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Experimental Investigation of Kerosene Fuel Combustion in Supersonic Flow

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An experimental investigation of kerosene fuel ignition and combustion stabilization in a two-dimensional scramjet combustor duct was conducted. The purpose of the study was to demonstrate scramjet operational parameters (flameholder design, ignitor technique, and area ratio) with kerosene fuel. The model was tested at the freejet Mach number M_∞ of 6. Hydrogen piloting was used for ignition and stabilization of kerosene combustion. Conditions were found where the kerosene combustion was sustained after the hydrogen pilot was no longer being injected. Distributions of gas-thermodynamic parameters along the duct, stability, and joint inlet-combustor operation are discussed.

Nomenclature

ER	=	equivalence fuel-air ratio
h_c	=	inlet entry height, 0.2 m
M	=	Mach number
p	=	pressure, Pa
T	=	temperature, K
$\bar{x} = x/h_c$	=	relative distance along the x axis
τ	=	time, s

Subscripts

lim	=	thermal chocking
t	=	total parameters
w	=	wall
∞	=	freestream parameters
1,4	=	kerosene injectors row numbers
2,3,5	=	hydrogen injectors row numbers

Introduction

THE combustion of kerosene in the scramjet with the supersonic flow in the duct (scramjet) is complicated by long ignition times and reduced reaction rates as compared to hydrogen. Thus, additional ignition and flameholding elements are required. For example, pilot flames with a sufficiently high concentration of active radicals or flame holders on the walls that create local recirculation zones are required. Poor mixing is also a physical factor that limits ignition and destabilizes combustion. System of shocks caused by geometrical peculiarities of the duct-flame layer can considerably improve mixing as it was shown in the work of Orth.[1] Highly reactive fuels such as silane and silane-hydrogen mixtures have also been used as pilots. However, hydrogen can also be used as a hydrocarbon fuel pilot. In fact, in the work of Isaac,[2] kerosene injected normally from the walls of the combustor into $M_\infty = 2$ flow was piloted by injecting a small amount of hydrogen from the walls of the chamber through a separate row of holes. When a rearward-facing step was used in these tests, more hydrogen had to be injected to ensure the combustion of the kerosene. Hydrogen was also recently used to ignite hydrocarbon fuels (ethylene and kerosene) in a model scramjet.[3,4]

The aim of this investigation was to determine the ignition, piloting, and flameholding characteristics in a scramjet combustor operating on kerosene. Hydrogen combustion was used as an ignition source for the kerosene. In order to improve the fuel distribution and mixing, the kerosene was injected from a pylon located in the center of the duct. An additional objective was to determine stable flameholding conditions after the ignitor/pilot fuel had been terminated.

Test Facility

The test facility was operated at the following total parameters: $p_{t,\infty} = (53–55) \times 10^5$ Pa, $T_{t,\infty} \approx 1500$ K, and $M_\infty \approx 6$. The vitiated heater burned kerosene. The mass percentage of oxygen in the vitiated air was maintained constant at 21% by oxygen addition. A model scramjet was installed at the exit of the 400-mm-diam facility nozzle. The test facility timing was controlled by a program-controller device. The duration of runs was about 30 s. Model fuel was injected after the $p_{t,\infty}$ became constant ($\tau = 15$ s). The data acquisition system included pressure gauges, thermocouples, fuel and air mass flow meters, and a computer. Schlieren photographs of flowfield near the cowl provided information about the inlet/combustor interaction.

