AN OPTICAL STUDY OF PROCESSES IN HYDROGEN FLAME IN A TUBE

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In the present study, to investigate into hydrogen combustion in an air flow, we registered the radiation intensity due to electron-excited OH radicals in the wavelength range 280-340 nm [1-3]. We examined correlation- and autocorrelation spectra for the local pulsations of glow intensity and acoustic pulsations produced by the flame. The experimental scheme is shown in Fig. 1. Gaseous hydrogen was fed into injector (1), which was positioned in a vertically installed transparent quartz tube (2). The diameter of the injector hole was $d = 1$ mm. The rate of the hydrogen flow was determined from the pressure drop across a hydroresistance included into the hydrogen supply system (3). To monitor the emission intensity due to OH radicals, we used an optical system that contained a narrow-band optical filter (4), a quartz lens (5), and a photomultiplier (6) FEU-39A. The transmission factor of the quartz tube in the UV spectral region was no less than 90%. The flame noise was measured by a piezoceramic sensing element (7) I4310 that was located near the lower end of the quartz tube. Between the tube and the optical system, an opaque screen (8) was installed with a horizontal slot of 3-mm height. The screen could exert displacements along the tube on a traversing gear with a rheochord, which enabled us to scan the emission intensity along the tube length. The output electric signals generated by the optical system, acoustic emission detector, rheochord, and hydrogen flow meter were simultaneously recorded by a multi-channeled magnetograph (9) (NO 67) with a channel bandwidth of 20 kHz. The spectral and correlative analyses were carried out on a personal computer (10) using the recorded data.

A number of experiments were performed with removed quartz tube or screen, which allowed us to register the radiation emitted by the diffusive hydrogen flame. Additionally, photographs of the flame in the UV and visible spectral regions were taken. In the first case, instead of the secondary emission photocell, in the optical system we used an electron-optical image intensifier equipped with a camera. In the second case, only the camera was used.

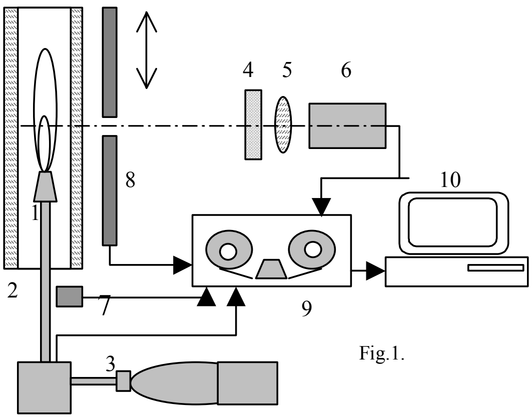

Fig.1.

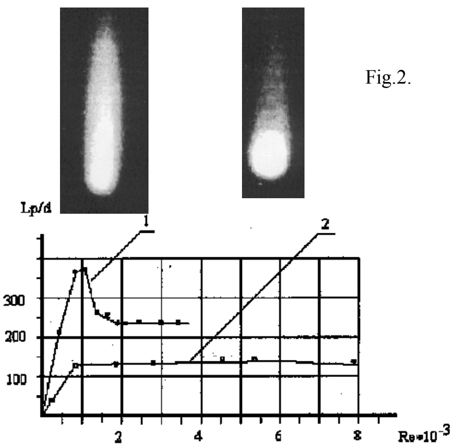

Fig.2.

Report Documentation Page

Report Date	Report Type	Dates Covered (from... to)
23 Aug 2002	N/A	-

Title and Subtitle An Optical Study of Processes in Hydrogen Flame in a Tube	**Contract Number**
	Grant Number
	Program Element Number
Author(s)	**Project Number**
	Task Number
	Work Unit Number
Performing Organization Name(s) and Address(es) Institute of Theoretical and Applied Mechanics Institutskaya 4/1 Novosibirsk 530090 Russia	**Performing Organization Report Number**
Sponsoring/Monitoring Agency Name(s) and Address(es) EOARD PSC 802 Box 14 FPO 09499-0014	**Sponsor/Monitor's Acronym(s)**
	Sponsor/Monitor's Report Number(s)

Distribution/Availability Statement
Approved for public release, distribution unlimited

Supplementary Notes
See also ADM001433, Conference held International Conference on Methods of Aerophysical Research (11th) Held in Novosibirsk, Russia on 1-7 Jul 2002

