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**HEAT AND MASS TRANSFER AND PHYSICAL GASDYNAMICS**

# Hydrogen Combustion under Conditions of a High-Temperature Supersonic Flow

**V. A. Zabaykin**

*Khristianovich Institute of Theoretical and Applied Mechanics, Siberian Branch, Russian Academy of Sciences, Novosibirsk, 630090 Russia*
*e-mail: lvz64@mail.ru*

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**Abstract**—Some results of studying the combustion of hydrogen in a high-velocity air flow at stagnation temperatures below 3000 K are given. Flame shape and combustion zone length change at temperatures above 2000–2200 K due to deterioration in the fuel–oxidizer mixing process. It has been shown that dissociation processes have an effect on the process of hydrogen combustion at a high temperature. In experiments, they can be detected by a change in the intensity of radiation from the intermediate OH* radical.

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## INTRODUCTION

Promising hypersonic flight speeds of aircrafts are characterized by air flow stagnation velocities above 2000 K after attainment of Mach number M = 6. This enables the ensured self-ignition of fuel in the combustion chambers of airbreathing jet engines. At the same time, the relative heat supply from fuel burning in a combustion chamber is decreased at high supersonic flight speeds, leading to a deterioration in the tractive and economical characteristics of the propulsion assembly of aircrafts. It is necessary to take into account a change in the fuel–oxidizer mixing conditions at high temperatures and energy losses due to the dissociation of combustion products. These factors have not been sufficiently studied by experiment, as the creation of supersonic air flows with stagnation temperatures above 2000 K under ground conditions is a complicated task. There currently exists a limited number of high-enthalpy setups designed for the study of combustion processes. The detection of combustion processes in supersonic flows and, consequently, the study of a three-dimensional flame structure also present some difficulties. This work is aimed at studying the combustion of hydrogen within a broad range of air flow temperatures beginning from the temperatures providing its self-ignition. The main information was acquired by registering the radiation from an air-hydrogen flame within the ultraviolet wavelength range to enable the experimental estimation of the effect of high temperatures on dissociation processes and a change in flame structure.

## SCHEMATIC OF EXPERIMENTS AND RESULTS

This work was performed on a supersonic combustion test bench [1, 2] with an electrical arc air heater (EAH) within a range of air flow stagnation temperatures of 1200–3000 K. An air jet was formed in an axially symmetric profiled nozzle with Mach number M = 2.2 and an outlet diameter of 50 mm. Hydrogen was supplied through an injector installed along the nozzle axis and self-ignited in a hot air jet. Concurrent supply injectors designed for Mach numbers 1.0, 2.0, and 2.7 alongside with crossflow supply injectors were used [3]. The fuel jet off-design degree ($n = 0.5–1.3$) and the flow rates of media of up to 1 kg/s for air and 1.5–4 g/s for hydrogen were varied in experiments. Special attention was paid to questions on the quality of air flow at the inlet into a working section, i.e., the retention of the percentage of main compounds ($O_2$, $N_2$) and the reduction of contamination with extraneous admixtures. For an electrical arc heater, such contaminating elements as carbon oxides and water vapor (whose appearance leads to a change in the $O_2/N_2$ ratio) are absent, and there is also no need to oxygenate the flow. At the same time, nitrogen oxides appear, and the high-temperature erosion of electrodes takes place. These problems were carefully studied and solved when adapting the electrical arc heater to the supersonic combustion bench. By improving the plasmotron (by fitting the geometric parameters of EAH elements and the rates of air flows into the EAH cathode and anode sections and forechamber and their ratios), we have managed to provide a low level of specific erosion in the working regimes throughout the entire required range of setup working parameters. The performed works on the refinement of EAH and the bench as a whole are detailed in [1, 2].

The quality of the flow has also been improved by (1) organizing the disposal of the most contaminated gas fraction from the cathode chamber into the atmosphere; a major fraction of erosion products is withdrawn from the cathode without entering the forechamber due to the separation of particles to the electrode wall (the flow in the chamber is vortex), thus improving the purity of air;

(2) installing the forechamber (mixing chamber) immediately after the plasmotron to enable the mixing of additional cold air to the hot air leaving the plasmotron in its initial section. When the gas passes through the forechamber (length, 1 m; air velocity, 50–70 m/s), recombination or oxidation takes place for unstable compounds, which may be formed in the plasmotron.

