Acoustic control of the structure of the gas torch

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Abstract. Diffusion torches in the transverse acoustic field studied experimentally. The structure and the luminosity of the torch were recorded by a high-speed camera with shadow device and photodetectors. The dependence of the length of a laminar methane plume on the average velocity and volumetric flow rate was measured. The frequency spectra of the luminosity of the flame at different flow rates of methane are obtained. Flame flicker frequency depending on the volume flow of methane defined according to the obtained spectra. It was found that the flame flicker frequency is not dependent on the diameter of the burner. It is shown that the flickers are caused by changes in the geometric dimensions of the flame due to the convective instability of the column of hot gas surrounding the torch. The repetition frequency of the vortices in the column of hot gas surrounding the torch coincides with the frequency of the flicker of the flame. It is shown that the limits of flame detachment from burner and flame quenching does not change at the acoustic impact on the torch, the biggest acoustic impact has on the contrary attaching detached torch. Fuel speed range, in which there is detached steady torch, increases.

1. Introduction

In various technical devices and natural conditions, the type of combustion when the fuel and oxidizer are spatially separated and not pre-mixed occurs. Under such conditions, a chemical reaction of combustion between the fuel and oxidant takes place only after the reactants mixing as a result of molecular or turbulent diffusion. Therefore, for these types of flames the term diffusion flames was fixed. The main difference between the diffusion combustion and premixed burning is that the rate of chemical transformations at the diffusion combustion is limited by the conditions of mixing. The dependence of the height of the flame on the speed of the fuel gas was obtained in [1] based on the consideration of scale effect. Most burners the convection significantly affects the emissions of combustion products, the rate of combustion and flame stability limits, such as slip and flameout. The convection causes oscillations (flickering) of the flame front at a low frequency, typically in the range 10–20 Hz for propane stream, burning in air, and about 18 Hz for town gas [2]. The structures in the combustion front, which have reduced the intensity of its own glow, are registered in the study of lifted diffusion flame in the mode of transition from laminar to fully developed turbulent [3]. A one dimensional premixed laminar methane flame was subjected to acoustic oscillations and studied in [4]. In [5] the effect of artificial gravity on stability and flicker of diffusion propane flame jet was studied. It is found that the lift of the flame from the burner nozzle, and flameout are strongly dependent on gravity.

The purposes of this paper are: to investigate the dependence of laminar methane torch length and flicker frequency on the average velocity and volumetric flow rate; to determine the...
change of limits of flame detachment and contrary attachment from burner and flame quenching at different parameters of acoustic impact.

2. Experimental setup
The diffusion methane jet flames (torches) in the atmosphere were investigated. Shadow device IAB-451 was used for visualization of the jet. Schematic diagram of the setup is shown in figure 1.

Ultra-high camera Cordin 222-16, allowing to obtain a series of 16 shots with a time delay between exposure and frames from 5 ns, equipped with lenses Nikon 80-200mm f/2.8 and Sigma 150-500mm f/5-6.3 was used as the recording device. For the low-speed color recording Sony Cyber-shot DSC-H10 camera was used. Methane gas pressure vessel was connected in series with a pressure reducer, gas flow fine adjustment valve NV3-H-12M, gas rotameter RM 02-0.25GUZ and the burner for the formation of the flame. The burner is a thin pipe arranged vertically with an open upper end. Pipes with internal diameters of 0.52, 0.58, 0.82, 1.00, 1.13 and 1.58 mm were used in the experiments. The length of the pipes exceeds an inner diameter of at least a hundred times, so that the velocity profile at the outlet of the pipe can be considered a classic Hagen–Poiseuille, provided laminar flow. As is known, the critical Reynolds number for the flow in the tube is about 2300, which corresponds to a volumetric flow rate 0.09 m$^3$/h for a pipe with an internal diameter of 1 mm at normal conditions. In the experiments, the methane flow rate ranged from 0 to 0.325 m$^3$/hr, thereby allowing to simulate burning both laminar and turbulent gas jets. The system for external acoustic impact consisted of sound amplifier and transmitter Ibanez SWX20, 2-channel arbitrary waveform generator Aktacom ANR-3122. Digital sound level meter AZ 8922 was used to determine the sound pressure level. Microphone ISU with AGC was used for the registration of profile of the sound wave in the frequency range 200–10000 Hz. Silicon-based photodetector with an input lens FD-256 was used to register a flicker of flame. The photodetector was placed at a distance of 200 mm from the axis of the burner at a height of 100 mm from the burner nozzle so that the symmetry axis of the photodetector is perpendicular to the pipe axis.
Figure 2. Photographs of the torches at various average methane velocities: (a)—2.4 m/s; (b)—7.1 m/s; (c)—11.9 m/s; (d)—16.6 m/s; (e)—21.3 m/s; (f)—35.6 m/s.