Model Scramjet

The uncooled scramjet model, with an inlet frontal area 0.2 × 0.2 m², and exit combustor area 0.066 × 0.2 m², consisted of an inlet, rectangular combustor and shortened nozzle, as shown in Figs. 1 and 2. A two-dimensional inlet with an inlet contraction ratio equal to 5 included three compression surfaces with cumulative turning angles of 25 deg and an isolator duct with 2-deg divergence angle from $\bar{x} = 3.66$ to $\bar{x} = 4.7$. Figure 3 shows the different configurations of the struts and

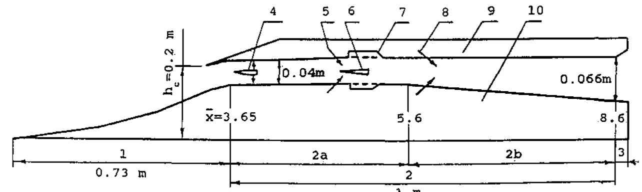

Fig. 1 Scheme of the investigated two-dimensional scramjet: 1—inlet; 2—combustor (2a—constant area section, 2b—expanding section); 3—nozzle; 4—kerosene injector; 5, 8—H_2 injectors; 6—hydrogen strut-stabilizator; 7—cavity flame holders; 8—cowl (upper wall); 9—lower wall.

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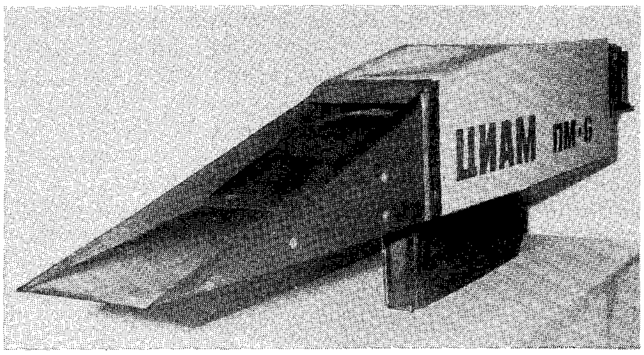


Fig. 2 Experimental scramjet.

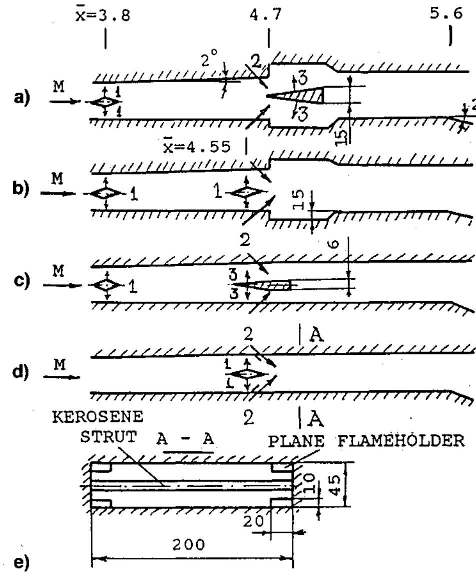


Fig. 3 Schemes of combustors with one-row kerosene injector (bold pointers show fuel injection): 1—kerosene; 2, 3—hydrogen (these and all following dimensions are given in mm).

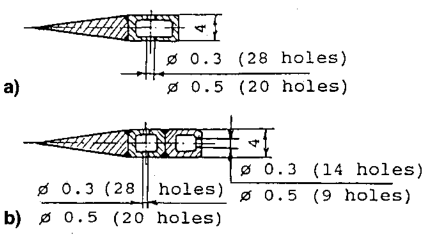


Fig. 4 Schemes of a) one- and b) two-row kerosene injectors.

piloting techniques used with normal injection of kerosene. Cavity flameholders located on the upper and lower walls were closed when other flameholders were used. In front of the cavities was a row of hydrogen wall-injectors (designated by 2 in Fig. 3) consisting of 14 holes on each side of the channel. At an axial distance of $\bar{x} = 5.6$, the channel expanded at an angle of 2 deg for all the experiments where the single strut was used for normal injection of kerosene.

Side wall injectors were located at various axial stations down the combustor length. Two 4-mm-thick struts were used for kerosene injection. One strut had a single fuel passage for normal injection through either 28 holes, 0.3 mm, or 20 holes, 0.5 mm in diam. The two-row strut allowed both normal and tangential injection by adding either 14 holes, 0.3 mm, or 9 holes, 0.5 mm diam, to the base of the one-row injector. See Fig. 4 for strut details. Kerosene was injected normally (kerosene 1) and tangentially (kerosene 4) for the two-row strut.