Abstract

Subject Terms

Report Classification unclassified	**Classification of this page** unclassified
Classification of Abstract unclassified	**Limitation of Abstract** UU

Number of Pages
6

Figure 2 exemplifies application of various optical methods to studying flames. Curve 1 shows the relative length of the diffusive hydrogen flame as a function of the hydrogen-jet Reynolds number [4]. The authors of [4] extracted this dependence treating images of flames in the visible light. At the same time, in the UV spectral region the flame length obeys another dependence (curve 2). For a laminar hydrogen jet (Reynolds number $Re < 10^3$ according to the classification of [5]), a linear growth of the hydrogen-flame length with the hydrogen flow rate was observed, whereas for a turbulent hydrogen jet (Reynolds number $Re > 10^4$ [5]), the flame length remained almost constant and varied only *weakly* with the flow rate of hydrogen. For a subsonic jet flow, flame images display an elongated shape of flame. An elongated bright burning zone is distinctly seen. For comparison, Fig. 3 shows how a hydrogen flame appears in the UV for a supersonic hydrogen jet ejected from a bleed. The burning zone looks as an almost ideal sphere with a weak conical feature attached to it. The images shown were obtained for hydrogen flow rates 0.85 and 1.48 l/s.

Figure 3 shows four photographs of the flame in tube. The tube with the inner diameter 18 mm had the length L=180 mm. Photographs (a), (b) and (c) were taken in the visible light, and photograph (d) in the UV spectrum. The latter photograph was given an additional treatment on a computer to sharpen the picture contrast. Marks 1, 2, and 3 in the figure indicate the position of the lower end section of the tube, that of the spray orifice in the tube, and that of the upper end section of the tube. All the images are aligned with respect to these marks. Photos (a), (b), (c), and (d) are taken for the volume rates of hydrogen flow Q = 0.66, 1.2, 1.56, and 1.58 l/s. The critical flow rate for the transition from a subsonic to a supersonic jet is about 1.1 l/s. Photos (a) and (b) refer to the first mode of the vibratory flame, for which a moderate value of the sound level is typical and the flame above the upper end section of the tube (outside plume) has an elongated shape. The first stage of vibratory burning is observed already at Q<0.4 l/s, i.e., when the hydrogen jet is subsonic. Photo (c) shows a typical situation at the second stage of vibratory burning (developed vibratory burning); the transition to this stage with increasing Q happens abruptly, with a sharp rise in the sound level and a change in the flame shape. The

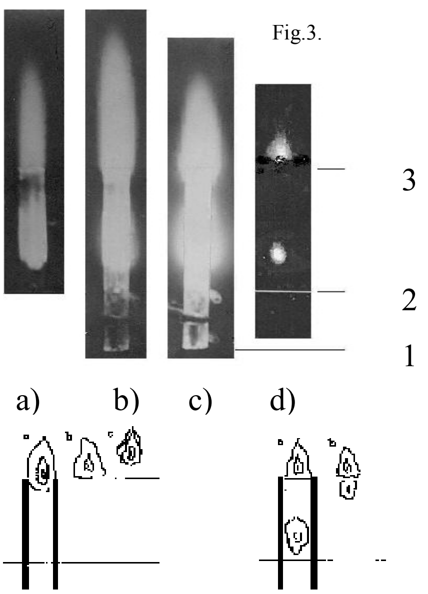

Fig.3.

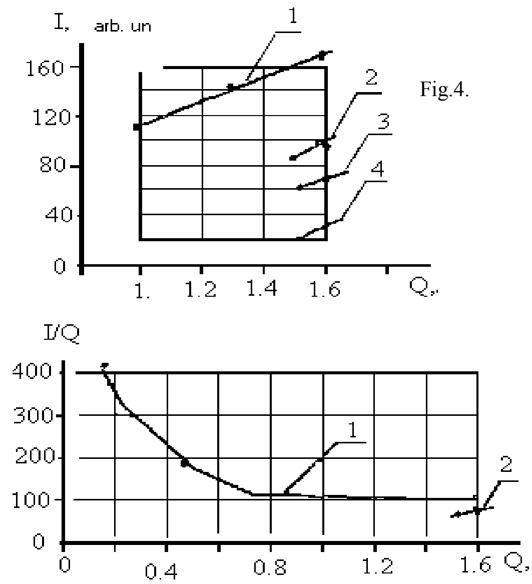

Fig.4.