3. Height of diffusion methane torch

Figure 2 shows photographs of the torches with different average over the cross section speeds of methane, the inner pipe diameter 1.00 mm. As we see from figure 2, at low speeds, a jet of methane flame is laminar, its boundary is stable, smooth, and the flame combustion flows quietly (no noise). As the jet velocity increases the flame height increases to a certain limit speed of the jet. With further increase in the velocity of the jet flame boundary becomes unstable, the instability occurs first at the top of the flame (this can be seen in figure 2e) and then extends downstream to the outlet of the burner. Simultaneously, the flame height is reduced. If we continue to increase the speed of a jet flame height is no longer dependent on the speed of the jet and becomes almost constant. Flame border rapidly pulsing, burning accompanied by a loud noise (the same occurs in the case of a Bunsen flame in a turbulent flow of pre-mixed gas). The area in which the height of the flame is not dependent on the speed of the jet stream corresponds to turbulent flow. The area in which the flame height increases with the gas velocity of the fuel jet refers to a laminar diffusion flame. There is a transition region between these two types of flame. The transition from laminar to turbulent diffusion flame is determined by changing the behavior of the flow of the jet. Obviously, the combustion flow affects the behavior of the jet, so the laminar–turbulent transition in flames does not coincide with the laminar–turbulent transition in jets without burning. If one increases the speed of the jet of combustible gas at the turbulent diffusion combustion, the flame separates from the edge of the burner and is set at a certain distance above the burner (figure 2f). Such flames are called “lifted flames”. The flame boundary is strongly pulsating, burning accompanied by a loud noise. Figure 3 shows the dependence of laminar flame length on the section average velocity of methane and the volumetric gas flow rate for pipes of different diameters.

As seen from figure 3a, at low speeds, the fuel gas flame length is linearly dependent on the speed of the methane jet. As seen from figure 3b, at the same volumetric flow rate of methane flame length does not depend on the diameter of the pipe. Flame length is linearly dependent on the volumetric flow rate of flammable gas (dashed line in figure 3b) up to volumetric flow
rates 0.08 m³/h. A similar result is indicative of the linear dependence of the height of the flame speed on fuel gas can be obtained by considering the effect of scaling [1].

4. Convective instability, flame flickering

The human eye is sufficient to see that the diffusion flame burners of household is always chaotic and uneven pulses at low frequencies, typically in the range 10–20 Hz. These oscillations of the flame, better known as flicker, reflect changes in the geometric dimensions of the flame, vibrations of heat release, pressure and other characteristics, which play an important role in the dynamics of the flame, the flame radiation and energy efficiency. In experiments it was found that flicker is not always observed. For example, the burners of internal diameter 0.52 mm and 0.82 mm no flicker at any velocity jet of fuel gas (methane). In contrast, for burners of internal diameter 1.00 and 1.58 mm, flicker observed almost at all values of the fuel jet velocity, including the case of laminar flames. Figure 4a shows a waveforms of the photodetector PD 256 mounted on a distance of 200 mm from the axis of the burner at a height of 100 mm from the burner nozzle so that the symmetry axis of the photodetector is perpendicular to the pipe axis, the inner diameter of the burner 1.00 mm. Figure 4b shows the frequency spectrum of the signal of the photodetector (10 s duration) for the case of the methane jet section average velocity of 7 m/s. The burner with inner diameter of 1.00 mm was used in the experiment. As seen from figure 4, the photodetector signals contain high harmonic component. The spectrum (figure 4b) of the signal in addition to the fundamental harmonic components are also present higher harmonics.

