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THE PROBLEMS OF COMBUSTION AT SUPERSONIC FLOW

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Abstract. The efficiency of heat supply to the combustion chamber based on the analysis of literature data on combustion processes in a confined high-velocity and high-temperature flow for known initial parameters is considered. The process efficiency is characterized by the combustion completeness and total pressure losses. The main attention is paid to the local intensity of heat release, which determines, together with the duct geometry, techniques for flame initiation and stabilization, injection techniques and quality of mixing the fuel with oxidizer, the gas-dynamic flow regime. A high intensity of the local heat release may lead to a flow transition to a subsonic one in a normal shock, the throttling effect, and upstream propagation of the elevated pressure with a possible formation of a pseudo-shock and reduction of the integral efficiency of combustion. The problem is discussed, which arises at high values of the Mach number and which is related to a high level of static pressure at the combustion chamber inlet. The results of experimental studies available in the literature as well as the data obtained at the ITAM SB RAS on the supersonic combustion test facility give a reason for a more detailed investigation of the role of dissociation processes and a search for ways to increase the heat release efficiency.
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The flights of the unmanned flying vehicle X-43A executed within the framework of the "Hyper-X" program (2rd flight — 27.03.2004, M=6.83 and 3rd — 16.11.2004, M=9.68) have been recognized in USA to be successful. About 20 talks were presented by now at International conferences (see the 13th International Space Planes and Hypersonic Systems and Technologies Conference 16-20 May 2005, Centro Italiano Ricerche Aerospaziali Capua, Italy; 28th JANNAF Airbreathing Propulsion Subcommittee Meeting. Charleston, SC. June13-17, 2005; ISABE'05, 17th International Symposium on Airbreathing Engines 4-9 September, 2005 Munich, Germany), in which the results are presented for the comparisons of characteristics of individual flight phases with computed data and the data of tests in ground-based wind tunnels and test benches. During the second flight, the vehicle acceleration was achieved under the propulsion unit thrust (15 miles per 11 seconds). During the third flight at M=9.68 and altitude of 110, 000 ft the vehicle surmounted 20 miles per 10.5 seconds. The measured thrust proved to be 2% higher than the expected one. The research goals were reaching the aircraft acceleration while executing the experiment with the thruster; obtaining of the data at all flight phases, including the free flight videorecords, the obtaining of data on aerodynamics, etc. The determination of the most important thruster characteristics, the specific impulse, was also among the problems, which were posed prior to flights. The advances achieved at the execution of this program are undoubted. Certain questions concerning the working process arrangement in the thruster duct, however, arise. In particular, the use of silane (monosilane – SiH_4 the gaseous silicon hydride, from the series of noxious pyrophore substances, at its content of less than 10% in an inert medium is self-ignited at its contact with air at room temperature) to initiate and support combustion requires the elaboration of special safety measures and is little probable for practical application. This is an apparently forced step possibly due to the absence of certainty in the reliability of typical systems for combustion initiation in the combustion chamber and the necessity of combustion intensification for M=9.68. The presence of insulator in the thruster duct confirms the existence of a problem related to a possible violation of the inlet operation at combustion. Its solution depends on the way in which the hydrogen injection is implemented (and consequently, on the quality of mixing with air stream) and the heat supply from its combustion. If the combustion process is localized, then an intense heat release causes the flow deceleration down to subsonic speeds in the insulator ahead of the combustion chamber inlet. The subsonic combustion (the silane also contributes to it considerably) leads to large losses in total pressure and to a reduction of thruster efficiency. The silane supply affected significantly the working process. It was supplied during about 5-7 seconds (from 10 seconds of thruster operation), and after the interruption of its supply, the deterioration of the thruster work was appreciable (from the published temporal variations of the vehicle acceleration). Unfortunately the data on pressure distribution along the thruster duct are qualitative, and this does not enable quantitative estimates to be drawn. The results on thruster efficiency (the specific impulses) are not presented. It is nevertheless possible to talk about the feasibility of obtaining the thrust in natural flight. The optimistic estimates for the specific impulse (I_{sp}) for a hypothetical flying vehicle made on the basis of thrust data are presented in [1]. I_{sp}= 2900 and 2300 s for M=6.83 and 9.68, respectively, and they coincide exactly with computed values published in the literature. Knowing the unmanned flying vehicle weight (~1.3 t), the time and length of the flight interval with operating thruster, one can find the specific impulse if the mean lift-to-drag ratio (K) of the flying vehicle is known, or one can determine the lift-to-drag ratio if the specific impulse values are assumed to be known. The values K=3.6 (M=6.83, the mean value of the attack angle 2.5 deg., [2]) and K=4.4 (M=9.68, the same angle of attack, [2]), correspond to optimistic values of Isp, which are close to the experimental maximum values obtained at the investigations in ground-based tests (see [3]). The value K=4.2 for M=6 and for the absence of flow through the thruster was presented in [4] for the model X-43A. In the case of such a flow, the "K" must be higher. It is difficult to draw more definite conclusions.