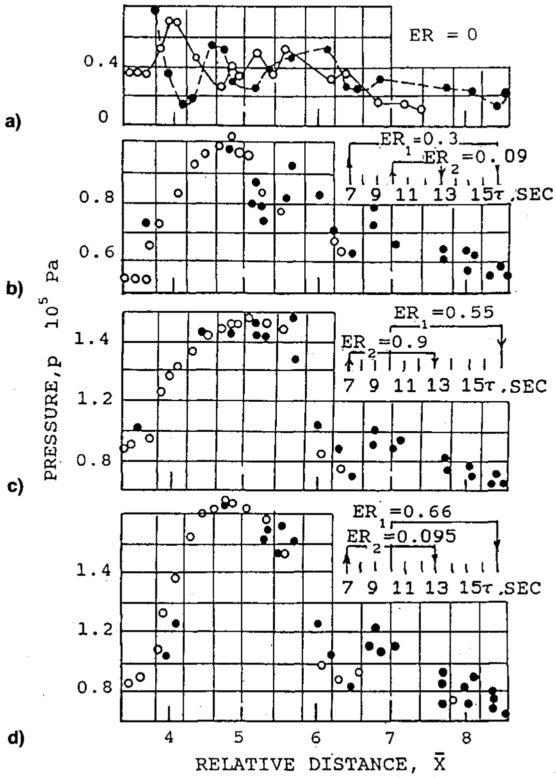


Fig. 5 Pressure distribution along the combustor with one-row kerosene injector and cavity flameholders: a) scheme of combustor in Fig. 3a and without the struts; b), c) scheme of combustor in Fig. 3b, kerosene injector at $\bar{x} = 3.8$, $\tau = 16$ s; d) scheme of combustor in Fig. 3c, kerosene injector at $\bar{x} = 4.55$, $\tau = 16$ s; •—upper wall, ○—lower wall.

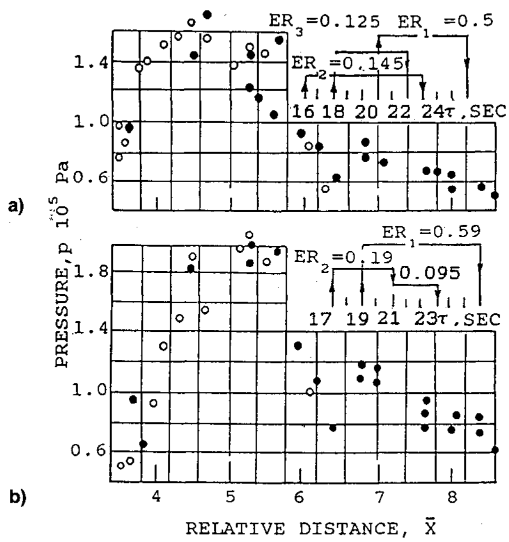


Fig. 6 Pressure distribution along the combustor with one-row kerosene injector: a) scheme of combustor in Fig. 3c; $\tau = 13.5$ s; b) scheme of combustor in Fig. 3d, $\tau = 26$ s; •—upper wall, ○—lower wall.

Results and Discussion

Experiments with One-Row Kerosene Strut

Figures 5 and 6 show the static pressure distributions along the duct for several of the pilot and flameholder configurations tested. There was a good correlation between the measured and designed pressure in the inlet for the initial duct configuration. At a hydrogen $2\,ER_2 = 0.1$, the hydrogen autoignited and combustion caused the pressure to increase ≈15–20% at the end of the first combustor section. For the configuration shown in Fig. 3a, the leading edge of the strut-stabilizator was destroyed, when the hydrogen ignitor flow was increased ($ER_3 = 0.2$); but the base part of the strut showed little effects of heating. Based on these heating patterns it was concluded that the combustion resulted from flameholding by the hydrogen jets and not by the recirculation at the base of the strut. Since the pressure increased by approximately 50%, the kerosene injected as kerosene 1 was also burning, but less than expected. A local increase in static pressure near the cavity flameholders up to 1.2×10^5 Pa resulted from waves from the large cross section (30% of throat section) of the strut-stabilizator.