The gas and spectral analyses of the flow coming from the nozzle show that the applied plasmotron with gas vortex arc stabilization in normal operational regimes provided a specific erosion of less than $10^{-7}$ (up to $10^{-9}$ kg/C) and a nitrogen oxide concentration of less than 0.06%, which produce little if any effect on the accuracy of performed combustion experiments. This provided reliable study of the physics of combustion processes in a high-temperature supersonic flow, including the temperature range of 2300–3000 K, which is inaccessible for setups with fired air heating.

To acquire some information on the combustion process, optical detection in different spectral ranges of wavelengths was applied. In the visible spectral region, the radiation of a hydrogen–air flame was detected by artificial vision cameras with an exposure time from $10^{-5}$ to $10^{-2}$ s. In the ultraviolet spectral region, the two-dimensional detection of radiation from a hydrogen flame (OH* radical) was performed using an electron-optical image converter with a UV light filter and the fixation of an image by an artificial vision camera. This enabled the acquisition of precise data on the zones of chemical reactions, as the excited OH* radical radiation intensity (transition $^2\Sigma^+ \rightarrow {}^2\Pi$; $\lambda$ = 280–350 nm) is proportional to the volumetric heat release rate for a hydrogen–air flame [4, 5], and the lifetime of the electron transition responsible for this radiation ($\tau \sim 10^{-8}$ s) is much shorter than the characteristic times of gas flight trough torch gasodynamic structure elements ($\tau \sim 10^{-5}$ s at air flow velocities of 1000–2000 m/s). As a result, the information on the structure of combustion zones and the effect of dissociation processes on the characteristics of a flame in a supersonic high-temperature flow was obtained.

### Effect of High Temperatures on the Geometry of a Flame

The earlier performed experiments [6–8] have shown a considerable change in the character of hydrogen combustion upon transition from temperatures of less than 2000 K to higher temperatures. At lower temperatures of a supersonic air flow, combustion was generally observed in the central part of a jet in the zones of post-shock pressure increase and temperature [9]. The structure of a flame is transformed with increasing flow temperature. First, the delay of ignition disappears, and the ignition of hydrogen occurs immediately at the injector edges (Fig. 1). Second, the main zones of chemical reactions shift from the center of a jet to its periphery into the air–hydrogen mixing region (an "annular" character of combustion is observed) [6]. Third, the total length of a flame increases. All these phenomena are associated with an increase in the air temperature: the ignition delay abruptly decreases at high temperatures, thus entailing the "flashy" chemical reaction between fuel and oxidizer portions coming in contact before the major volume is mixed. For this reason, early ignition worsens the mixing of hydrogen with air in the initial zone of injection due to the appearance of combustion products in the region between the fuel and the air, which "screen" one flow from the other.

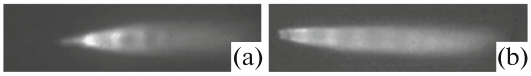

**Fig. 1.** Two-dimensional OH* radiation intensity distribution (UV spectral region) at two temperatures $T_0$ of (a) 1850 and (b) 2500 K and $M_{H_2} = 1$.

Such a combustion character is similar to the kinetic effect, when the application of promoting additives reduced the ignition delay, but enlarged the total combustion zone [7]. The considered effect of high temperatures may be called a direct effect exhibiting as a change in flame geometry.

### Effect of High Temperatures on Dissociation and Experimental Detection of Dissociation Processes

Another important factor producing an effect on the process of combustion at high temperatures is the dissociation process, which is poorly observable by external signs, but causes appreciable energy losses due to the decomposition and formation of molecules. It is noteworthy that there are almost no systematic experimental studies on the effect of dissociation on the combustion process. There only exist some isolated works performed on short-term operation setups, where the efficiency of combustion was observed to decrease with increasing air flow temperature [10–12].

From the reference data (Fig. 2), it can be seen that the effects of the dissociation of hydrogen (water)

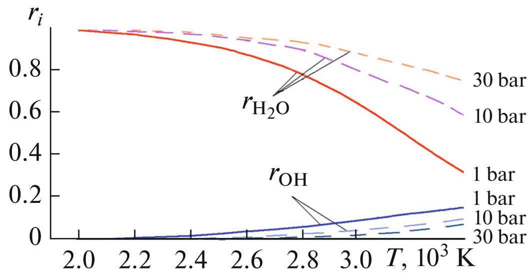

**Fig. 2.** Water dissociation degree versus temperature at different pressures and corresponding increase in the OH concentration [13].

combustion products may exhibit when 2000 K is exceeded, especially at low pressures. The most appreciable increase is observed in the amount of OH hydroxyl molecules, whose content attains nearly 10% (of the $H_2O$ volume) in a free state at 3000 K and atmospheric pressure [13].