Thus, one can summarize that the questions of improving the combustion process in the thruster duct remain topical. It is known (see, for example, [5]) that the value of the entropy increase (ΔS) is a characteristic of the perfection degree of the heat supply to the flow. The minimum entropy growth was shown to be reached in a combustion chamber consisting of the constant section interval, in which the flow decelerates at the expense of heat supply down to the value M=1, and of the interval of expanding section with preserving M=1=Const and heat supply. This result is physically understandable because $dS=dQ/T$ (Q is the heat supplied per unit time, T is the static temperature). To obtain the minimum entropy growth one must then supply the heat under a possibly higher static temperature. While formulating the investigations of the combustion process the main attention is usually drawn to the intensification of the mixing of fuel with air. This is natural because the quality of mixing determines the burn-out process and the combustion completeness. A high intensity of the local heat release can, however, lead to a flow passage to subsonic velocity in the normal shock, and this results in maximum losses of the total pressure.

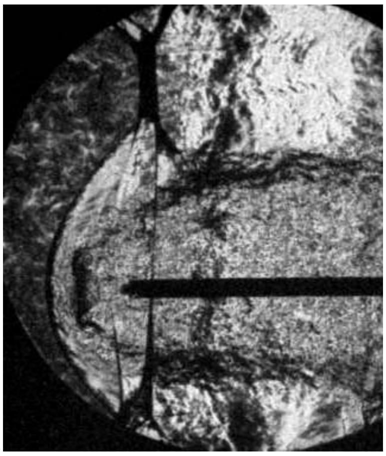

Figure 1. The hydrogen counter-jet combustion.
The duct 200x200 mm, M = 2.0.

The flow pattern presented in Fig. 1 (the experiment of ITAM) may serve as an example of such a passage and it illustrates the flow "choking" when a hydrogen counter-jet burns in supersonic flow. The pseudoshock formation upstream from the local heat supply location (at plasma injection) was shown very well in [6]. This process was registered in terms of the pressure distribution on the duct wall and by visual observations of the gas-dynamic flow structure. A larger distance by which the wave structure propagated from the injection location corresponded to a more intense heat supply.

The combustion in supersonic flow at moderate Mach number values at the combustion chamber inlet ($M_к<3$, which corresponds to the flying vehicle flight up to $M\approx8$) is followed as a rule by the formation of a gas-dynamic structure with the pseudoshock properties. In these regimes, heat release from the fuel combustion with the air excess coefficient $\alpha=1$ is sufficient for a "thermal" flow choking. The realization of two combustion regimes with the pseudoshock formation is possible in the duct with constant section. This is illustrated in Figs. 2 and 3. In experiments of [7] (see Fig. 2) the kerosene combustion in a duct with constant section resulted in a supersonic flow deceleration down to M=1 by the end of the constant section duct (as this follows from the quasi-one-dimensional analysis), and the pressure growth started from the location of fuel supply. In experiments of [8] the combustion was more intense, which is obviously related to a different mixing process, physical and chemical characteristics of the fuel, duct geometry, etc. It is seen from Fig. 3 that the flow decelerates down to subsonic speeds (on the average over the duct section), which reduces the thermodynamic efficiency of combustion process.

Consider the possibility of experimental realization of a flow regime, when the flow decelerates down to the Mach numbers no lower than M=1 with a subsequent satisfaction of condition M=Const at the expense of the duct expansion and conservation of the constancy of the mean rate of heat release. To this end, it is necessary to know the pseudoshock properties. Its investigation was initiated from the work [9]. A large amount of investigations of various peculiarities of such a passage from the supersonic velocity to the subsonic one has been carried out by now. We dwell only on those properties, which are needed to substantiate the chosen regime.

