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EXPERIMENTAL STUDY OF THE LENGTH AND STRUCTURE OF A FREE-DIFFUSION BURNING-GASES FLAME

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Experimental studies of the length of vertical isolated burning flames with hydrogen and methane outflow from cylindrical nozzles of diameter 2, 3, 5 and 10 mm into the atmosphere at Re_0 = 100–6800 have been made. The data obtained have been approximated by simple calculated dependences. The application of various methods for recording the length of a luminous flame (visual, black-and-white photography, video and digital cameras) has made it possible to not only explain the discrepancies between sizes but also record (at short exposures) elementary bending bright cylindrical jets creating, when superimposed on the another, one known spindle-shaped form of the flame.

Keywords: *combustion, flame, length of burning jets, laminar and turbulent regimes.*

Introduction. The combustion intensity of gaseous fuels outflowing into the oxidizer volume both in the form of isolated jets and their combination is of great practical interest, since exactly this parameter determines the sizes of all kinds of furnaces and combustion chambers. One major characteristic of the combustion intensity is the length of these burning jets (flames), i.e., the distance at which the fed combustible gas has time to react with the oxidizer and even somewhat cool off (lose luminescence). Such burning jets are called diffusion flames and their investigation has been the subject of many works. Analysis of many of them was performed in monographs [1–4], which became classical. It is thought to be an established fact that on going from laminar to turbulent combustion, as a consequence of the mixing intensification, the rate of combustion increases and, consequently, the flame length L decreases and becomes asymptotic, remaining practically unaltered with increasing outflow rate U_0.

An additional dependence of L/d_0 on the nozzle diameter d_0 was obtained in processing a large array of experimental data on the height of the burning hydrogen flame [5]. Figure 1 presents the dependence of the relative height of the flame on the Reynolds number (Re_0) of the outflowing jet in a wide range of nozzle diameters d_0 (from 1.45 to 51.7 mm). Lines *a–a* and *b–b* delineate the regions of laminar (A) and turbulent (B) flames. Between them the transition region (C) is situated. In the laminar region (for better illustration the region of $\mathrm{Re} \leq 2000$ is "extended" along the abscissa axis by a factor of 4), there is a strong (to power $n = 0.5$) dependence of the flame height L on the Reynolds number Re_0 and on the nozzle diameter d_0, and in the turbulent region a weaker dependence on Re_0 (n = 0.2–0.3) but as strong on d_0 is observed. In the transition region C, after the *a–a* line there is either a sharp decrease in the flame height in the case of outflow from small-size nozzles or a bend of the curve ($L/d_0 = f(\mathrm{Re}_0)$) at medium and large values of d_0. The region C, rather wide in terms of Re_0 for small diameters d_0, narrows significantly (several times) on passing to large d_0. In so doing, while for small-diameter jets ($d_0 \approx 1.5$ mm) the critical value of Re_{cr1}, at which the transition from laminar to turbulent combustion begins, is equal to 2300, i.e., it is close to the Re_{cr} value for pipes, but already at $d_0 = 15$ the value of Re_{cr1} decreases to 1800.

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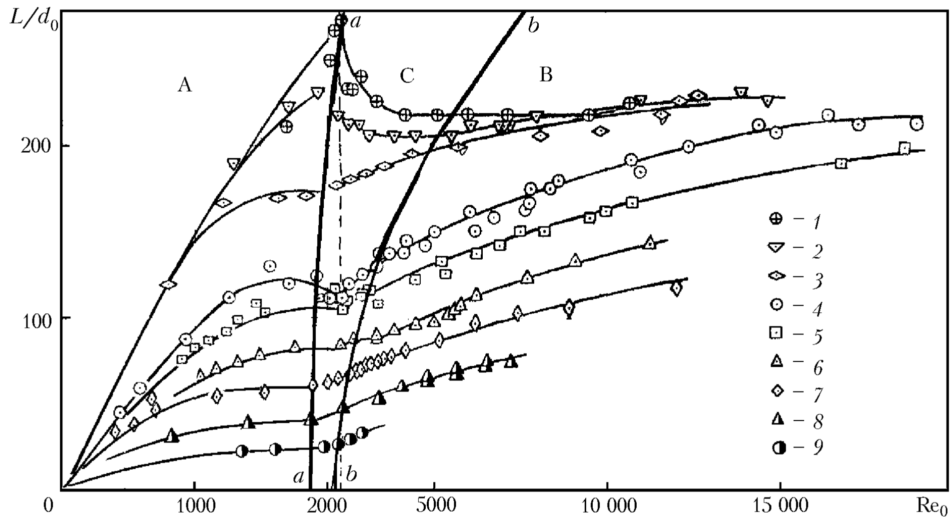

