

Some Effects of Hydrogen Self-Ignition and Combustion in Supersonic Flow

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Abstract

Results are presented of computational and experimental investigations of the influence of temperature and flow composition on the hydrogen combustion kinetics for a coaxial fuel supersonic flow. Depending on the flow parameters, combustion is shown to occur with an intense heat release governed by the speed of chemical reactions, or a diffusion combustion with heat release governed by mixing. The computational results are in good agreements of with laboratory data and portrays many important features of supersonic combustion. The influence of the gas temperature and composition on the diffusion combustion of a circular hydrogen jet in supersonic coaxial flow at the over expanded exhaust regimes is investigated. It is found that at low flow temperatures ($T_2 \sim 900$ K) and in the absence of water vapors in the oxidizer gas composition, the speed of chemical reactions is the determining factor for combustion. An increase in the flow temperature ($T_2 > 1200$ K) causes a reduction of the induction time of the reactive mixture, because the mixing of fuel with oxidizer decreases, and a “sluggish” diffusion combustion of non-mixed gases is observed. The presence of water vapor and active radicals in the gas ensures the self-ignition from the start of the mixing, and the diffusion combustion mode is limited by mixing of the hydrogen jet with the coaxial flow (similar to the case with high initial temperatures of the air stream). In the case of the delay combustion process the maximum pressure level on the wall is 10% more than that in the combustion mode with ignition at the start of mixing. A sluggish combustion regime may lead to an incomplete hydrogen burnout.

Introduction

The combustion in supersonic flow with coaxial input of a central hydrogen jet into the air stream portrays many interesting features. Depending on the flow parameters, different intensity of heat release is realized and depends on both the process kinetics and the rate of fuel mixing with oxidizer. As the results of previous experiments [1, 2] indicate, one succeeds in obtaining intense combustion in a channel in the pseudo-shock mode. To achieve enhanced intense combustion mode and avoid thermal lockout in a channel of uniform section, it is necessary to either utilize flame stabilizers, or to monitor the hydrogen flow rate. The control of the pseudo-shock combustion mode is a separate complex problem [2, 3], and requires an accurate control of heat supply. In this case, the level of heat supply must be maintained after flow deceleration in the pseudo-

shock, so that the flow does not revert to subsonic condition [4].

The combustion process controlled by kinetic effects is possible via inhibiting additions, catalysis, temperature gradients, etc. [5, 6]. Also, various injectors and injection techniques have been developed for mixing enhancement [7, 8]. In most previous work, usually a single technique for combustion enhancement is, investigated without considering the effects of other factors. The air temperature increase is an example. Up to certain limits, this is a positive factor because it creates better conditions for the flame ignition and stabilization. However, at flight Mach numbers exceeding 8-10, high temperatures become a problem leading to combustion deterioration and a subsequent loss of the engine thrust. In this case, the flow stagnation temperature exceeds over 2000 K, and a high gas enthalpy and becomes insignificant [9]. Dissociation effects

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at high air temperatures are rarely studied experimentally, because of the difficulties of conducting the experiments at high temperature levels. This is due, to the complexity of the device, the difficulty of obtaining information with existing methods, and absence of experimental setups enabling a long-term realization of the modes with the flow stagnation temperature above 2000 K [10]. In this connection, there are no possibilities of a reliable verification of computational investigations for example [11]. Until recently, there has been no systematic research on the influence of dissociation on combustion in hypersonic ramjet engines; only a few experiments are conducted in shock tubes.

The influence of air pollution by heating products in fire heaters is another factor affecting experiments at high-temperatures. Several studies have been conducted [12-14], mostly computational; only in one study [15] is known among the direct comparisons.

In this work, the influence of kinetic factors related to the air stream temperature and composition on the hydrogen burnout process are considered under high initial temperatures ensuring the hydrogen self-ignition, including that above 2000 K. The problem is investigated by analyzing the experimental and computational data for the case of a coaxial input of hydrogen jet to supersonic air stream.