As it is known the reason of flicker is natural convection, which results in low frequency oscillations of the length and width of the flame (figure 5). These fluctuations reflect the instability of the column of hot gas surrounding the jet torch. In the case of a small burner diameter its diameter slightly affects the characteristic dimensions of the column of hot gas and flame length (figure 3b), and therefore the flicker frequency is practically independent on the diameter of the burner in the range of 1.00–1.58 mm. Figure 5 and figure 6 show the direct (exposure 200 µs) and shadow (10 µs exposure) photography flame, respectively. Photos were
Figure 4. (a)—photodetector readings: 1—background; 2—$V = 15$ m/s, $Re = 880$; 3—$V = 10$ m/s, $Re = 600$; 4—$V = 7$ m/s, $Re = 440$; 5—$V = 3$ m/s, $Re = 180$. (b)—frequency spectrum at $V = 7$ m/s.

Figure 5. Photographs of the methane torch (pipe diameter—1 mm, methane average velocity—7 m/s) at various time moments: (a)—0; (b)—$\tau/6$; (c)—$\tau/3$; (d)—$\tau/2$; (e)—$2\tau/3$; (f)—$5\tau/6$, where $\tau = 1/f$.

taken at various time points: 0, $\tau/6$, $\tau/3$, $\tau/2$, $2\tau/3$, $5\tau/6$, where $\tau = 1/f$, i.e. at different moments during one oscillation period of the flame radiation. Instability of hot gas column surrounding the jet torch in the case of axisymmetric flames generates vortices following one another at regular intervals (at the widest part of figure 6). These vortices arise in the combustion products, along the reaction zone by natural convection. The layer of the reacted gas thickness changes periodically due to the regular passage of vortices through it also the supply of oxygen to the zone of chemical reaction changes periodically. The surface of the flame, in turn, deforms (figure 5) in accordance with a change in the oxygen flow involved in the combustion process.
Figure 6. Shadow photographs of the methane torch (pipe diameter—1 mm, methane average velocity—7 m/c) at various time moments: (a)—0; (b)—\(\tau/6\); (c)—\(\tau/3\); (d)—\(\tau/2\); (e)—\(2\tau/3\); (f)—\(5\tau/6\), where \(\tau = 1/f\).

Table 1. Limits of detachment–attachment as well as failure of the diffusive torch.

| d, mm | \(V_d\), m/s (Re) | \(V_a\), m/s (Re) | \(V_f\), m/s (Re) |
|-------|-------------------|-------------------|-------------------|
| 0.82  | 29 (1430)         | —                 | —                 |
| 1.00  | 34 (2030)         | 18 (1060)         | 23 (1350)         |
| 1.58  | 23 (2190)         | 14 (1290)         | 29 (2760)         |

5. Effect of acoustic impact on the limits of detachment–attachment of the diffusive torch

In diffusive combustion, when the fuel gas flows into the surrounding space, combustion reactions occur at the contact surface between fuel and air. In this case, sound waves interact with the flame, both directly and indirectly. Direct interaction between the wave and the flame in the combustion zone, whereas indirect interaction occurs in the flow field has not yet reacted gas, regardless of the characteristics of the flame. Depending on the frequency and amplitude of the sound, the appearance of the site, which is imposed acoustic impact, can seriously affect the structure and movement of the flame as a whole. Turbulization jet methane acoustic action described above, leads to a change in the limits of detachment–attachment and flame failure. Table 1 shows the average value of the jet velocity of methane at which the detachment \(V_d\), attachment \(V_a\) and failure \(V_f\) torch for jets of various diameters. In brackets are the equivalent Reynolds number. Similar data for the case of acoustic action are shown in table 2. In all cases, the sound pressure level was 100 dB. Each measurement was repeated 5 times, the mean square error in determining the velocity and Reynolds number did not exceed 2 m/s and 40 respectively.