Figures 5b–5d show the results of experiments with the combustor where the products of hydrogen 2 ignited the flame with normal injection of kerosene through the strut. Analysis of wall temperature and pressure oscillograms showed that there was no self-ignition of kerosene 1, when the hydrogen 2 ignitor was not used. However, only a small amount of hydrogen 2 ($ER_2 = 0.09$) was required to ignite the kerosene. With this small hydrogen ignitor, kerosene burned well for $ER_1 = 0.3$–0.66, as Figs. 5b–5d show. A combustor/inlet interaction occurred when ER_1 was increased to 0.3 or above, i.e., a normal shock wave appeared near the cowl. At $ER_1 = 0.3$–0.66, this normal shock caused a decrease in the airflow rate of approximately 10–15%. The kerosene injectors were moved downstream from $\bar{x} = 3.8$ to $\bar{x} = 4.55$, and the cavities closed as shown in Fig. 3c. This configuration resulted in good kerosene combustion until ER_1 was greater than 0.33.

The fact that there was a separated shock wave near the cowl showed that the heat addition was maximum, i.e., the kerosene was burning when a system of shocks or pseudoshocks existed in the combustor. This shock-like process of combustion can be imagined as follows. Products of hydrogen burning in the cavities form the active contact surface and ignite the kerosene. If heat addition is near maximum, the pseudoshocks are formed in the duct where drops of kerosene are atomized, vaporized, and efficiently mixed with air. This rapid vaporization results in part of the kerosene being entrained in the cavities and burning even after the hydrogen ignitor is terminated. Products from combustion in the cavities ignite the mixture of kerosene and air in the core of the flow, and the burning of kerosene is self-stabilizing.

Following these tests with the severe upstream interaction, a strut-flameholder of a smaller size, 6 mm, was then evaluated. For these tests the contact surface was formed by burning jets of hydrogen near the strut walls. The cavities were closed as shown in Fig. 3c. It was assumed that in this case local shock waves resulting from the strut and increased pressure would provide necessary conditions for self ignition and burning of hydrogen injected from the strut, hydrogen 3 and wall injectors, hydrogen 2. Initial tests with wall-pilot hydrogen $ER_2 \leq 0.1$ and strut-flameholder injection, $ER_3 = 0.06$, did not pilot the kerosene. Increasing the strut and wall hydrogen ERs to 0.125 and 0.145, respectively, was required to ignite the kerosene. Kerosene combustion terminated when the wall-pilot was turned off. Installation of the hydrogen strut had little effect on the duct pressure distribution. Pressure distributions shown in Fig. 6a indicate that the pressure level and, consequently, combustion efficiency in this combustor configuration was lower than for the configuration with the cavity flameholders, but more than for the configuration with the 15-mm strut-flameholder previously tested.

Note, that the strut-stabilizator had traces of damage to the material on the leading edge, but not in the base section, i.e., kerosene combustion must have been stabilized close to the hydrogen jets and in general burning of kerosene, after ignition, began upstream of the strut-stabilizator. Creating contact surface of pilot products from the wall hydrogen jets was the most important factor in the flameholding of kerosene combustion.

As an option to the cavity flameholders, four plane flameholders, 10×20 mm^2 each, were installed in the corners of the combustor in front of hydrogen 2 injectors, as shown in Figs. 3d and 3e. The cross section of these plane flameholders was considerably decreased in comparison with the strut-stabilizator, also the flameholders were installed in the corners of the duct, where the boundary layer was the thickest.