Experimental Setup and Measurement Techniques

Experimental investigations are conducted at the supersonic combustion setup of ITAM SB RAS [16]. The application of a plasmatorch for air stream heating is a feature of the setup. This enables a heated air stream without water vapor, which is always available in the setups using the fire air heating. The use of a plasmatorch with a power of 2 MW gives the possibility of conducting the experiments in the continuous operation regime with the stagnation temperature in the range 1500 to 3000 K. This is broader than that in most fire heaters.

Figure 1 shows the experimental setup. A three-chamber plasmatorch with the cylindrical cathode and anode and the backward-facing step at the outlet is used for air heating. Cold air is supplied to the prechamber, and mixes with the hot air emanating from the plasmatorch and is heated up to the temperature required in the experiment. The hydrogen is fed via the injector located along the axis of a supersonic ($M_2 = 2.2$) air nozzle with the exit diameter of 50 mm. Supply of extra active or passive mixtures to the prechamber is possible. The channels of various shapes are connected directly to the nozzle, or the jets exhaust into the ambient space. The primary results are obtained for the latter case.

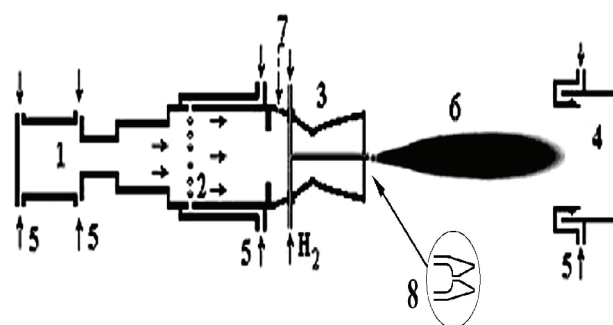


Fig. 1. Experimental setup diagram: 1 – electric-arc heater; 2 – prechamber; 3 – supersonic nozzle; 4 – ejector (exhaust system); 5 – air supply; 6 – flame; 7 – location of the mixtures supply to the prechamber; 8 – injector with a slanted outlet part ($M_1 = 2.7$).

The high temporal and spatial resolution and providing the radiation intensity in different spectral ranges directly from the flame are the primary of optical methods. These methods provide more comprehensive information about combustion, thus enabling the capture of physical effects. The registration in ultraviolet range of the emission of the excited intermediate radical OH (transition ${}^2\Sigma^+ - 2\pi$; $\lambda = 280\text{-}350$ nm) is the most informative for the hydrogen-air flame. To this end, an electrical optical transducer with an ultraviolet light filter was applied, which was matched with the technical vision camera. The obtained information enables determination of the flame structure, combustion intensity, and burnout completeness [17].

The injector has an external diameter of 10 mm and is located on the air nozzle axis used for a cocurrent hydrogen input. The Mach number of the central hydrogen jet is $M_1 = 1$ and 2.7; the H_2 flow rate amounted to 1.5-10 g/s. For the stream, the stagnation temperature T_{20} is in the range 1500 to 2800 K, the Mach number $M_2 = 2.2$, and the flow rate is 0.5-1 kg/s. The measurements are carried out in a region 0.8 m in length between the air nozzle exit and the ejector inlet.

Experimental

Our experiments indicate that at moderate stagnation temperatures of the air stream (up to 2000-2200 K), the basic heat release zones lie in the central part of the fuel jet where most of the burnout of the hydrogen occurs. As the stagnation temperature increases to the level of 2500-2600 K, the structure of combustion zones alters substantially. Flame recording shows that hydrogen oxidation occurs only in the external part of mixing zone and combustion is absent in the near-axis region. Figure 2 illustrates

the difference in the flame shape at moderate and high stagnation temperatures. In those experiments, the hydrogen flow rate was varied within broad limits (the air excess coefficient was varied from 2 to 12); the ignition delay length at temperatures below 2200 K was varied. At high temperatures, self-ignition occurred near the injector edge and there was practically no ignition delay (Fig. 2b).