As can be seen from the tables, the acoustic impact virtually no effect on the limits of flame detachment. The speed at which the detachment of the flame under acoustic excitation occurs also changes slightly. Acoustic exerts the greatest influence on torch reverse attachment, namely, the speed at which the torch attaches is reduced by 22% \((d = 1.00 \text{ mm})\) and 28% \((d = 1.58 \text{ mm})\), see table 2 and table 1. Dashes in table 1 \((d = 0.82 \text{ mm})\) mean that stable detached flame was not observed in the experiment, in contrast to the case with the acoustic effect. Figure 7 shows
Table 2. Limits of detachment–attachment as well as failure of the diffusive torch at acoustic impact.

| d, mm | \( V_d \), m/s (Re) | \( f \), kHz | \( V_a \), m/s (Re) | \( f \), kHz | \( V_f \), m/s (Re) | \( f \), kHz |
|-------|----------------------|--------------|----------------------|--------------|----------------------|--------------|
| 0.82  | 26 (1290) 10         | 14 (670)     | 3.90                 | 18 (870)     | 3.90                 |
|       |                     | 15 (740)     | 1.50                 | 21 (1010)    | 1.50                 |
|       |                     | 14 (830)     | 3.90                 | 22 (1290)    | 3.90                 |
| 1.00  | 32 (1900) 10         | 14 (830)     | 2.00                 | 23 (1350)    | 2.00                 |
|       |                     | 14 (830)     | 1.50                 | 23 (1350)    | 1.50                 |
|       |                     | 12 (1120)    | 3.90                 | 29 (2700)    | 3.90                 |
| 1.58  | 24 (2240) 5          | 10 (930)     | 2.00                 | 28 (2660)    | 2.00                 |
|       |                     | 10 (930)     | 1.50                 | 28 (2660)    | 1.50                 |

Figure 7. Shadow (a) and direct (b) photographs of the methane lifted torch (pipe diameter—0.82 mm, methane average velocity—16 m/s) at acoustic impact with frequency of 3.9 kHz and acoustic pressure level of 100 dB.

The direct and shadow photographs detached flame \((d = 0.82 \text{ mm}, V = 16 \text{ m/s})\) for acoustic exposure with a frequency of 3900 Hz and a sound pressure level of 100 dB. As you can see from the photos, under the influence of the sound stream of methane becomes turbulent, taking “Y” shape. Thus the flame is stabilized at a certain distance from the division of the jet and also has a “Y” shape.

Thus, we can conclude that the acoustic impact extends beyond the stability of detached flames. Speed range of fuel for which there is a steady lifted torch increases. In addition, the acoustic impact provides stable lifted flame in burners of small diameter, for which, in the case without acoustic impact, lifted flames are not observed.
6. Conclusion
The dependence of the length of a laminar methane plume on the average velocity and volumetric flow rate has obtained. The frequency spectra of the luminosity of the flame at different flow rates of methane have obtained. Flame flicker frequency depending on the volume flow of methane has defined according to the obtained spectra. It was found that the flame flicker frequency is not dependent on the diameter of the burner. It is shown that the flickers are caused by changes in the geometric dimensions of the flame due to the convective instability of the column of hot gas surrounding the torch. The repetition frequency of the vortices in the column of hot gas surrounding the torch coincides with the frequency of the flicker of the flame. It is shown that the limit of flame detachment from burner does not change at the acoustic impact on the torch, the biggest acoustic impact has on the contrary attaching detached torch. Fuel speed range, in which there is detached steady torch, increases.

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