High-temperature continuous fire-heated aerodynamic setups are usually operated at air stagnation temperatures of up to 1800 K (methane combustion). Maximum air temperatures may attain 2200–2350 K (when kerosene or gasoline is used for heating), which in principle are sufficient for the process of dissociation to begin to appear for water formed as an end reaction product when hydrogen is used as a fuel. However, such parameters take place at the utmost capacities of fire-heated setups and are very rarely attained in practice.

It should be noted for setups with fire heating of air that the difference between the heated gas and pure air compositions grows with an increase in the heating temperature. In particular, the water content becomes considerable at a high level of fire heating (above 2000 K), and this leads to a decrease in the adiabatic hydrogen combustion temperature in addition to a change in ignition characteristics [14]. A decrease in the level of static pressure inside the combustion chamber upon the change of electrical arc heating by fire heating is pointed out in [15], where the content of water in the working gas of the set-up attained 22%. In other words, the distortions introduced into the flow composition in the case of fire heating may lead to the incorrectness of quantitative results, a consequence of which the effect of dissociation will be almost imperceptible.

However, dissociation processes must be taken into account just when attaining the temperature level of 2000–2200 K and higher. The above-considered series of studies was performed on a setup with electrical arc air heating, which allowed us to avoid the appearance of additional $H_2O$ molecules in the air flow. The time of operational regimes was several tens of seconds, and the level of attained temperatures was both appreciable higher (from 1200 K) and much higher than 2000 K (up to 2800–3000 K). The used approach was the following: the effect of temperature on the combustion process and the characteristics of radiation from a hydrogen–air flame was experimentally determined by radiation from the OH radical, which is one of the components participating in both the forward $H_2$ oxidation reaction and the dissociation and recombination reactions. It is expected that the appearance of additional OH hydroxyl molecules upon dissociation must have an effect on an increase in the integral flame radiation intensity in the UV spectral region, and this can be detected with high precision (similarly to the optical method of estimating the hydrogen combustion completeness) [4, 5]. To accomplish this, the flame radiation intensities at different temperatures were compared during the processing of experimental results.

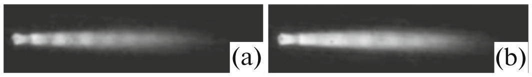

**Fig. 3.** Two-dimensional distribution of radiation from the OH* radical in a flame at (a) $T = 1900$ K, $G_{H_2} = 2.9$ g/s, $P_0 = 6.3 \times 10^5$ Pa and (b) $T = 2800$ K, $G_{H_2} = 2.6$ g/s, $P_0 = 6.7 \times 10^5$ Pa.

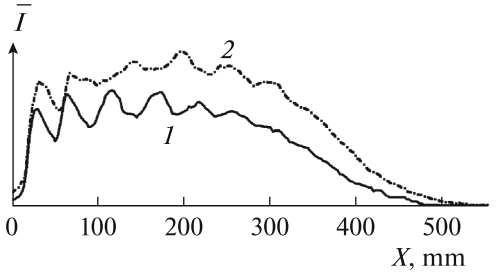

**Fig. 4.** OH radical radiation along the flame length at (*1*) $T = 1900$ K, $G_{H_2} = 2.9$ g/s, $P_0 = 6.3 \times 10^5$ Pa and (*2*) $T = 2800$ K, $G_{H_2} = 2.6$ g/s, $P_0 = 6.7 \times 10^5$ Pa.

A typical two-dimensional distribution of flame radiation intensity in the UV spectral region at temperatures differing from each other by 900 K is shown in Fig. 3, and the integral $I_{OH}$ distributions obtained along the flame length by processing the images shown in Fig. 3 are illustrated in Fig. 4.