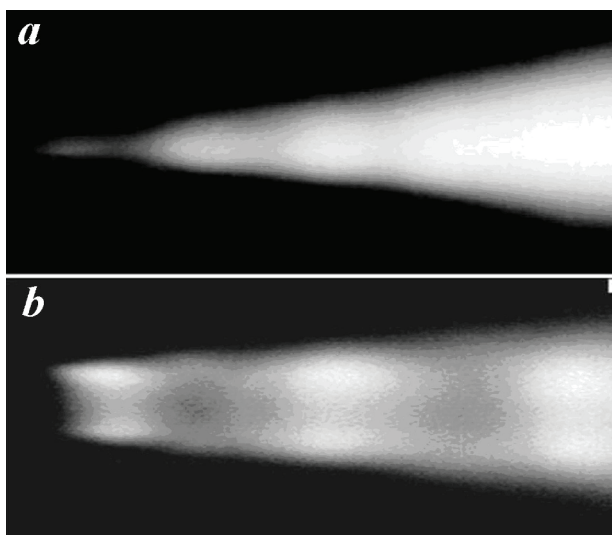


Fig. 2. Form of the initial interval of the hydrogen flame at different temperatures of the air stream. Direct photographs denoting the visible range of waves. $M_1 = 1$. $M_2 = 2.2$. a: $T_{20} = 2000$ K, b: $T_{20} = 2600$ K.

Figure 3 shows the flame shape in the ultraviolet range – the measurement results for the proper radiation of the OH radical under the stagnation temperature variation from 1850 K to the level of 2500-2600 K.

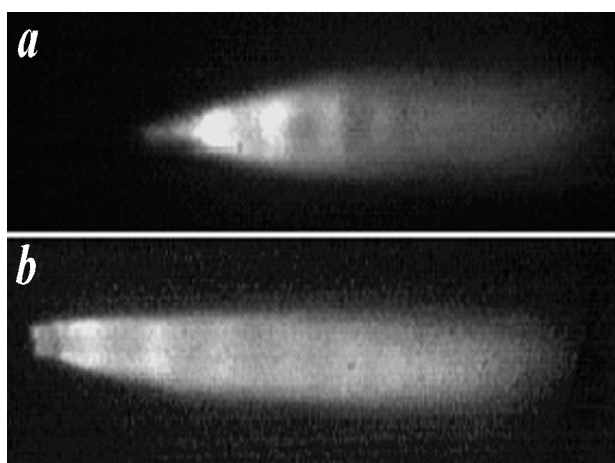


Fig. 3. The OH radiation intensity. $M_1 = 1$; $M_2 = 2.2$. a: $T_{20} = 1850$ K; b: $T_{20} = 2500$ K.

Figure 3 also shows the alteration of the hydrogen burnout with the air stagnation temperature variation. Zones with the elevated combustion intensity as well as the ignition locations shift to the external region of the mixing layer. Also, a comparison of the flame shape at temperatures 1850 K and 2500 K, shows that the flame length increases with the elevation of the air stagnation temperature.

In the next series of experiments, an injector is with a slanted outlet part (Fig. 1, notation 8). At the hydrogen input at the outlet, a separation zone formed near the injector, which acts like a flame stabilizer ensuring the ignition of H_2 . This causes self-ignition and combustion of hydrogen jet at different air stream temperatures without significant ignition delay. A typical two-dimensional distribution of the flame radiation intensity is presented in Fig. 4 in the ultraviolet region for two temperature levels. Figure 5 shows the integral distribution radiation intensity of the OH. One can see a considerable increase in the hydrogen torch radiation intensity in the ultraviolet range at an increase in the air stream stagnation temperature. The increase elevation of radiation may be due only to the appearance of additional excited OH radicals arising, in particular, after a thermal disintegration of the H_2O molecules – the final product of the chemical reaction. The alteration of the amount of the OH radiation intensity by the value of up to 40% was kept fixed in experiments at the air stagnation temperature increase from 1500 to 2800 K. A considerable increase in the integral radiation intensity is observed at the stagnation temperatures above 2000 K, which directly plays a considerable role of dissociation in high-temperature flows.

