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The application of supplementary fuels for the control of supersonic reacting air-fuel mix flows in the combustion chamber

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Besides gas-dynamic methods, chemical ones are also suitable for the implementation of stable supersonic combustion of hydrocarbon fuels. Organoelemental compounds are known for their high reactivity, so attention was paid to organosilicon liquid during the research on the experimental model. The obtained estimates of the laminar flame speed in a mixture of vapors of this liquid with air were $0.72-0.8$ m/s, which is higher than that of ethylene successfully used in supersonic combustion tests. The tested compound can be considered as a candidate for supplementary fuel to control the supersonic reactive flows in the combustion chambers of ramjet engines.

For high combustion efficiency of the hydrocarbon fuel in ramjet engines the flow Mach number must be maintained greater or equal than 1 in the part of the combustor channel occupied by flame. The conditions at the entrance of the combustor are: $M = 2-3$, $T = 800-1000$ K and $p = 0.5-1$ atm [1]. The flow residence time in that area is just a few milliseconds. As example, the ignition delay time of kerosene-air mix is 2 ms at 1400 K, while for kerosene cracking products 1550 K is required [2]. Thus, to realize combustion in the channel, the temperature increase is necessary. It is achieved, among other means, by mixing the products of combustion (POC) with air and fuel in turbulent vortices, as illustrated by calculations of the chemical reaction time in diffuse supersonic flames [3]. Therefore, the reactivity of fuels at high initial temperatures is their important property. The Mach number below the fuel injection point is adjusted by changing the air-fuel ratio [4]. However, it's dufficult to stabilize the flame speed by such a method. For example, it has been shown for a combustor with two pylons that hysteresis phenomena occur around $M = 1$ when the fuel flow rate is regulated at the injector of the upstream pylon [5].

The use of fuels, which release energy much faster than kerosene during combustion, would enable altering the pressure profile in the combustor along a shorter part than usual (see [6] for detalis). Such fuels include hydrogen, ethylene, and monosilane, which have been used in both ground-based and flight experiments, but are difficult to handle and use as actual aircraft fuel. Known liquids that have been successfully used in high-speed combustion tests are either highly toxic or pyrophoric. For that reason, the usage of supplementary fuels in scramjet propulsion studies has been limited to gases, till now. The aim of this study is

to propose an express selection method for supplementary liquid fuels.

Beside the experiments with model combustors and numerical calculations of reaction kinetics in supersonic flows, the activity of fuels can be also estimated by semi-empirical methods. There is, for example, a monotonic relationship between the laminar flame speed in air-fuel mixtures (AFMs) of hydrogen, syngas [7], ethylene, and the ignition delays of these fuels in a heated supersonic flow [8]. The structure of the laminar premixed flame front can be represented as consisting of a heating zone, in which the reagents are heated to high temperatures, and an adjacent reaction zone, in which a significant change in the mixture composition occurs. The speed of such flames is determined by the thermal conductivity of the mixtures and the reaction time in them (which is about 1 ms at 1 bar). Thus, the laminar flame speed can indicate the reaction kinetics in AFM, including high initial temperatures. Therefore, the results of laminar flame studies can be used for implementing supersonic combustion systems. It should be noted that only turbulent flames exist in supersonic flows, either premixed or diffuse, i.e., the laminar premixed flame is an extremely simplified experimental model and serves mainly to screen possible supplementary fuels. Currently, laminar flame velocities of AFMs are being measured in spherical explosions or using burners.

As an example of fuels with good chemical kinetics we can take organosilicon compounds. Some of them are liquids and, unlike their analogues (organoaluminum, organoboron) are relatively safe to handle, while being resistant to heating up to $400°$C [9]. According to tests done in the 1950s, they burn faster than kerosene and often faster than ethylene [10]. In modern study [11] the laminar flame

Main combustion products of TMDS (in molar fractions)

