Experimental study of premixed methane–air flame coupled with an external acoustic field

K Yu Arefyev, A I Krikunova and V A Panov
Moscow Institute of Physics and Technology, Institutskiy Pereulok 9, Dolgoprudny, Moscow Region 141700, Russia
E-mail: krikunovaai@gmail.com

Abstract. An external acoustic effect on conical methane–air premix flame is experimentally studied at frequencies from 10 to 450 Hz. Conditions of flame blow-off in a wide range of mixture equivalence ratio have been determined. The visualization of the perturbed flame has been performed. The dependences of blow-off velocity limit are shown upon amplitude of the acoustic-induced velocity fluctuations and excitation frequency. Flow velocity fluctuations in the outlet section of the nozzle have been measured for investigated range of acoustic excitation frequencies. Also, the coupling between the blow-off conditions and flow velocity fluctuations has been established. The obtained results could be useful while analyzing stable operation conditions for the high-speed combustion chambers of the advanced propulsion plants.

1. Introduction
Recently, methane-based propulsion plants with high-speed combustion chambers have become relevant for aerospace engineering. The use of methane makes it possible to create propulsion plants with high integrated efficiency due to the higher density of liquefied methane (≈ 6 times higher than for cryogenic hydrogen), high volumetric heat of combustion, its environmental safety, low cost and satisfactory operational properties. However, several fundamental problems such as limited ignition range as well as combustion instability at higher air flow rates preclude further development of advanced methane-based propulsion plants with high-speed combustion chambers. Recently, methods of acoustic effect on fuel-oxidizer mixing zones have shown intensification of mixing process and combustion [1]. The acoustic impact also alters the main characteristics of the flame, such as the extent of the mixing and combustion zones, the flame stability [2], oscillations and the flame front structure [2–4]. It is noteworthy that in addition to the mixing intensification, the acoustic impact is accompanied by pressure and velocity fluctuations agitation in the combustion zone, which can cause thermo-acoustic instability.

The thermo-acoustic instability onset is one of the reasons of the propulsion plants failure and can lead to flameout. A great number of works are devoted to the study of thermo-acoustic instability onset and its effect on the operating process in various propulsion plants [5–8]. Ongoing fundamental studies are aimed to determine the patterns of combustion under acoustic impact [4, 9–12]. Despite a large number of works, the overall rules of amplitude and fluctuations frequency influence on the flameout conditions at various fuel–air ratios and flow velocity can be hardly established. The abovementioned determines the need to study the characteristics of the turbulent flame extinguishment under acoustic impact. The experimental
simulation of the forced acoustic impact on the flow is one of the most effective methods to investigate the influence of the spectral characteristics of velocity fluctuations on the premixed combustion process and the flameout conditions.

In this paper we investigate the blow-off limit of premixed methane–air flame influenced by external acoustic field while varying mixture equivalence ratio.

2. Experimental setup
The setup is intended for the premixed methane–air combustion study under subsonic flow and atmospheric conditions. The setup scheme is shown in figure 1.oxidizer (air) and fuel (methane) enter the premix chamber. A cone with a loudspeaker is attached to the lower part of the premix chamber, and a burner is attached to a top part of this chamber. The diameter of the outlet section of the burner nozzle is $D_{ex} = 15$ mm. The configuration of the burner nozzle is close to the configuration of the Vitoshinsky nozzle, which ensures a rectangular velocity profile in the outlet section [13]. Mass flow controllers are used to ensure a given fuel–air equivalence ratio $\phi$ and reacting mixture mass flow rate. The loudspeaker produces acoustic impact. An arbitrary waveform generator and an amplifier are used to feed the loudspeaker with a sinusoidal signal with a given spectrum at a given frequency. The amplitude and frequency of the signal are recorded by the oscilloscope. Flame visualization is carried out by a high-speed camera. The frame rate is up to 2000 fps, field of view is $30 \times 40$ mm$^2$, the camera sensor size is $1280 \times 800$ pixels.

The possibility of constant temperature anemometry (CTA) hot-wire probe installation in the burner nozzle outlet is provided to determine the velocity characteristics of the flow under the operating regimes without combustion. The velocity fluctuations are measured at the symmetry axis directly in the nozzle outlet. The measurements are made at the CTA sampling rate of 10 kHz. The system is operated under control of the computer.

Components mixing uniformity is provided by a considerable extension of the mixing channel $L_{mix}/D_{mix} > 30$, where $L_{mix}$ is the length of the mixing chamber, $D_{mix}$ is the diameter of the mixing chamber. The investigated flame without external acoustic impact has an axisymmetric conical shape, which confirms the high quality of fuel components mixing as shown in previous experimental studies [14]. The experiments presented in the paper were carried out at air mass flow rate $G_a = 0.013–0.106$ kg h$^{-1}$ and methane mass flow rate $G_m = 0.358–1.767$ kg h$^{-1}$. The equipment makes it possible to provide the mass flow rate error 0.2% at most. The mixture equivalence ratio was defined as the ratio of the fuel mole fraction in the experiment to the fuel mole fraction in the stoichiometric mixture. It is varied in the range of $\phi = 0.75–1.10$ in the experiments. The time-averaged velocity $u$ in the outlet section of the burner nozzle could be estimated using the following formula:

$$u = \frac{4(G_a + G_m)}{\rho \pi D_{ex}^2},$$

where $\rho$ is the density of the fuel mixture under normal conditions. The maximum flow velocity in the nozzle outlet section in experiments reaches a value of 2 m s$^{-1}$. In this case, the Reynolds numbers in the nozzle outlet section do not exceed 2000. The acoustic impact on the flow of a fuel mixture with fluctuation is studied at frequencies $f = 10–450$ Hz. The presented experimental setup makes it possible to study combustion of a methane–air mixture in a wide range of regime parameters, visualize flame structure, and determine the flameout characteristics under acoustic impact.