Fig. 1. Dependence of the relative height L/d_0 of vertical flames of burning hydrogen on Re_0 in a wide range of change in d_0 [5]: 1) d_0 = 1.45 mm; 2) 1.9; 3) 2.9; 4) 4.0; 5) 6.0; 6) 10.75; 7) 15.5; 8) 21.9; 9) 51.7.

In the turbulent region, we can see one more specific feature of the dependence of the relative height of the flame on the nozzle diameter: In the range of 3 mm $\le d_0 \le$ 52 mm the L/d_0 value is inversely proportional to $d_0^{0.5}$, whereas at $d_0 < 3$ mm its influence is practically not manifest.

As is seen from Fig. 1, the laminar region has been investigated only at Re > 600, and at smaller Reynolds numbers additional investigations are needed. This was the immediate aim of the present work.

In [5], the L value was determined from the photographs of the flame located near the scale rule on black-and-white film. In many previous investigations this was done visually and the values of L/d_0 differed somewhat. Therefore, comparison between different measuring techniques for L, including the present-day methods and color printing, as well as an attempt to describe the structure of the flame are of certain interest. This was another aim of our work.

Experimental Facility and Method of Investigation. Experiment were performed at the M. V. Keldysh Center on the ad hoc facility schematically represented in Fig. 2. A combustible gas (hydrogen or methane) was supplied from the header 1 through the pressure regulator 2 with a controlling valve 3 to the experimental section 4 representing a collector with a cylindrical nozzle 5. The gas flow rate was measured either by a PM-02-type rotameter 6 or at large flow rates by the measuring nozzle 7. To obtain the least possible flow rates, the gas flow from the collector was split, i.e., was supplied through three identical specially calibrated nozzles sufficiently widely separated from one another to avoid their mutual influence. Combustion of the gas was triggered by a special device. To determine the flame height L, a scale rule 8 was set adjacent to the nozzle. Recording of L was carried out by a photochronograph 9 in four ways: visually, by means of photography on black-and-white film, by a VM-C3700 video camera, and a Nikon CoolPix870 digital camera. The last two methods provided a sharp image of the whole flame with account for the weak glow of its upper part whose color with increasing height approached dark-orange with a gradual loss of its visibility against the black background. The visual determination of the upper boundary of the flame is the least reliable and depends on the quality of observers' eyesight in the absence of a concrete objective estimate of this quality, as well as on the working conditions. For instance, according to [6], "in investigating hydrogen flames in the case of gas outflow from a hole of diameter 4.6 m, it appeared that the visually observed length of the flame in a darkened room was larger by 10% than the length of the flame in a lighted room." As for the black-and-white photography, as is known, it just does not react to the dark-orange color.

Photography with a video camera made it possible to observe the dynamics of the jets, especially the pulsating flow of the turbulent flame in its upper part at large Re_0 numbers.

In the experiments, we used for nozzles cylindrical tubes of diameter 2, 3, 5, and 10 mm with a relative length of 15 calibers. The output edge of the tubes was sharp.

