization of combustion. In the case of the equivalence ratio *ER* = 0.67, it was necessary to mix about 15% of hydrogen (by mass) with propane. This results in a stationary asymmetric flow with subsonic combustion (Fig. 3, a, c). The stabilizing role is played by the separation upstream from the jet of the upper injector. The major part of heat is released in the subsonic zone of separation upstream from the injector. In the second section of the constant cross section, the flow is subsonic in the average (over the cross-sections), although the flow at the symmetry axis remains supersonic. On these grounds, one can regard this flow as a special case of a pseudoshock.

For *ER* = 0.33, about 30% of hydrogen was required to provide stable propane combustion. In this case, a stationary symmetric flow with predominantly supersonic combustion arises (Fig. 3, b, d). Although there are near-wall regions where the heat release proceeds at $M < 1$, these processes have secondary character. The beginning of the heat release occurs in the region of supersonic flow. The average Mach number remains supersonic along the entire length of the duct.

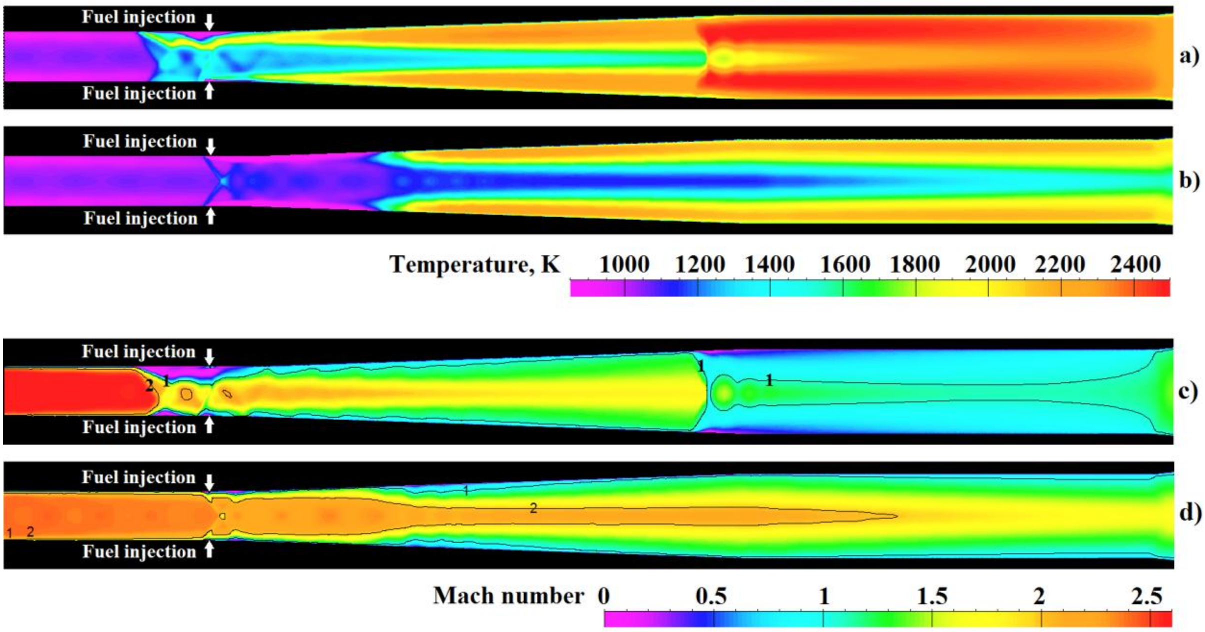

Fig 3. Field of temperature (a,b) and of Mach number (c,d) with stabilized combustion

The drawback of the 2.5D approach is the replacement of round fuel jets with flat ones. Other effects are possible due to the flow non-uniformity along the lateral coordinate. To take these effects into account, 3D calculations have also been performed. The results of calculations in 3D formulation are compared with 2.5D calculations.

In the autumn 2018, preliminary experimental tests in TsAGI T-131 facility for testing various combustion regimes will be performed. Dependence of flow structure upon the integral value of the equivalence ratio *ER* will be studied. First results of these experiments will be presented and compared with results of calculations.

Acknowledgement

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References

1. A. Vincent-Randonnier, Y. Moule and M. Ferrier, "Combustion of hydrogen in hot air flows within LAPCAT-II dual mode ramjet combustor at Onera-LAERTE facility - experimental and numerical investigation," in 19th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, p. 2932 (2014)
2. Babulin, A.A., Bosnyakov, S.M., Vlasenko, V.V., Engulatova, M.F., Matyash, S.V., Mikhailov, S.V.Experience of validation and tuning of turbulence models as applied to the problem of boundary layer separation on a finite-width wedge. Computational Mathematics and Mathematical Physics 56 (6), pp.1020-1033 (2016)
3. Vlasenko, V.V., Shiryaeva, A.A. 2.5D approximation for numerical simulation of flows in engine ducts. Proceedings of 6th European Conference for Aeronautics and Space Sciences (EUCASS), 13 pages (2015).
4. Talyzin V.A., Vlasenko V.V., Voloschenko O.V., Ivankin M.A. Experimental and 2.5D numerical investigation of the high-speed combustion chamber within the international HEXAFLY-INT project. 21st AIAA International Space Planes and Hypersonics Technologies Conference, p.2326 (2017).
5. Sabel'nikov V.A., Penzin V.I. Scramjet research and development in Russia. In a book: "Scramjet propulsion", ed. by Curran E.T. and Murphy S.N. In series "Progress in astronautics and aeronautics", Vol.189, AIAA, pp.223-367 (2001).