When this idea was used, the combustion of kerosene was successful, as shown in Fig. 6b. The wall hydrogen 2 self-ignited at $ER_2 = 0.19$, then the kerosene was ignited. After the fuel rate of hydrogen was twice decreased and even, when the hydrogen pilot was terminated, the kerosene continued burning. The pressure distribution in Fig. 6b shows that the pressure increased in the throat region, when kerosene was burning even at an $ER_1 = 0.59$. The minimal flow rate of hydrogen 2, in this combustor configuration was $ER_2 = 0.09$. Without ignition of the hydrogen 2 ignitor/pilot, no kerosene combustion was observed. The flameholders were not damaged during these runs. In order to determine the effectiveness of the corner flameholders, a control test was conducted without the plates, and no autoignition was observed with hydrogen $ER_2 = 0.09$–0.2.

In constant cross-sectional combustor ducts with an average inlet exit $M = 2.7$ flow, there is a limited ER, ER_{lim}, where upstream interaction does not occur. It was supposed, that ER_{lim} is the maximum ER_1, when the duct is thermally chocked. In order to burn more fuel, it is necessary to expand the duct, but when the angle increases, the combustion efficiency usually decreases. At large expansion angles, burning can be completely quenched. The most efficient expansion angle of a scramjet combustor is considered to range from 0.5 to 1.5. The mixing efficiency of hydrogen jets burning in a diffusion mode in the expanding duct was previously investigated.[5] It was shown that since combustion was limited by mixing, combustion efficiency was not very high, when the fuel was injected from the walls or from the struts.

In the combustion model suggested in this work, burning of kerosene jets in the constant area duct resulted in pseudoshocks, i.e., in most cases combustion was not occurring in the purely diffusion mode. Ignition and flameholding occurred in the pseudoshock mode, if $ER \geq ER_{lim}$, and then mixing of the fuel jets considerably changes the gas dynamic, thermal, and physical processes within the duct.

Experiments with Two-Row Kerosene Strut

Based on the previous tests it was decided that a two-row strut (tangential-kerosene 4 and normal-kerosene 1) should be used to control the heat release distribution. Plate-flameholders in the corners of the duct were again used. The constant area section was followed, as before, by an expanding section with an angle of 2 (Fig. 7). The proposed ignition/piloting scheme was as follows: kerosene 1 was ignited in the constant area section by walls jets of hydrogen 2, and kerosene 4 was ignited by the flame products of kerosene 1 downstream in the expanding section. Since kerosene 4 was injected tangentially, the mixing from these jets was slower. As a second variation of the expanding section, a channel with an 8-deg expansion angle and a set of hydrogen 5 injectors, consisting of 14 injectors (holes) on both sides of the walls was evaluated. At the end of the expansion section there was a forward-facing flameholder followed by a 2-deg diverging duct (Fig. 7c).

Details of the two-row strut are shown in Fig. 4b. The diameter of injector holes was 0.3 mm, the number of injectors varied from 9 to 14 for the set of kerosene 4 and from 20 to 28 for the set of kerosene 1.

First, the strut was installed in the cross section at $\bar{x} = 3.8$ in the beginning of the combustor. The diagram of Fig. 8a shows the static pressure distribution in the duct when kerosene 1 and 4 were injected with $ER_{1+4} = 0.26$. No combustion was observed. When hydrogen 2 with $ER_2 = 0.16$, kerosene 1 with $ER_1 = 0.25$, and kerosene 4 with $ER_4 = 0.12$ were injected into the combustor, both kerosene jets ignited. However, when the hydrogen 2 injection was terminated, the kerosene combustion stopped.