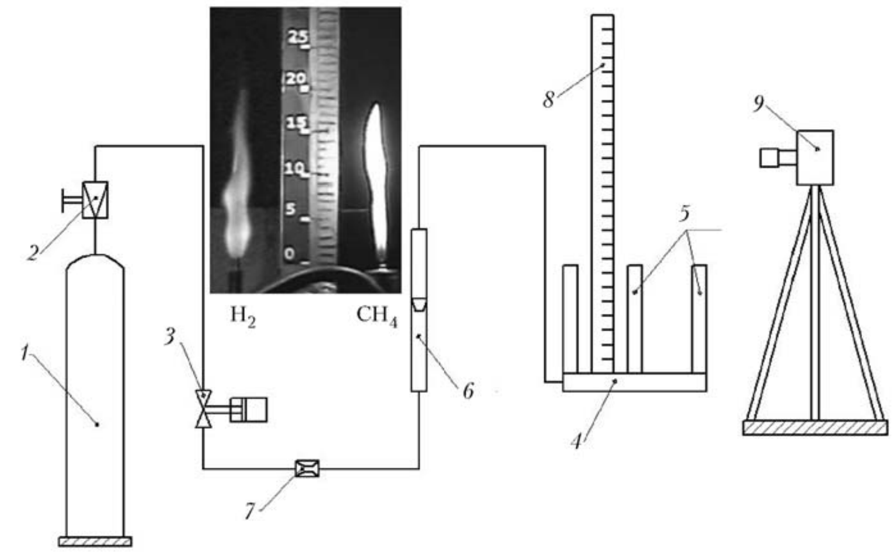

Fig. 2. Schematical representation of the experimental facility and characteristic black-and-white photographs of burning laminar flames of hydrogen and methane. Re_0 = 400, d_0 = 3 mm.

The experiments performed with burning flames of hydrogen and methane outflowing from nozzles of diameter 3 and 5 mm have shown that the values of the lengths of flames at Re_0 = 167–2000 recorded by a video camera practically did not differ from the lengths determined visually, whereas the black-and-white photographs underestimate L by a value of up to 40–50 mm.

In the transition and turbulent regions of burning of jets at $Re_0 > 2000$, measurements of the length of flames made visually and by means of a video camera gave a large spread, which is due to the change with time in the position and the configuration of the upper part of the flame. The upper boundary of the flame, as follows from the relatively high-speed photographs obtained with a short exposure, represents luminous regions with clearly defined, sometimes widely spaced boundaries. It should be noted that such a complex temporal configuration (breaks of jets, eruptions of shreds, etc.) of the upper part of turbulent flames is characteristic, first of all, of "bright" flames, e.g., of hydrocarbons.

Hydrogen flames, probably by virtue of their much lower luminosity (Fig. 2), decrease it smoothly, without rupture and separated volumes, to the level determined by the resolution of the recording device or the measuring technique.

The digital camera, the eye, and the video camera registering a color image of the flame and its fluctuations, as would be expected, demonstrate identity of the flame lengths.

Results of the Investigations. The objects of investigations were vertical flames of isolated burning hydrogen and methane jets flowing out of cylindrical nozzles into an unbounded undisturbed air volume. Investigations were carried out at atmospheric pressure and at room temperature. The height of flames L was measured at subsonic speeds in the range of variation of Re_0 numbers form 100 to 6800. At nozzle diameters d_0 = 2, 3, and 5 mm measurements were made visually, and at d_0 = 5 and 10 mm by means of digital and video photography.

The results of the investigation in the form of dependences of the relative height of the flame L/d_0 on the Reynolds number satisfying the conditions of outflow from the nozzle ($Re_0 = U_0 d_0/\nu$) are presented in Fig. 3. The general picture fully follows the dependences given in Fig. 1. In experiments with nozzles of d_0 = 2 and 3 mm, with increasing Re_0 there is a sharp increase in the relative height of the flame L/d_0, and then upon reaching L/d_0 = 240–250 the value of this quantity dropped to 190–200 (transition region), after which, already in the turbulent region, its smooth increase was observed. At $d_0 = 5$ mm in transition region (Re_0 = 1800–2600) L/d_0 is const and then its smooth increase was abserved too. In experiments with nozzles of d_0 = 10 mm, the change in L/d_0 of the burning-methane flame in going from the laminar region to the turbulent one is monotonic, which is characteristic, according to [5], of large d_0.