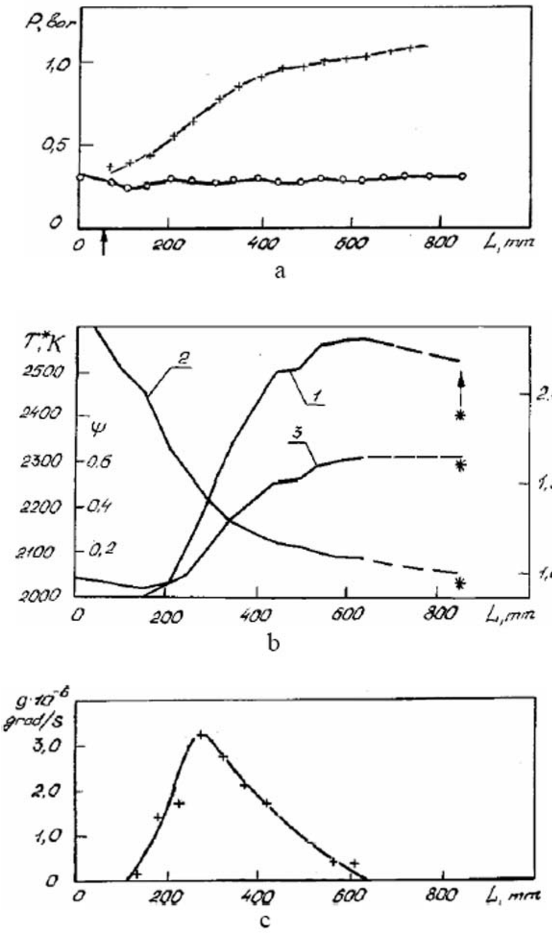

Figure 2. Kerosene injected from the wall F=Const; M=2.48; T_t^0=2000 K.

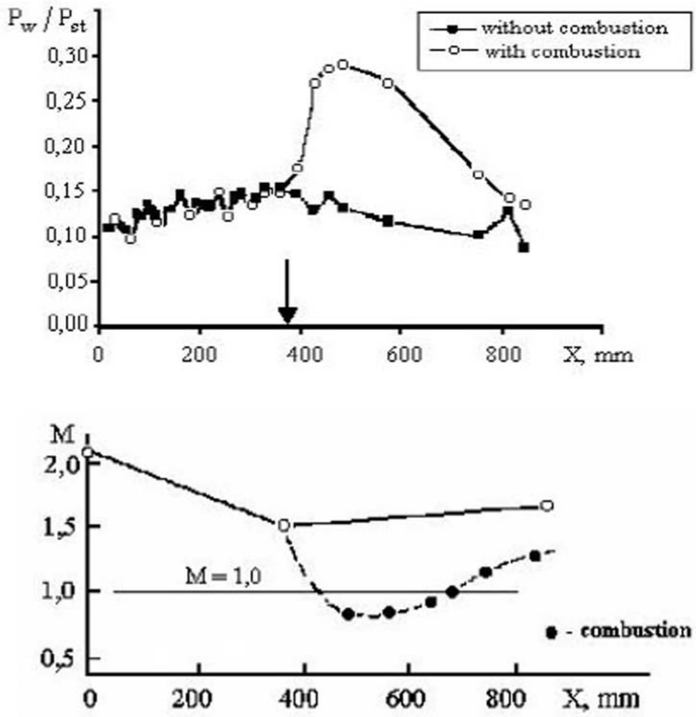

Figure 3. M=2; T_t^0=1850 K; mixture of 50% H_2 +50% C_2H_4.

First of all, it is necessary to note that the dimensionless length of the pseudoshock (for a duct with F=Const) depends only on the Mach number under the corresponding choice of the reference cross size “a” of the duct (for a circular section, this is the duct diameter, for the rectangular one this is $a=b^{0.7}\cdot h^{0.3}$, where b is the duct width, and h is the duct height). There are other generalizations, but all of them yield close results. The length of the supersonic interval of the pseudoshock is of interest – the distance from the start of pressure growth to a section, in which the mean value of the Mach number equals M=1. The one-dimensional approach implies that the pressure excess over the initial pressure in this section equals a halved pressure jump between the end value and the initial value in the pseudoshock The dimensionless length of this interval also depends only on the M number and is shown in Fig. 4 as a fraction of the total pseudoshock length. Another property, which is inherent in this flow, is the universality of the distribution of the relative pressure jump versus the relative pseudoshock length. And it is not important what was the mechanism of its formation. These might be the mechanical or gas-dynamic techniques of the duct throttling, including the process of heat supply at the expense of fuel combustion, [10]. The above properties enable the determination of the pseudoshock length (or its supersonic part) for various configurations of the duct section and of the pressure variation over the duct length versus the Mach number.