The comparison of two regimes, which appreciably differ from each other only by their temperatures, demonstrates a growth in the integral intensity of radiation from a hydrogen–air flame in the UV wavelength range with an increase in the air flow stagnation temperature above 2000–2200 K, when dissociation processes play an increasingly greater part. This entails the appearance of additional excited OH* radicals formed after the thermal decomposition of $H_2O$ molecules representing an end product of the occurring chemical reaction. In the performed studies, such an increase in the intensity of radiation from a hydrogen–air flame was experimentally detected within the UV range at high temperatures.

Due to the fact that the combustion process occurs at high (often ultimate) parameters, this raises an important question on the regime maintenance and measurement precision at 2000–3000 K. Some special series of experiments, which allow us to verify the correctness of results, have been performed. The OH radiation intensity distribution curves recorded at different time moments in the same regime with constant temperature, air flow pressure, and hydrogen flow rate are plotted in Fig. 5. The curves plotted with different lines correspond to recording at every 1.5 s, i.e., a rather long time period. (The time of high-temperatures regimes including the stabilization of a regime was usually 8–15 s). It can be seen that they almost

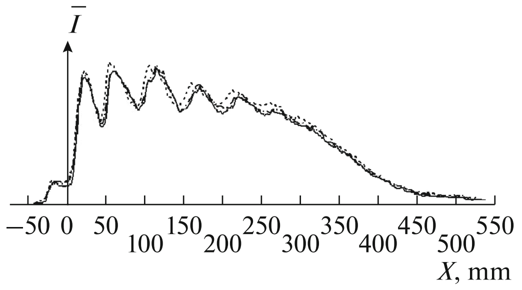

**Fig. 5.** Regime maintenance and determination precisions at $T = 2000$ K, $G_{H_2} = 2.8$ g/s, $P_0 = 6.5 \times 10^5$ Pa.

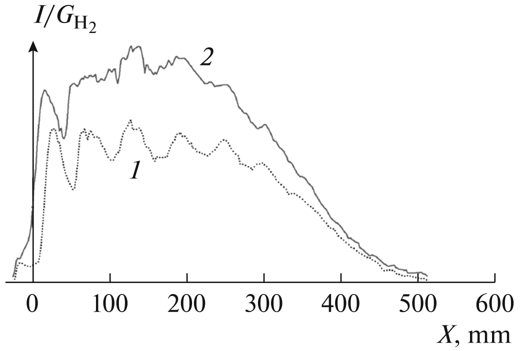

**Fig. 6.** Radiation from the OH radical along the flame length at a constant pressure, $G_{H_2} = 2.9$ g/s, $P_0 = 6.9 \times 10^5$ Pa, and different temperatures $T_0$ of (*1*) 1750 and (*2*) 2600 K.

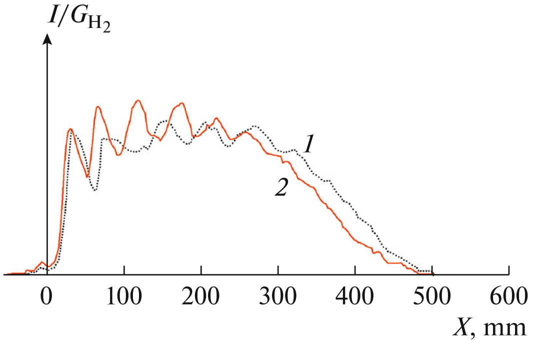

**Fig. 7.** Radiation from the OH radical along the flame length at a constant temperature, $G_{H_2}$ = const = 3 g/s, $T$ = const = 2100 K, and different pressures $P_0$ of (*1*) 7.4 × $10^5$ and (*2*) 6.3 × $10^5$ Pa.

completely coincide in the considered heat-stressed regime. Verification performed at 1500 and 1750 K has also demonstrated good agreement.

For the plot shown in Fig. 5, it is necessary to clarify that an observed increase in the radiation intensity at the left of coordinate $X = 0$ mm (from 0 to ≈ −25 mm) means combustion in the detachment zone on the side surface of an injector. The edges of all the concurrent-supply fuel injectors were specially beveled to stabilize the flame and provide the beginning of combustion in the same place within a broad range of temperatures (from 1200 to 3000 K) without delay of ignition at low temperatures. Thereby the beginning of combustion was fixed at one point, and it was possible to compare strongly different regimes. The coordinate $X = 0$ corresponds to the hydrogen injector end beyond the nozzle edge. Moreover, to form a set of statistical data and perform a comparison of regimes with different hydrogen flow rates, the curves were plotted using the ratio of the OH radiation intensity to hydrogen flow rate ($I_{OH}/G_{H_2}$) as an ordinate. As a result, not only the radiation intensity distribution along the flame length was recorded, but also the dependence between the integral radiation intensity $I_{OH}$ of a hydrogen–air flame on the air flow temperature was determined.