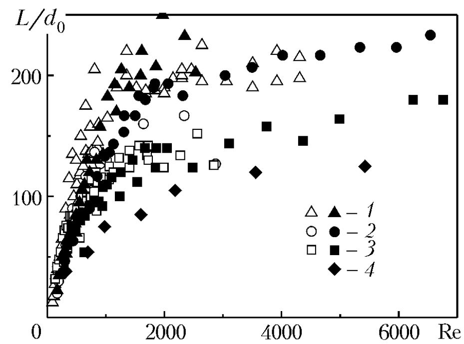

Fig. 3. Dependence of L/d_0 on Re_0 and d_0 for burning flames of hydrogen and methane: 1) d_0 = 2 mm; 2) 3; 3) 5; 4) 10. Open symbols denote hydrogen, solid ones — methane.

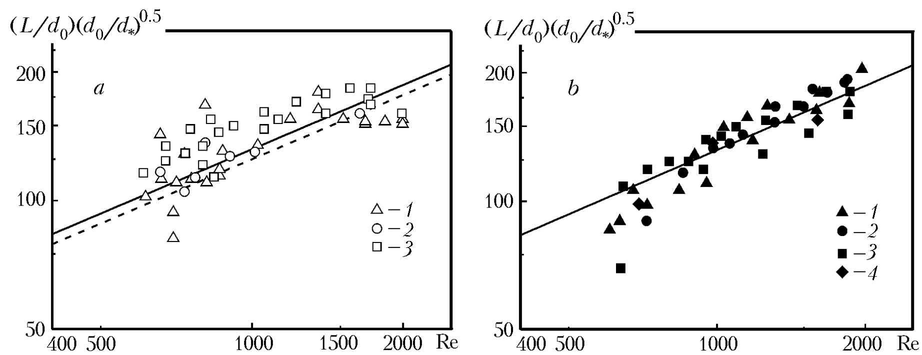

Fig. 4. Generalization of the data in the form $L/d_0 = f(Re_0, d_0/d_*)$ in the case of laminar combustion of hydrogen (a) and methane (b): designations 1–4 are same as in Fig. 3. Solid lines show dependences (4) and (5), and dashed line the result of calculation in [5].

More detailed analysis of Fig. 3 points to the existence in the region of small Reynolds numbers ($Re_0 < 600$) of a unique dependence of L/d_0 on Re_0 without the characteristic for [5] point bundle with changing d_0. On the basis of these data we have obtained the following empirical formulas for the flame height:

for the hydrogen flame

$$L/d_0 = 0.20 Re_0 , \tag{1}$$

for the methane flame

$$L/d_0 = 0.16 Re_0 . \tag{2}$$

As to their form and values of constant coefficients, they turned out to be close to the formulas obtained in [7] as a result of the generalization of a large body of experimental data of different authors.

The processing of the data obtained at Re_0 = 600–2000 in accordance with the proposed in [5] dependences of the type

$$L/d_0 = A\, Re_0^n \,(d_0/d_*)^{-0.5} , \tag{3}$$

where d_* = 3 mm, has shown a fairly good agreement and made it possible to obtain empirical formulas for the height of laminar flames (Fig. 4):

for hydrogen

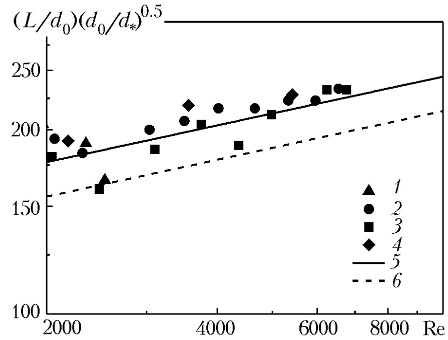

Fig. 5. Generalization of the data in the form $L/d_0 = f(\mathrm{Re}_0,\ d_0/d_*)$ in the case of turbulent combustion of methane: designations 1–4 are same as in Fig. 3; 5) dependence (6); 6) result of calculation in [5].