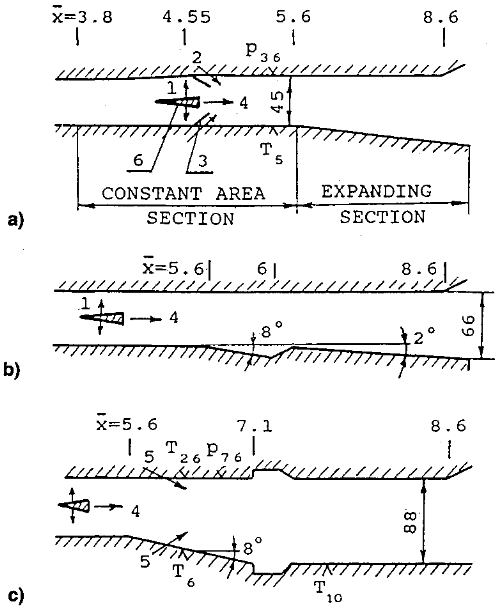


Fig. 7 Schemes of combustor with two-row strut kerosene injector: a) total scheme of combustor, b) section with 2 divergence, and c) section with 8 divergence; 1—normal kerosene injection; 2, 5—H_2 injectors, 3—plane flameholders; 4—tangential kerosene injection; 6—two-row kerosene strut; 7—cavity flameholders; p_{36}, p_{76}, and T_5, T_6, T_{10}, T_{26}—pressure gauges and thermocouples.

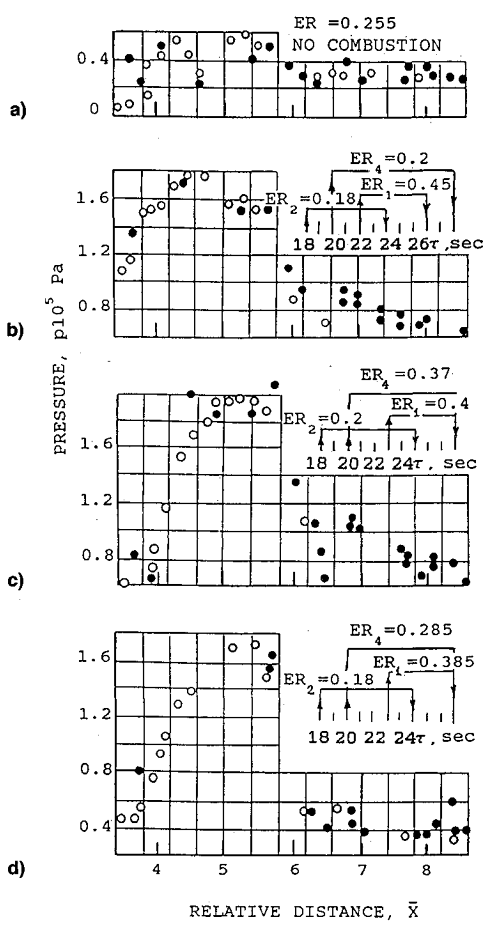


Fig. 8 Pressure distribution along the combustor with two-row kerosene injector and flameholders: a); b) scheme of combustor in Figs. 7a and 7b, kerosene injector at $\bar{x}$ = 3.8, τ = 26 s; c) scheme of combustor in Figs. 7a and 7b, kerosene injector at $\bar{x}$ = 4.5, τ = 27 s; d) scheme of combustor in Figs. 7a and 7c, kerosene injector at $\bar{x}$ = 4.5, τ = 24 s; ●—upper wall, ○—lower wall.

To determine the location where burning of kerosene 4 starts, the rate of kerosene 4 injection was increased, and the mode of fuel injection was alternated (after hydrogen 2, kerosene 4 was injected, and then kerosene 1). These results are shown in Fig. 8b. Kerosene 4 was also ignited in the jets of hydrogen 2. The maximum of heat release location resulting from joint combustion of hydrogen 2 and kerosene 4, as indicated by the maximum static pressure, was close to $\bar{x}$ = 5.5. Since ER_{2+4} was equal to 0.38, i.e., $ER_{2+4} > ER_{\lim}$, a shock wave appeared in the cowl. After injection was increased to 0.66, the pressure rise from kerosene burning resulted in a normal shock in the inlet. When kerosene 1 was terminated, kerosene 4 stopped burning. This test enabled us to conclude, that kerosene 4 was ignited by the hydrogen 2 jets, but fuel didn't penetrate into the recirculation zones behind the plate-flameholders into the corners of the duct as in the previous tests.