flame gets thrown onto the external surface of the tube, and the length of the outside plume decreases. The bright area in the central part of the photos is a region where the burning is most intensive. In photo (a), a dark zone is seen in the upper part of the tube. This observation shows that the burning process is interrupted inside the tube and hydrogen afterburning occurs above the upper end section of the tube already after the hydrogen gets mixed with air. The newly formed mixture gets ignited due to the high temperature of the gases emanating from the tube. The images taken in the UV spectral region for the flames shown in photos (a) and (b) display only little difference from photo (d). This difference is only in the position of the bright burning zones. The lower zone (first burning zone) lies closer to the injecting orifice, whereas the upper zone (second burning zone) is situated closer to the upper end of the tube. These photos are not shown here. In the case of a developed vibratory burning (photos (c) and (d)), the position of the first burning zone is as follows: the lower end section of the glow region is situated at $l/2L = 0.22$, whereas its upper end section at $l/2L = 0.29$, i.e., the region where heat releases most actively lies in the middle part of the tube, which, according to the theory of vibratory burning [6], constitutes one of the necessary conditions for occurrence of vibratory flame modes. The upper heat-releasing zone is situated above the tube section $0.51 < l/2L < 0.57$; according to the theory, the heat release in this zone cannot cause any vibratory burning mode. Here l is the separation between the lower end section of the tube and the radiating zone. The excess in the amount of injected hydrogen and the deficit of the air injected into the tube during the burning furnish a clear explanation to the flame discontinuity, but, as will be shown below, the burning process may follow different scenarios. The phenomenon of burning-zone disintegration into two zones can be observed in the visible light in experiments with propane combustion in a tube. Shown are flame sketches for various tube diameters and various propane flow rates, determined by the nozzle diameter. In the case of small tube diameters (the image at the left), the propane-air mixture burnt in the outside plume. Under these conditions, no sound was generated. With increasing tube diameter, the air ejection factor also increased, and the burning of rich fuel mixture occurred inside the tube. If the burning zone was situated in the middle part of the tube, an intense sound was generated in full compliance with the solutions given by the linear theory. At the same time, occurrence of separated burning zones gave rise to no sound at all if the separated flames were situated near the upper end section of the tube, also in compliance with the linear theory of vibratory burning [6].

Figure 4 shows the measurement data and compares the measured UV intensities from the diffusive hydrogen flame and from the flame in the 18-mm-diameter tube. Along the abscissa axes, the volume rate of hydrogen flow Q is plotted. In Fig. 4 (a), plotted along the ordinate axis is the glow intensity I (in arbitrary units). In Fig. 4 (b), plotted along the ordinate axis is the I/Q ratio (also in arbitrary units). Curves 1 and 2 show the measurement data for the diffusive flame and for the flame in the tube, respectively. Curve 3 shows the glow intensity from the outside plume, whereas curve 4 shows the glow intensity from the burning zone near the orifice plug. The sum of these intensities equals the total glow intensity shown by curve 2. The glow intensity from the outside plume is higher than that from the burning zone near the orifice plug. The region in the tube in between the heat-releasing zones is almost invisible in the UV spectral region. A comparison of the glow intensities from the diffusive flame and from the flame in the tube have shown that the total UV radiation emitted during the vibratory burning is lower than that from the diffusive flame, i.e., the emitted intensity is determined by the combustion process and by the dimensions of the burning zones. The observed behavior of the I/Q ratio with the flow rate Q for the diffusive flame is quite typical of such flames; it was previously reported in many other studies. For a laminar flame in the range of flow rates

$Q < 0.7$ l/s (the injected-jet Reynolds number below 1500 [5]), with Q increasing from 0 to 0.7 l/s the relative glow intensity decreases rapidly and then flattens out. The latter observation is indicative of a transition to a turbulent burning that features a linear relation between the glow intensity and the rate of hydrogen flow. There are some data in the literature which show how the diffusive-flame length varies with the rate of hydrogen flow [4, 7]. The length of a laminar diffusive hydrogen flame increases with Q, whereas in the case of a turbulent burning the flame length remains constant and independent of the rate of hydrogen flow, which regularity was also found to be the case in the present study. It should be noted that the relative glow intensity from the flame in the tube increases with Q and seemingly should saturate at a level characteristic for the diffusive flame. Here, the main portion of the intensity emitted from the flame in the tube falls on the intensity emitted in the outside plume, where the burning is turbulent.