The possible effect of the air jet off-design degree on the obtained results was also checked. The series incorporated the measurements of $I_{OH}$ in the cases of

(1) pressure measurements at a constant temperature, and

(2) temperature measurements at a constant pressure.

The results of performed experiments are shown in Figs. 6 and 7. The integral radiation intensity grew by up to 40% at air flow stagnation pressure $P = 6.9 \times 10^5$ Pa with increasing temperature from 1750 to 2600 K, while the hydrogen flow rate in these regimes remained constant ($G = 2.9$ g/s = const). In Fig. 6, the increased OH radical radiation intensity peaks are smoothened at a temperature of 2600 K, thus arguing for a probable decrease in the effect of the wave structure of an air off-design jet on the hydrogen combustion process with increasing temperature. An increase in the total pressure from 6.3 to 7.4 × $10^5$ Pa at a constant temperature of 2100 K leads to a certain redistribution in the combustion intensity in compliance with a changed wave structure and a slight downstream shift of the combustion zone. The total level of flame radiation in the UV range does not change in this case (Fig. 7). An increase in the intensity of radiation $I_{OH}$ from a hydrogen–air flame may be explained only by the effect of dissociation processes.

The possible effect of the central hydrogen jet off-design degree on $I_{OH}$ was studied in a special series of experiments. To accomplish this, the combustion of hydrogen from two nearly geometrically similar injectors with the same inlet Mach number M = 2, but different off-design degrees (in experiments, $n_1 = 0.6$–$0.8$ and $n_2 = 1$–$1.3$) were compared at the same hydrogen flow rate. The OH radiation intensity curves for these two types of injectors in the same regime for air at nearly the same hydrogen flow rates are shown in Fig. 8.

It can be seen that the application of injectors with different off-design degrees has not led to any distinctions between the above-described results. The curves nearly coincide, and a minimum deviation may be due to the incomplete correspondence of these regimes to each other (which are very difficult to maintain absolutely the same in different startups) and the precision of measurements.

The final result of several series of measurements is shown in Fig. 9 as the temperature dependence of the integral radiation intensity $I_{OH}$ (normalized to the hydrogen flow rate). The major number of experiments was performed within a temperature range from 1200 to 2800 K, varying all the available parameters within a broad range. Different symbols in Fig. 9 denote different series of experiments. The plot incorporates all the points with the greatest deviation from the obtained "corridor" of values. At higher and lower temperatures, only isolated startups were performed due to the difficulty of ignition and stabilization (low-temperature range) and a lower precision in the measurement and maintenance of parameters at $T \approx 3000$ (up to 3300 K). The results within these ranges do not contradict the data, but they have not been incorporated into the resulting plot due to the instability of regimes (as this has produced some effect on the precision of measurements).

It can be seen that the effect of dissociation at a temperature of 1200–1900 K is slight, but becomes essential on attainment $T \approx 2000$ K and its further increase. If the excess OH* radiation intensity is assumed to be directly proportional to the dissociation losses, they may attain a half of the chemical energy evolved in the hydrogen oxidation reaction. This is not energetically advantageous for the organization of combustion in the propulsion assemblies of aircrafts, so it is necessary to conduct the process in such a way as to decrease the dissociation losses. As shown above, high temperatures decrease the fuel–oxidizer mixing intensity.

An excess in the level of radiation over the value typical for $T \leq 2000$ K actually means energy losses (equivalent to a decrease in the combustion completeness) due to the dissociation of reaction products. In practice, this may serve as "a mark" for the beginning of these processes.

An additional result of this work may be the experimental confirmation of "the optical method of estimating the hydrogen combustion completeness" [4, 5] with a specified upper limit of its application. Figure 9 indicates that the intensity of radiation $I_{OH}$ from a hydrogen–air flame below 2000 K does not change at a constant hydrogen flow rate at 100% combustion completeness. Deviations arise when this level of temperature is exceeded. From the practical viewpoint, this proves the applicability of this method for setups with fire air heating almost throughout the entire range of their operation (up to ≈2000 K). It is worth noting that the fire heating of air is applied in the overwhelming majority of high-temperature benches with a continuous operational regime.