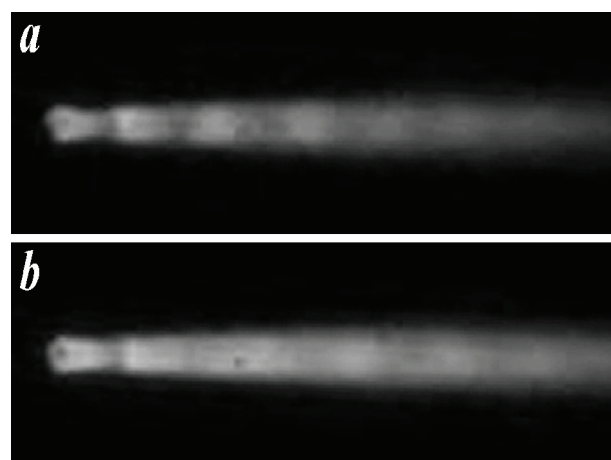


Fig. 4. Two-dimensional distribution of the OH radical radiation (injector $M_1 = 2.7$). a: $T_{20} = 1900$ K, $G_{H_2} = 2.9$ g/s, $P_0 = 6.3 \cdot 10^5$ Pa, b: $T_{20} = 2800$ K, $G_{H_2} = 2.6$ g/s, $P_0 = 6.7 \cdot 10^5$ Pa.

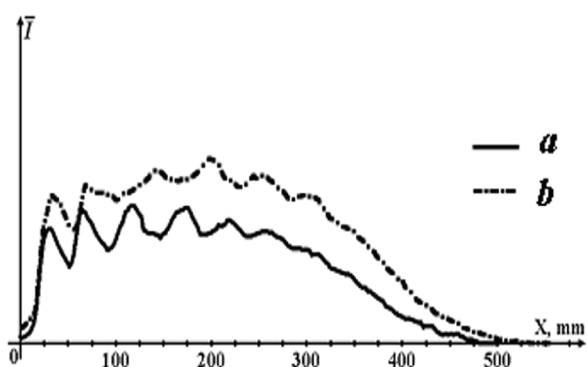


Fig. 5. Radiation intensity of the OH radical over the flame length (the parameters are the same as those in Fig. 4.).

To study the influence of radicals on the ignition and combustion, additional experiments were conducted, in which a small amount of chemically active substances – hydrogen peroxide H_2O_2 or pure hydrogen H_2 was fed into the prechamber at the distance of 220 mm from the nozzle exit (Fig. 1, notation 7). In previous computational work [5, 6] it has been shown that addition of H_2O_2 in the amount of less than 10% (by volume) in the methane-air mixture or in the CH_4/O_2 / air mixture with the initial level of temperatures $T_{20} = 1200 \div 2025$ K reduces the ignition delay time considerably. One can ensure the ignition of H_2 in a co-current supersonic air flow ($M_2 = 2$, $T_{20} < 1400$ K) by burning a part of H_2 in the prechamber or by a mixture of 10% H_2O_2 to the fuel [6]. In our experiment, pure hydrogen did not ignite under these conditions. The acceleration of chemical reactions is related to the radicals influence (including OH and H). It was, therefore, assumed that the input of chemically active mixtures to the prechamber directly ahead of the nozzle must contribute to the formation of active radicals and, thus, influence combustion. After passing the nozzle, these active radicals must affect the basic flame.

The input of hydrogen and hydrogen peroxide to the prechamber acted equally efficiently, the ignition delay time considerably reduced. The fraction of additions amounted to 5% of the main fuel flow rate. However, in this case, the torch length increased; that is the heat release rate decreased in the presence of active radicals within the air stream.

Figure 6 shows the flame configuration in the open jet at the switch-on and switch-off of the H_2O_2 input to the prechamber. It is observed that in the absence of the H_2O_2 , there is an ignition delay and the flame is separated from the injector. At an input of a small amount of H_2O_2 (~5% of the H_2 flow rate), the ignition delay is greatly reduced. The total flame length, however, increases because the process is controlled by mixing (fast kinetics). Thus, the igni-

tion delay time reduction can be obtained both by the air increase of the air stream temperature and at the use of promoting mixtures creating the active radicals. The heat release rate will, however, be limited in this case by mixing due to which the combustion zone length may even increase. Furthermore, an increase of the chemical reaction zone may occur because of the dissociation of the reaction products of the hydrogen with air, which was registered at high levels of the air stream deceleration (2200-2500 K and higher) this was revealed for the first time in Ref. [18].