α	p, atm	T, K	N_2, %	H_2O, %	CO_2, %	SiO_2 (*liq.*), %	CO, %	H_2, %
1	1	2418	71	14	6.2	3.8	1.6	0.6
0.85	1	2420	69	14	4.5	4.2	4.4	2.2
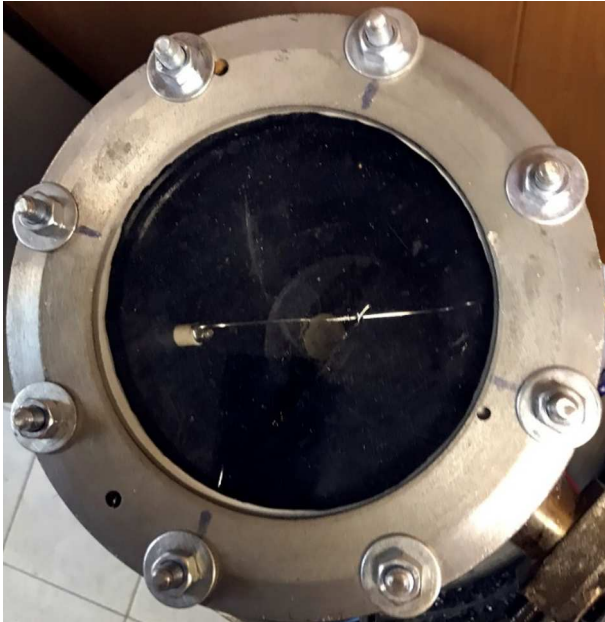
AFMs study reactor.

speed of tetramethylsilane has been verified to correspond to that previously measured (0.6 m/s). One can pay attention to 1,1,3,3-tetramethyldisiloxane (TMDS), which is used as a reducing agent in organic synthesis [12]. Its boiling point is 71°C, its density is 0.76 g/cm³. The thermal stability of this compound is lower than that of the alkyl-substituted silanes, but the products of its dry pyrolysis by the dominant mechanism include 50% dimethylsilane [13], which suggests that the chemical kinetic properties of superheated TMDS would not degrade. We obtained an express estimate of laminar flame speed of that compound by photoregistration of a spherical explosion of AFM. Combustion reaction equation for TMDS is:

$$C_4H_{14}Si_2O + 9O_2 = 4CO_2 + 7H_2O + 2SiO_2. \quad (1)$$
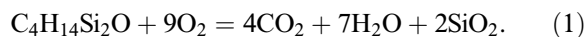
Silicon dioxide (SiO_2) is found in nature and is part of industrial products. Because of high reaction temperatures a fine-crystalline phase SiO_2 is present in combustion products, while its concentration in indoor air must be strictly limited. Therefore, the test reactor (see figure) was operated to discharge into a closed auxiliary vessel through an easily destroyed diaphragm, the vessel to be flushed after each experiment. Pressure rise in the reactor was limited, and the research was carried out in a „constant pressure"mode. The diameter of the viewing window in

the reactor is 140 mm. There are two sharp electrodes in the center of the reactor. The interelectrode distance varied from 1 to 3 mm. The experiment was initiated using a spark generator with a spark energy of the order of a few mJ. The volume of the reactor was 1.25 dm³. Using a hexane-air mixture, the limiting radius of the undistorted flame (~ 2.5 cm) was estimated, and the pressure increase Δp did not exceed 5%. Measurements were taken by a camera with a maximum frame rate of $1200 \, \text{s}^{-1}$. Tests were performed at initial temperatures $T_0 = 280-290$ K.

Laminar velocity is calculated according to the law of conservation of media flow through the flame front

$$u_L = (\rho_1/\rho_0)dR/dt = (T_0V_0/T_1V_1)dR/dt$$

$$= (T_0N_0/T_1N_1)dR/dt, \quad (2)$$

where R is flame radius at time t, ρ_0 is AFM density, ρ_1 is POC density, V_0 is specific volume of AFM under normal conditions, V_1 is specific volume of PS under normal conditions; then we get from calculation of burning 1 mol of TMDS: N_0 is the amount of AFM components in a mol, N_1 is the number of PS components in a mol, except for condensed phase that occupies no volume. The excess air coefficient α was set to about 0.85. The recorded flame propagation velocity is in the range of $6.3-7$ m/s, taking into account the measurement error. Frames with $R \geq 5$ mm were used for the calculations, and no correction of the velocity was performed considering the curvature of the flame front. Calculation using the TERMORAS application program showed that the T of the TMDS flame does not exceed 2420 K. To calculate N_1, we used the results of calculating the composition of the POC (see Table), which differ slightly from the proportions following from the right side of equation (1). Estimates of u_L TMDS by formula (2) are in the range $0.72-0.8$ m/s, while ethylene has $u_L = 0.7$ m/s.

Thus, it seems realistic to consider liquids instead of gaseous fuels to control supersonic reactive flows, for example, in the combustors of ramjet engines. When selecting such compounds, the handling and reactivity hazards must be taken into account as well.

Conflict of interest

The authors declare that they have no conflict of interest.

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