Relocating the two-row strut at $\bar{x}$ = 4.5 permitted, as the static pressure distribution in Fig. 8c shows, the engine to operate with kerosene up to ER_{1+4} = 0.66 with minimal distortion of the flow in the inlet. The maximum heat addition of kerosene 4 burning with hydrogen 2 was close to the cross-section location $\bar{x}$ = 5.6, i.e., in the place, where flame products of hydrogen 2 jets from opposite walls intersected. The pressure level in the duct both in the constant area section and in the expanding section did not increase as had been expected when the two-row strut was used.

In an experiment with this cavity configuration, the pitot microprobe was installed in the flow at the cross section $\bar{x}$ = 5.4 location. These results showed, that with kerosene combustion, pressure pulsations occurred when the flow in the burning area was close to sonic. The value $p_t/p_{t,\infty}$ (here p_t—pressure measured by a pitot tube) without burning was 0.09, and with burning was 0.06–0.07. These data indicate interdependence of the combustion processes with the pseudoshock system.

The duct was modified by increasing the angle of the duct lower wall from 2 to 8 deg, as shown in Fig. 7c. Combustion of kerosene with ER_1 = 0.39, ER_2 = 0.18, and ER_4 occurred as indicated in Fig. 8d. However, combustion stopped, although ER_1 and ER_4 were greater than $ER_{\lim}$, when ER_2 hydrogen injection was terminated. When the rate of kerosene 1 was increased up to ER_1 = 0.48, the result was the same: the pseudoshock was destroyed and burning stopped. These results testified to the fact that, as before in the combustor with the 2-deg-expansion angle, the duct length and area ratio were sufficient to establish the pseudoshock, and combustion could continue when the pylot hydrogen was turned off.

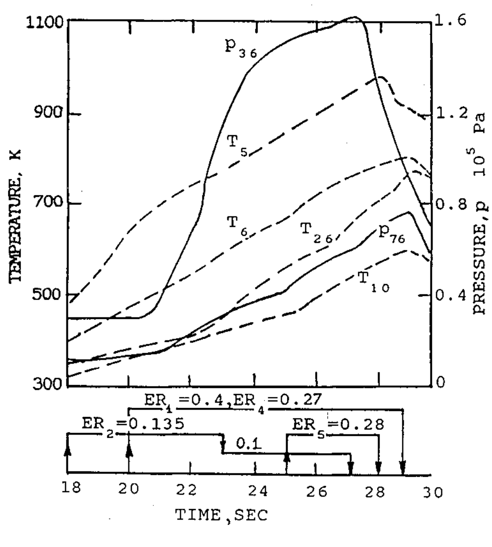
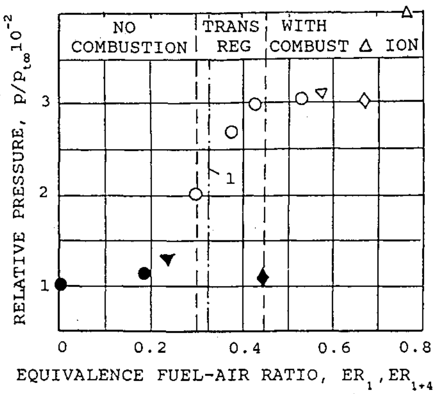


Fig. 9 Pressure and temperature oscillograms for the scheme of combustor in Figs. 7a and 7c.



Sign	Kerosene injector	$\bar{x}$	Flameholder
○	One-row	3.8	Cavity
◇	One-row	4.5	Cavity
∇	One-row	4.5	Plane
Δ	Two-row	4.5	Plane

Fig. 10 Pressure at $\bar{x}$ = 5.5 vs kerosene-air ratio (*1*—corresponds to ER_{lim} for constant area section, light signs—with combustion, dark—no combustion).