$$L/d_0 = 4.17\mathrm{Re}_0^{0.5}\,(d_0/d_*)^{-0.5}\ , \tag{4}$$

for methane

$$L/d_0 = 4.15\mathrm{Re}_0^{0.5}\,(d_0/d_*)^{-0.5}\ . \tag{5}$$

The data on turbulent combustion of hydrogen (Fig. 3) turned out to be insufficient for obtaining a reliable dependence for the flame height, and the experimental points corresponding to the turbulent flames of methane fell well along the line (Fig. 5)

$$L/d_0 = 38.7\mathrm{Re}_0^{0.2}\,(d_0/d_*)^{-0.5}\ , \tag{6}$$

which is 15% higher than the corresponding dependence from [5]. The possible reason for such a difference from [5] could be the different methods of measuring the flame height: black-and-white film in [5] and color images obtained by us.

On the Structure of the Methane Flame. In the process of photography with the usual camera on black-and-white film, varying widely the sensitivity of the film and the exposure, we managed to eliminate continuous illumination of the flame and resolve zones of maximum luminescence by which it is possible to represent the qualitative pattern of intensive combustion zones (Fig. 6). The photographs were taken at laminar combustion of methane flowing out of a nozzle of d_0 = 10 mm at Re_0 = 800. The considered zones have the form of multiply bent cylindrical jets vibrating with a high temporal frequency which finally, summing up their luminosity over the exposure time, give the flame the known spindle-shaped form.

High-speed color photography of flames has made it possible to reveal one more reason for the discrepancy in determining the length (height) of the flame by different methods. It is the high instability of the upper (end) part of the flame. Usually this is observed at a developed turbulence of the jet. The high-speed photography of flames having $\mathrm{Re}_0 > 2000$ recorded the appearance and separation from the main flame of rather widely spaced luminous formations with clearly defined boundaries of each (Fig. 7). Apparently, on a considerable time interval (visual observation, long-exposure photography) there occurs averaging of separation pulsations at the upper boundary of the flame with a gradual decrease in the luminescence until complete disappearance of luminescence. The level of this upper boundary is determined by the sensitivity of the recording apparatus (eye, film, electronic equipment). The change (increase, decrease) in the luminosity of the upper boundary, and, consequently, the recorded length of the flame are largely determined by the frequency, size, and luminosity of the arising and separating luminous formations.

Since the black-and-white film is almost insensitive to the dark-orange and red colors of the spectrum dominating in the upper part of the methane flame, it does not register the appearance and rupture of these luminous formations, which leads to a lower measured height of the flame compared to the visual or color measuring techniques.