Fig. 6. Hydrogen flame in a supersonic air jet. $M_2 = 2.2$; $M_1 = 1$. a: within input of hydrogen only; b: with input of hydrogen to the injector + H_2O_2 to the prechamber.

Computational Model

Mixing and reaction in a circular hydrogen jet in a coaxial supersonic air stream are investigated via computational simulation. The cold hydrogen jet with temperature T_1 flows into the hot air stream with temperature T_2 . The boundary layers on the nozzle and combustion chamber walls are assumed to be very thin because of high velocities of gases. The mixing zone starts from the nozzle exit, a reacting mixture form which self-ignites yielding combustion of the hydrogen (see Fig. 7).

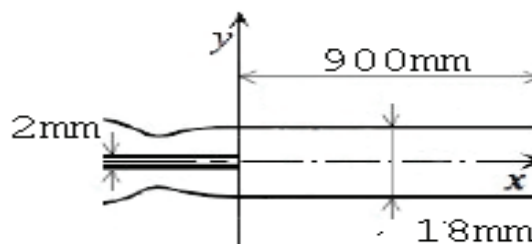


Fig. 7. Schematics of the cylindrical combustion chamber.

The flow is assumed to be supersonic in the direction of the chamber axis, the gas is assumed viscous, heat-conducting, and the flow regime is turbulent. The system of parabolized Reynolds-averaged Navier-Stokes equations are used to describe the flow [7, 19-21]. Hydrogen combustion in air is described by a multi-stage mechanism including 18 chemical reactions, in which there are eight active species including H, O, OH, H₂O, O₂, H₂, HO₂, H₂O₂ [5, 7, 17, 22, 23]. The nitrogen contained in air is assumed inert. The turbulent eddy viscosity coefficient ν_t is found by the, $k-\varepsilon$ turbulence model for compressible flow [24].

The influence of turbulence on of chemical reactions is taken into account with the model [22, 25, 26] for the unmixedness. The boundary conditions of the system of equations in the initial section of the jet and flow are specified in the form of constant values of transport variables. Symmetry condi-

tions are imposed on the combustion chamber axis. Boundary conditions on the combustion chamber wall are determined via reflection and using wall functions [5, 21]. The system of equations together with boundary conditions are solved by Beam and Warming method.

The simulated computational results are compared with the experimental data [22, 26]. Computations are conducted with $M_1 = 2.0$, $T_1 = 251$ K, $C_{H_2}^0 = 1.0$, $M_2 = 1.9$, $T_2 = 1495$ K, $C_{H_2O}^0 = 0.281$, $C_{O_2}^0 = 0.241$, $C_{N_2}^0 = 0.478$. The jet and the flow pressures were kept the same ($P_1 = P_2$). Figure 8 shows the distributions of the concentration of the vapors of water, oxygen and nitrogen at $x/d_1 = 8.76$, where self-ignition occurs. The computed values of concentration of water vapors C_{H_2O} , oxygen C_{O_2} , and nitrogen C_{N_2} (see notes on Fig. 8) denote self-ignition and are in fair agreements with experimental data [22, 26].

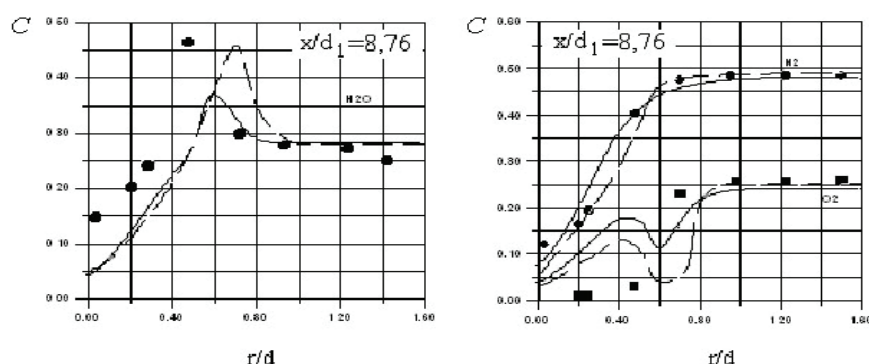


Fig. 8. Distributions of concentrations C_{H_2O} , C_{O_2} and C_{N_2} . (Present work; Computational results in Ref. [26], the dots are the experiment data in Ref. [22]).