Fig.5.

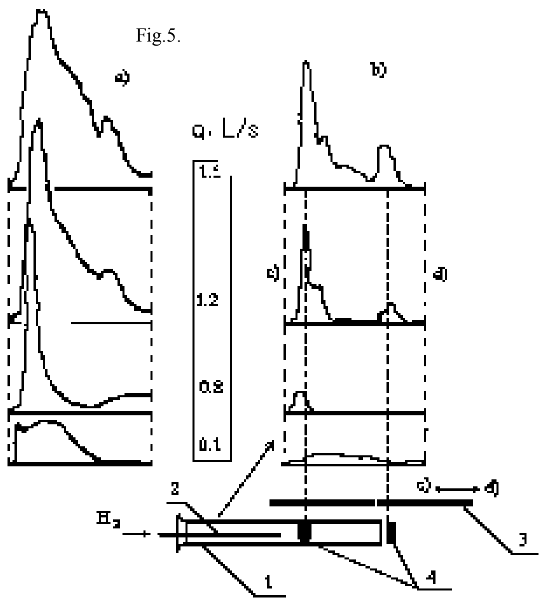

Figure 5 shows the measured intensity of the steady (below 5 Hz) and alternate (from 5 Hz to 20 kHz) UV-emission components during hydrogen combustion in a vertical tube with length 233 mm and inner diameter 23 mm. For the sake of convenience in representing results, the tube in this figure is shown as if it were horizontal. Symbols (c) и (d) show the ultimate positions of the screen; in Fig. 5b these positions are shown as vertical lines. The image of the tube with the screen is properly aligned with Fig. 5b and the scale is the same as in Fig. 5a. Figure 6a shows the distributions of the permanent glow-intensity component for various rates of hydrogen flow. The flow rates are listed in the table. Figure 6b shows the amplitude of glow intensity pulsations for the same rates of hydrogen flow. At $Q = 0.1$ l/s, the amplitude of the pulsations is ten times increased. The data of Fig. 5a shows that the combustion processes occurring at different rates of hydrogen flow differ drastically from one another. For the flow rate 0.1 l/s, a complete combustion of hydrogen inside the tube was observed without any developed glow-intensity pulsations (and no sound was generated here). An increase in the rate of hydrogen flow for the case of a subsonic hydrogen jet gave rise to a vibratory burning. In this case, at $Q = 0.8$ l/s a predominant portion of the hydrogen burns in a narrow zone near the orifice plug. A smooth rather than abrupt decrease in the glow intensity almost down to zero seems to be due to thermoluminescence of combustion products. The hydrogen afterburning takes place in the outside plume after the outflowing gases get mixed with atmospheric air. Here, the contribution due to the pulsating component to the total glow intensity is small. The incomplete combustion of hydrogen inside the tube was likely caused by thermal choking of the ejected air flow, which in turn had resulted in an excess of hydrogen in the air-hydrogen mixture upstream of the burning zone. In the case of a supersonic hydrogen jet (Q=1.2 l/s), the flame moves farther from the orifice plug, and the average glow intensity from the burning zone near the orifice plug starts decreasing. Simultaneously, the glow intensity from the outside plume also starts increasing. The contribution due to the pulsating emission component to the total glow intensity also increases. Almost zero amplitude of the glow-intensity pulsations in between the two burning zones is indicative of no flashbacks along the tube.

In the graph for the mean glow intensity from the region between the two burning zones, the descending curve exhibits a sharp kink that may be indicative of ceasing of the burning in the first zone. Further behavior of the glow intensity reflects thermoluminescence due to combustion products behind the first zone. The temperature of these products gradually decreases owing to heat removal through the walls, and the glow intensity decreases. The above tendencies become more pronounced as the rate of hydrogen flow increases. The contribution of the pulsating component to the total emitted intensity increases, whereas the mean glow intensity from the first burning zone decreases.

With the quartz tube 48 mm in diameter, to observe the developed vibratory burning modes, it was necessary to ensure the rate of hydrogen flow ~5 l/s. The stagnation temperatures of injected and ejected gases being identical, the ejection factor is known to vary in proportion to the ejector nozzle cross-sectional area and to the reciprocal of the total hydrogen pressure [8]. On assumption that the stationary relations are still applicable to ejectors that work under non-stationary operation conditions, an estimate of the excess factor of air in the described experiments, obtained with due allowance for the difference in the specific heats of air and hydrogen and the thermal choking of the flow, gives values which may be both greater or smaller than unity.