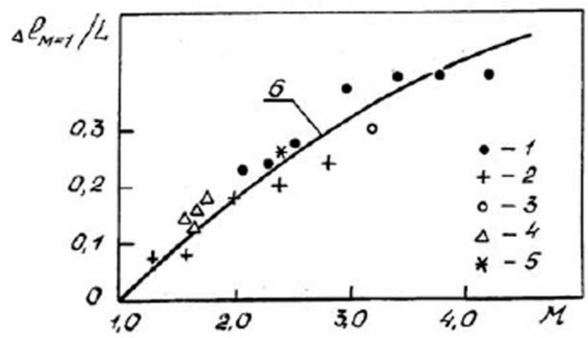

Figure 4. The length of the supersonic interval of the pseudoshock:
1-5 – literature data; 6 – averaging.

One more property of the pseudoshock is finally caused by the heat supply process (combustion). As was shown in [11], the one-dimensional conservation equations (for the mass, energy, and momentum) cannot be applied to the flow with a pseudoshock. However, if one introduces in the equation for mass conservation the inhomogeneity coefficient [12] (by analogy with the Crokko’s approach), then it turns out that its relative variation is related to the relative variation of the pressure jump over the pseudoshock length. It was shown in the works [12, 13] how this property may be used for finding the flow parameters that are mean over the section (the velocity and temperature as well as the heat release rate – the ratio of the total temperature increment from combustion and the residence time in the combustion zone, see Fig. 2.c). The heat release rate can generally be determined experimentally because it depends on the physical and chemical properties of the fuel It can be computed for hydrogen (using the data presented in Fig. 4). The knowledge of the heat release rate enables the determination of the length of the duct with F=Const, over which the sound velocity is reached (M =1) and, by specifying the mean heat release rate in the expansion interval, M=1, and the relative heat supply as well as the coefficients of impulse loss for the skin friction forces and heat losses on the wall one can find the angle and the length of this interval an, consequently, the length of the combustion chamber and its shape. The pseudoshocked regime of combustion in the duct F=Const with flow deceleration down to M=1 may serve as a measure for the combustion efficiency when studying the effects of mixing intensification.

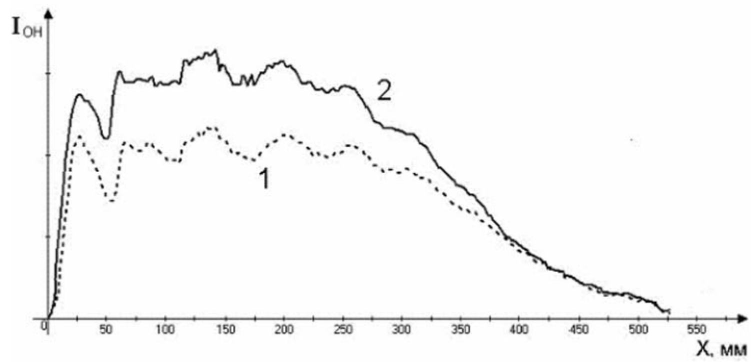

Figure 5. The temperature effect on the OH emission in the hydrogen flame.
P_t = Const = 7bar; G_{H2} = Const = 3g/sec; 1 – T_t^0 = 2000 K; 2 - T_t^0 = 2600 K

Another problem, which deserves attention, is the deterioration of the combustion process at an increase in the air specific enthalpy (the increase in stagnation temperature). As an illustration, Fig. 5 shows the results of measuring the radiation intensity of excited OH radicals at the hydrogen combustion in a high-temperature air co-flow. The experiments were conducted on a test bench for supersonic combustion investigation of the ITAM SB RAS. It was found that under the temperatures higher than 2000-2200 K, a sharp increase in the intensity of emission of excited OH radicals (up to 50%) occurs. It is probable that this is related to the dissociation process. Such a phenomenon was noticed in experiments of [14] on the recording of the pressure distribution over the duct length under the total enthalpy variation. It is noted that the losses for dissociation become considerable for Ho≥7Mj/kg because of the temperature growth (>2500 K). The integral efficiency of combustion reduces.

The following conclusions can be drawn.

- The processes of improving the implementation of the combustion process in the thruster duct remain topical;

- In the flight range of the flying vehicle M<8, the most efficient combustion is realized in a pseudoshock flow structure. The localized, intense heat supply may cause the duct choking prior to the thermal crisis;

- The combustion process deterioration because of the dissociation at flight speeds over M = 8 is one of the main problems, which require their solution.

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