Discussion of Results

The primary flow parameters are the imperfect expansion degree $n = p_1/p_2$, the Mach numbers of the jet M_1 and of the flow M_2 , the jet temperature T_1 and the flow temperature T_2 . The global coefficient of air excess is:

$$\alpha = \frac{G_{O_2}^0}{\theta \cdot G_{H_2}^0} \quad \theta = \frac{8 \cdot C_{H_2}^0}{C_{O_2}^0 + \frac{8}{3} C_{H_2O}^0}$$

where $G_{O_2}^0, G_{H_2}^0$ are the initial mass flow rates of oxygen and hydrogen, respectively, and θ is the stoichiometric coefficient. A listing of parameters in the computations is given in Table 1. The influence of these parameters on ignition and combustion is studied.

Figure 9 shows the concentration fields of the OH radical and temperature T for regimes 1 and

2 identified in the Table 1. For $T_2 = 980$ K, self-ignition starts at the distance of $x/r_1 = 140$ ($r_1 = 1$ mm is the jet radius), and combustion terminates at $x/r_1 = 250$. The hydrogen self-ignition and burnout occur in the near-axis zone (see Fig. 9 a, c). The fields of the radical OH concentration and temperature T show that under this condition, the speed of chain reactions is the determining factor for burnout.

An increase in the flow temperature up to $T_2 = 1270$ K results in hydrogen self-ignition which starts at the external boundary of the zone of mixing of the jet with the flow at the distance $x/r_1 = 60$ (see Fig. 9 b, d). It is known that in a high-temperature flow, the dissociation processes plays a major role. The extra excited O and OH radicals appear, in particular, after a thermal disintegration of the O₂ and H₂O molecules, initiating self-ignition (see Fig. 9 b, d). The decrease of the induction time decreases the length of the ignition delay by a factor of about two. Therefore, the conditions for mixing deteriorate,

which leads to an increase of the reaction zone (see Fig. 9, b, d). The computational predictions are in a qualitative agreement with experimental data.

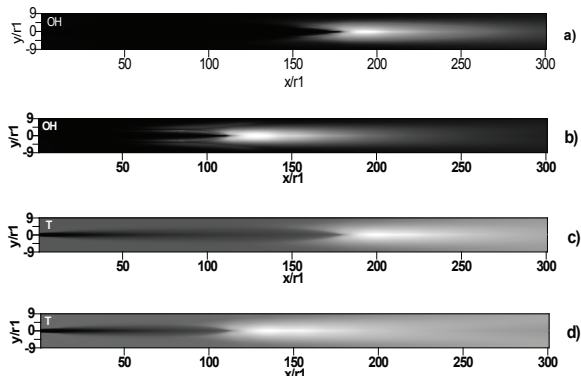


Fig. 9. Concentration of the OH radical (a, b) and temperature T (c, d) for the hydrogen combustion in supersonic flow: a, c: $T_2 = 980$ K, b, d: $T_2 = 1270$ K.

Table 1

Regime parameters modeling the “pure” (1,2) and fire (3,4) heating.

Parameters	Regime 1	Regime 2	Regime 3	Regime 4
Mach number of the jet M_1	2.0	2.0	2.0	2.0
Mach number of the flow M_2	2.2	2.2	2.2	2.2
Jet temperature T_1 , K	251	251	251	251
Flow temperature T_2 , K	980	1270	980	1270
Imperfect expansion degree n	0.7	0.7	0.7	0.7
Mass fraction of the jet hydrogen $C_{H_2O}^0$	0.4	0.4	0.4	0.4
Mass fraction of the jet nitrogen $C_{N_2}^0$	0.6	0.6	0.6	0.6
Mass fraction of the flow oxygen $C_{O_2}^0$	0.232	0.232	0.232	0.232
Mass fraction of the flow water vapor $C_{H_2O}^0$	0.0	0.0	0.281	0.281
Mass fraction of the flow nitrogen 2 $C_{N_2}^0$	0.768	0.768	0.487	0.487
Global coefficient of the excess air α	5.7	5.7	8.7	8.7