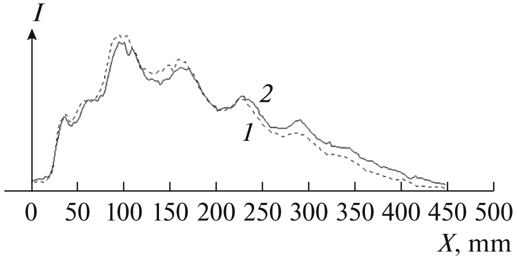

**Fig. 8.** Effect of the hydrogen jet off-design degree at M = 2.2 and $M_{H_2} = 2$ for (*1*) injector no. 1 ($n = 0.6$, $G_{H_2} = 1.7$ g/s) and (*2*) injector no. 2 ($n = 1.1$, $G_{H_2} = 1.8$ g/s).

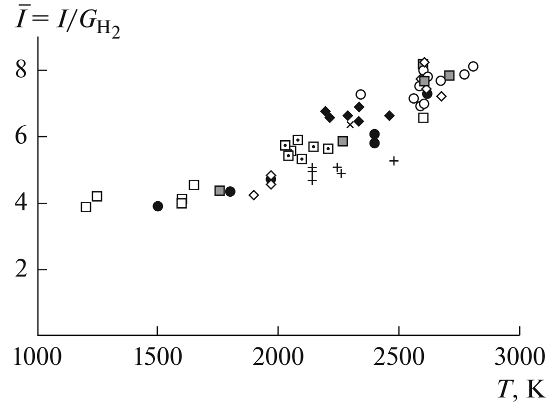

**Fig. 9.** Experimental data on a change in the OH* radiation intensity (normalized to the hydrogen flow rate) at different air flow temperatures and $G_{H_2}$ of 1.5–3.3 g/s, $T_0$ of 1200–2800 K, $P_0$ of $(5.5–8.3) \times 10^5$ Pa, and $M_{H_2}$ of 0, 2, and 2.7.

## DISCUSSION

The presented experimental results provide the possibility to use a new approach to the problem of the organization of an efficient working process in the combustion chambers of advanced high-speed aircrafts [16, 17]. The range of temperatures above 2000 K is very poorly studied due to the nearly no continuous setups operated in this regime and, therefore, the impossibility of the reliable verification of computational studies. Thus, it has been obtained in the calculations performed in the Central Institute of Aviation Motors in the 1990s that the losses for dissociation in a hydrogen–air mixture in a combustion chamber may attain 40% at temperatures above 2700 K [18, 19]. To decrease the negative effect of high temperatures, some variants of a chamber with an initial divergent section were considered to provide lower temperatures and more energetically advantageous equilibrium states from the viewpoint of dissociation losses. However, this direction of studies could not be further developed at that moment, as no direct experimental verification was performed. The presented experimental results are a direct confirmation for the hypothesis made at the Central Institute of Aviation Motors on the need for special profiling of a combustion chamber with allowance for a settled flow temperature.

## CONCLUSIONS

The performed experiments and literature analysis show that the hydrogen ignition delay is decreased at a high level of air flow temperatures, and the reaction zone shift into the outer zone of the mixing layer. This entails a decrease in the fuel–oxidizer mixing intensity and an increase in the flame length.

The applicability of the optical method of estimating the hydrogen combustion completeness by measuring the intensity of radiation from a short-living intermediate OH* radical has been confirmed. It has been shown that the upper applicability limit of this method lies at a level of 2000 K. On the other hand, an excess in the integral intensity $I_{\mathrm{OH}}$ over the maximally possible level for 100% combustion completeness may serve as "a mark" for the beginning of dissociation processes in an observed flame.

It has been shown that dissociation processes begin to produce a considerable effect on the combustion of hydrogen in a supersonic flow at high temperatures. This can be detected by a change in the integral intensity of radiation from the intermediate OH* radical, as it grows with an increase in the air flow temperature above 2000 K. Such processes may lead to a change in combustion regimes and a decrease in the efficiency of heat supply in combustion chambers. Deterioration in the combustion process due to dissociation is one of the problems requiring a solution at aircraft flight speeds above M = 8–10.

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