Thus, to organize burning of kerosene in the expanding ducts, it is necessary not only to create conditions for stable pseudoshock, but to be able to move the pseudoshock from one section of the combustor to another. Such conditions were created by using an extra set of hydrogen 5 injectors (Fig. 7c), and a fuel injection sequence, as shown in Fig. 9. After the kerosene began burning with ER_{1+4} = 0.67, the rate of hydrogen 2 was decreased from ER_2 = 0.135 to 0.1, and hydrogen 5 was injected at the beginning of the expanding section. Only when the hydrogen injection was completely stopped at 27 s was combustion terminated. Figure 9 shows a number of oscillograms of pressures and temperatures at separate points of the model (see Fig. 7c for location numbers). It is evident, that after autoignition of hydrogen 2, ignition of kerosene 1 and 4 occurred. The kerosene continued burning after hydrogen 2 flow was decreased to ER_2 = 0.1. When hydrogen 5 was injected, pressure in the constant area section didn't change and in the expanding section the pressure increased downstream of the hydrogen 5 injector location. After hydrogen 2 injection was stopped, the pressure in the constant area section began to decrease due to the fact that upstream burning had stopped. Combustion continued in the expanding section. Changes in the wall temperatures in various sections, simultaneously with change in static pressure, confirmed the fact that kerosene 1 and 4 stopped burning in the constant area section after hydrogen 2 stopped being injected, and that the burning zone shifted to the eight-expanding section. When hydrogen 5 and kerosene 1+4 were burning simultaneously, the flow in the inlet was unaffected. When hydrogen 5 stopped being injected, burning of kerosene 1+4 also stopped. On the basis of the suggested model of the process, it can be assumed that the cavities of the expanding section were not effective flameholders in this case, because little of the kerosene was entrained in the cavity flow. For this reason other stabilizing elements on the walls and their optimal location should be investigated. Another explanation for flame-out of kerosene in the expanding section with 8-deg angle is possible: after hydrogen 5 stopped being injected, ER_{1+4} dropped to 0.6, i.e., to ER greater than ER_{lim} for the present experiment, the heat release decreased and the pseudoshock was destroyed.

These experiments showed that after ignition of kerosene 1+4 by pilot hydrogen 2 jets, combustion of kerosene will continue in a two-expanding duct if the ER is in the range of 0.3 as shown in Fig. 10 for a number of injector configurations.

Conclusions

A hydrogen pilot flame and plate flameholders were used to ignite and stabilize kerosene combustion in a two-dimensional scramjet combustor with a constant area section followed by an expanding duct with two- and eight-expansion angles at small ($ER \approx 0.1$) amounts of hydrogen injected. In some cases, kerosene combustion continued after pilot hydrogen flow was terminated.

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References

[1]Orth, R. C., and Cameron, J. M., "Flow Immediately Behind a Step in a Simulated Supersonic Combustor," *AIAA Journal*, Vol. 13, No. 9, 1975, pp. 1143–1148.

[2]Isaac, J. J., and Cookson, R. A., "Supersonic Combustion Aid for Liquid and Gaseous Fuels," *AIAA Journal*, Vol. 11, No. 7, 1973, pp. 1036, 1037.

[3]Kay, I. W., Peschke, W. T., and Guile, R. N., "Hydrocarbon-Fueled Scramjet Combustor Investigations," AIAA Paper 90-2337, July 1990.

[4]Waltrup, P. J., "Liquid Fueled Supersonic Combustion Ramjets: A Research Perspective of the Past, Present and Future," AIAA Paper 86-0158, July 1986.

[5]Mesheryakov, E. A., "Heat Addition in Supersonic Flows," *TSAGI Science Reports*, Vol. 18, No. 2, 1987, pp. 125–130.