Similar prediction are obtained for the value of temperatures of the supersonic flow at $T_2 = 1016$ K and $T_2 = 1321$ K. At $T_2 = 1016$ K, self-ignition and burnout occur in the near-axis zone, and at $T_2 = 1321$ K at the external boundary of the mixing zone, the length of the zone of chemical reactions increases with the temperature increase. Thus, it is concluded that at low flow temperatures (below 1100 K), the self-ignition delay leads to the formation of a mixture close to the homogeneous one, which leads to an intense chemical reactions with a hydrogen burnout in the near-axis zone. In the case of high flow temperatures, the process is limited by mixing of the hydrogen jet with the coaxial flow; therefore, the combustion zone length increases. High temperatures lead to dissociation of reaction products, which also increases the size of the reaction zone. A considerable alteration of the hydrogen burnout character with the stagnation temperatures from “low” (below 2000-2200 K) to “high” (2200-3000 K) temperatures has been also noted in Ref. [27].

In several previous experimental investigations [2, 7, 26], high-temperature flow is formed by combustion products, which are enriched by oxygen and contain water vapor. Here, the influences of the flow composition on combustion are studied. Figure 10 shows the concentrations of the OH radical and temperature T for regimes 3 and 4 of the Table 1.

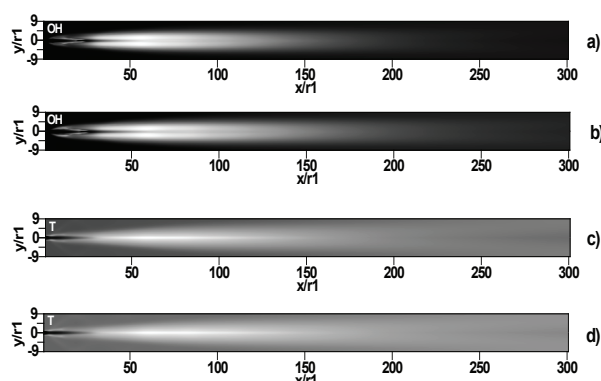


Fig. 10. Concentration of the OH radical (a, b) and temperature T (c, d) for the hydrogen combustion in supersonic flow: a, c: $T_2 = 980$ K; b, d: $T_2 = 1270$ K.

The self-ignition occurs from the start of the mixing (see Fig. 10). The OH radicals initiate self-ignition directly in the zone of the fuel in contact with oxidizer accelerating the ignition but slowing down the mixing process. Such an influence is qualitatively similar to the above-described influence of promoting additions at their input to the prechamber (Fig. 6).

Increasing of the Mach number of the hydrogen jet to $M_1 = 2.7$, self-ignition also occurs from the start of the mixing (see Fig. 11). The increase of the jet Mach number decreases the mixing, and the reaction zone extends up to $x/r_1 = 250$. This is consistent with known experimental data on the mixing reduction with increase at the Mach number.

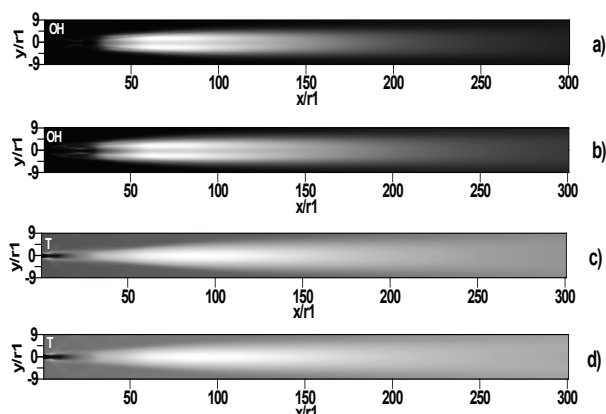


Fig. 11. Concentration of the OH radical (a, b) and temperature T (c, d) for the hydrogen combustion in supersonic flow: a, c: $T_2 = 980$ K; b, d: $T_2 = 1270$ K, $M_1 = 2.7$.