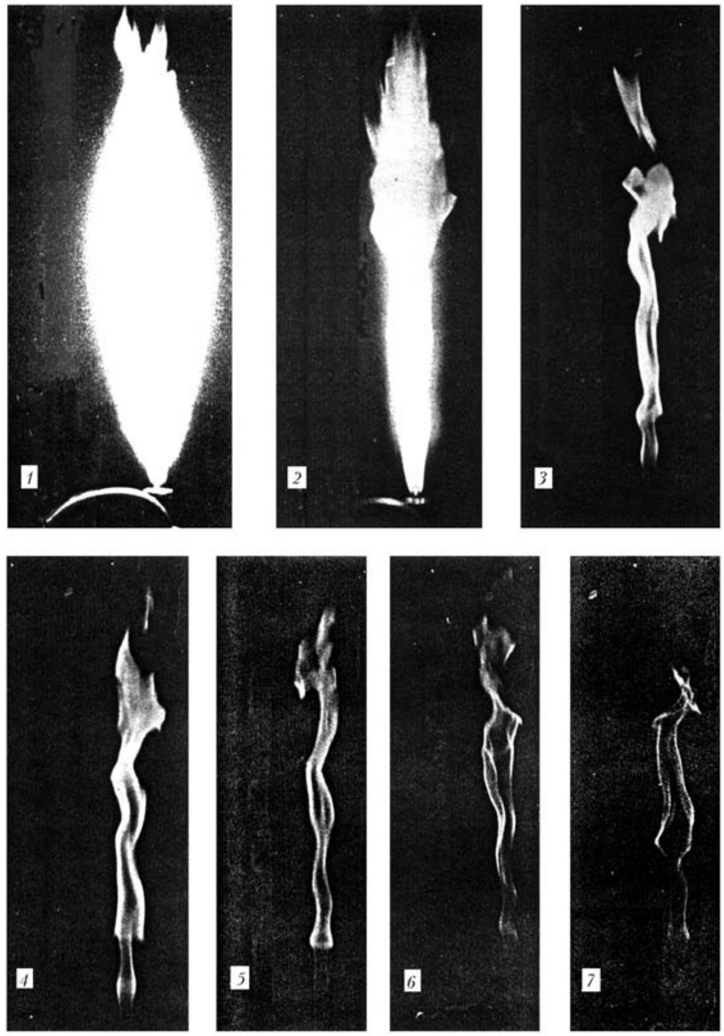

Fig. 6. Photographs of intensive luminescence zones obtained at different exposures and illustrating the shapes of burning flames of methane: 1) exposure of 2 sec; 2) 1 sec; 3) 1/30 sec; 4) 1/60 sec; 5) 1/250 sec; 6) 1/500 sec.

Fig. 7. Separation of luminous formations from the upper part of the turbulent flame at combustion of methane.

Obviously, exactly this reason explains the discrepancy between the experimental data on the height of the burning methane turbulent flame obtained in the present paper and in [5]. Thus, the photographs of flames shown in Figs. 6 and 7 point to the necessity of developing special averaging methods for objective determination of the flame length. They should be considered as an additional, very important and interesting material to be taken into account in investigating the temperature and concentration fields by inertial methods (sampling, thermocouples, thermograph) or in zonal investigations of the flame by low-inertia techniques when characteristics measured at different sites pertain to different instants of time, making it impossible to represent (record) the instantaneous state of the rapidly changing general pattern (structure of the flame). The fact revealed should also be taken into account in constructing physical models of flames, as well as in developing calculation programs.

CONCLUSIONS

1. An experimental facility has been created and a method of investigation has been developed. Different methods for determining the length of the burning flame have been tested. The advantage of color images over black-and-white ones has been shown.

2. The results of measurements of the heights of flames at combustion of hydrogen and methane flowing out of nozzles of diameter 2, 3, 5, and 10 mm at Reynolds numbers Re_0 = 100–6800 have been presented.

3. The extension of investigations to the regions of small Reynolds numbers Re_0 = 100–500 has made it possible to reveal a zone of unique and linear dependence of the flame height on Re_0.

4. The generalization of the experimental data in the form of the dependence $L/d_0 = f(Re_0, d_0/d_*)$ gave convenient calculation formulas. Comparison of these dependences with the data of other authors in the laminar region has shown their good agreement, and the somewhat higher values of L/d_0 at turbulent combustion of methane is likely due to the application of the more advanced method — color imaging of flames.

5. The use of the high-sensitivity black-and-white film has made it possible to resolve, at short exposures in the volume of the laminar methane flame, instantaneous bent cylindrical jets — zones of intensive combustion vibrating in time and space.

6. It has been shown that in the upper part of turbulent flames there appear and separate, with upward carry-over, luminous formations that increase the visible length of the flame.

NOTATION

d, nozzle diameter, m; *L*, flame length, m; Re, Reynolds number; *U*, velocity of the fuel jet, m/sec; ν, kinematic viscosity of fuel, m^2/sec. Subscripts: 0, nozzle outlet section; *, characteristic quantity; cr, critical.

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