To explain these observations, we propose the following scheme of combustion processes. Figure 6 shows the inflammability range of hydrogen [9]. In the graph, plotted along the abscissa axis is the volume percentage of hydrogen in the air-hydrogen mixture, and along the ordinate axis is the content (by volume) of inert additives in air. The inflammability region is the region bounded by the curve and by the abscissa axis. Beyond this region, no burning is possible. The inert additives are water, nitrogen, etc. It is well known that the inflammability range of hydrogen widens with increasing temperature and pressure, but this circumstance is ignored in the present qualitative description. The ejector diagram and position of burning zones are shown under the graph. Shown in the scheme are the quartz tube (1), the burning zone (2), and the regions where quartz deterioration occurs (3) (in the experiments, the outer surface of the tube in these regions scaled off and became lusterless). Points (a), (b), (c) and (d) show the positions a certain gas volume occupies at different times as the gas flows through the tube. The same points are also indicated in the graph that shows the inflammability range. The arrows show the path of motion of the chosen gas volume. Several possible scenarios of the burning process

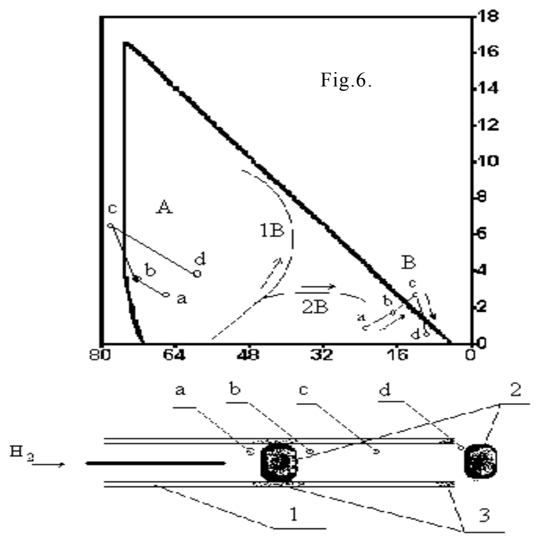

Fig.6.

can be figured out inspecting this graph. If for the air excess factor we have $\alpha < 1$ (scenario A), then the process proceeds in a commonplace manner. The burn-out of a certain part of the injected hydrogen and of almost all the oxygen available in the ejected air in the first burning zone gives rise to formation of inert additives in the form of water and residual nitrogen, which leads to coming out beyond the inflammability range and ceases the burning. The burning resumes after the resultant gas mixture leaves the tube and gets mixed with atmospheric air (point (d)). The ignition behind the tube exit happens due to the high temperature of the outflowing gases. Such burning regimes, if the region where the heat releases most actively (the first burning zone) lies in the middle part of the tube, display development of acoustic vibrations, in line with the theory of vibratory burning [6]. The burning process may take another course after adding an oxidant to the gases behind the first burning zone or after extracting inert additives (water or nitrogen) from them. The flame behind the tube outlet may also be extinguished if measures are taken to decrease the temperature in the region between the first burning zone and the tube outlet. The hydrogen survived in the first burning region will no longer ignite outside the tube. Another burning scenario (scenario B) is possible if $\alpha > 1$. The burning of hydrogen in the first zone leads to formation of inert additives in the form of water and air nitrogen after some part of oxygen burns out of the ejected air. Coming out of the inflammability region (point (c)) will quench the burning in the tube. Ignition of air behind the tube outlet will occur after the dilution of outflowing gases with atmospheric air, which will result in a decrease of the relative inerts content (point (d)). Development of acoustic vibrations at $\alpha > 1$ in the case where the heat-releasing zone is situated near the middle of the tube is predicted by theory [6]. Alternation of the combustion process in this case may be organized in various manners, for instance, via introduction of an additional portion of hydrogen into the tube past the first burning zone (shown by curve 1B in the graph) or via supply of an additional oxidant (curve 2B). Decreasing the gas temperature behind the first burning zone (for instance, by removing the released heat from tube walls), it is possible to totally eliminate the outside plume, which will result in an egress of a certain amount of hydrogen into atmosphere.

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