In summary, the computational results indicate: 1) When the air composition does not change after heating, the flow temperature affects self-ignition and combustion significantly. At low flow temperatures, the self-ignition delay increases, and as a consequence, a better mixing of the jet with flow leads to formation of a homogeneous mixture, which

burns out quickly in the near-axis zone. At high flow temperatures, the self-ignition delay reduces, and the combustion process is determined by mixing; 2) With addition of a considerable amount of water vapor, self-ignition of non-mixed gases occurs from the start of mixing.

The pressure alteration on the channel wall is also studied computationally. Combustion is known to influence the pressure field significantly [2, 5]. Figure 12 shows the computed data for the ratio of the pressure on the chamber wall and the flow stagnation pressure. Heat release gives rise to the compression and under pressure zones (which is noted as the pressure oscillation on the wall, see Fig. 12 a, curve 1). Upon termination of combustion, the pressure decreases monotonically. With $T_2 = 1270$ K, the pressure also grows from the self-ignition location (see Fig. 12 b, curve 2). A similar pressure oscillation is observed.

The presence of water vapor in the air composition and the self-ignition initiation lead to an abrupt pressure increase at the exhaust (see Fig. 12 a, curve 3). Agitation waves subsequently affect mixing of hydrogen with air, and thereby accelerate the chemical reactions, and the pressure increases with some oscillations. Comparing computed data one can note that a sluggish combustion reduces the maximum pressure increase (which is especially appreciable in Fig. 12 a).

The pressure increase depends on the intensity of chemical reactions. In our computations, the intense passing of the process (observed in the ignition delay presence) increases the pressure by 10% as compared to without the ignition delay.

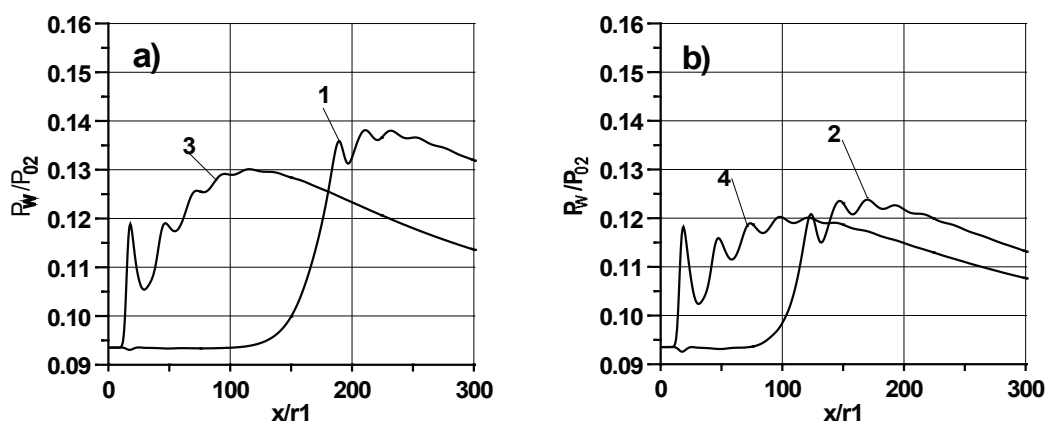


Fig. 12. Pressure distribution on the combustion chamber wall: The labels correspond to the regime parameters in Table 1.

Conclusions

The Summary and the Conclusions drawn from the Present work are itemized below:

1. The influence of the gas temperature and composition on the diffusion combustion of a circular hydrogen jet in supersonic coaxial flow at the over expanded exhaust regimes is investigated.

2. It is found that at low flow temperatures ($T_2 \sim 900$ K) and in the absence of water vapors in the oxidizer gas composition, the speed of chemical reactions is the determining factor for combustion. An increase in the flow temperature ($T_2 > 1200$ K) causes a reduction of the induction time of the reactive mixture, because the mixing of fuel with oxidizer decreases, and a "sluggish" diffusion combustion of non-mixed gases is observed.

3. The presence of water vapor and active radicals in the gas ensures the self-ignition from the start of the mixing, and the diffusion combustion mode is limited by mixing of the hydrogen jet with the coaxial flow (similar to the case with high initial temperatures of the air stream).

4. In the case of the delay combustion process the maximum pressure level on the wall is 10% more than that in the combustion mode with ignition at the start of mixing. A sluggish combustion regime may lead to an incomplete hydrogen burnout.

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