3. Results and discussion
Since velocity fluctuations are one of the reasons of flame blow-off it is important to know conditions of transition between stable combustion and unstable one for every presented mixture equivalence ratio, which are determined by mean and fluctuation components of flow velocity.
As the main criterion for the fluctuation component of the flow velocity in the outlet section of the nozzle, the relative root-mean-square deviation of the velocity $\sigma_u$ from the mean value of $u$ is used:

$$\sigma_u = u^{-1} \left[ (N - 1)^{-1} \sum_{i=1}^{N} (u_i - u)^2 \right]^{1/2} \times 100\%,$$

where $u_i$ is instantaneous flow velocity at the nozzle outlet section at the time $t_i$, $N$ is total number of the measurements. In order to obtain the blow-off conditions for methane–air mixture the experiments were carried out in three stages.

At the first stage, the amplitude-frequency characteristics of velocity fluctuations in the nozzle outlet section were determined at different excitation frequencies while preserving its amplitude. The experiments were performed for non-reactive air flow at different mean flow rates. The amplitude of the signal fed into the loudspeaker was constant and equal to 3 V. Experimental data are shown in figure 2. For the implemented setup, it is possible to distinguish the following features of the amplitude-frequency characteristic of velocity fluctuations. Pronounced harmonics with local maximums of velocity fluctuations were observed at frequencies close to the natural gas oscillation frequencies in the premix chamber with the attached burner and loudspeaker. The relative values of the root-mean-square deviation of the velocity fluctuations at frequencies around 10 Hz can reach 75% in the outlet section of the burner nozzle. For subsequent harmonics the fluctuation amplitudes decrease. In particular, for the frequency of 90 Hz, $\sigma_u$ does not exceed 40%; for the frequency 200 Hz, it is less than 20%. It should be noted
Figure 2. Amplitude-frequency characteristics of velocity fluctuations in the exit section of the nozzle at the basic amplitude of excitation signal fed to the loudspeaker for different mean flow rate: 1—0.16 g s\(^{-1}\) (0.7 m s\(^{-1}\)); 2—0.45 g s\(^{-1}\) (2 m s\(^{-1}\)); 3—2.26 g s\(^{-1}\) (10 m s\(^{-1}\)).

Table 1. The relative values of the root-mean-square deviation of the velocity fluctuations.

| \(f\), Hz | \(u\), m s\(^{-1}\) |
|----|----|
| 60  | 6.0 | 5.1 | 2.0 |
| 150 | 5.0 | 2.3 | 2.4 |
| 260 | 5.9 | 3.5 | 2.6 |
| 350 | 4.4 | 3.0 | 2.0 |
| 440 | 1.9 | 1.5 | 1.4 |

that increasing mean flow velocity leads to decrease in \(\sigma_u\) except for some local regions near the maxima. The local minima of \(\sigma_u\) are presented at frequencies 60, 150, 260, 350 and 440 Hz.

At resonant frequencies, the relative values of the velocity fluctuations increase significantly and stable combustion is hardly attainable. Therefore, further investigations have been done on acoustic effect at frequencies corresponding to the local minima. Table 1 shows these values of the velocity fluctuations for given mean velocity \(u\) at different excitation frequencies \(f\).

With increasing excitation frequency, the amplitude of the velocity fluctuations decreases. However, at low flow velocities (0.7 and 2.0 m s\(^{-1}\)) there is an exception at the frequency of about 150 Hz, where the amplitude of the velocity fluctuations drops sharply. This may be attributed to the characteristics of the loudspeaker and the dependence of the acoustic impedance of the implemented setup on the flow velocity. Such effect vanishes for a flow velocity of 10.0 m s\(^{-1}\).

At the second stage the flow velocities corresponding to the flame blow-off with additional acoustic effect were measured at different mixture equivalence ratios and excitation frequencies. The amplitude of the exciting signal during the experiments was kept equal to the base level.
Figure 3. Flame blow-off characteristics under various perturbation frequencies: 1—0; 2—150 Hz; 3—250 Hz; 4—440 Hz.
more uniform flame structure during the blow-off. In particular, the flame detachment occurs almost simultaneously along entire perimeter of the nozzle that differs from the results presented...
in [3], and the blow-off time also differs significantly. It should also be noted that the duration of the blow-off process is less under acoustic effect than without it.

4. Conclusions
The experimental study of the effect of acoustic perturbations on the blow-off premixed methane–air flame characteristics was performed. The combustion process is strongly influenced by the nonlinearity of the amplitude-frequency characteristic of velocity pulsations in the outlet section of the burner. For the implemented experimental setup, both local maxima (resonance frequencies) and local minima are present in the velocity fluctuation spectrum. For resonance frequencies, the relative root-mean-square deviation of the velocity fluctuation is in the range of 8–35% of the mean flow velocity, and at the local minima it does not exceed 6%.

It is shown that blow-off limit of the flow velocity is reduced by 15–45% under external acoustic influence comparing to undisturbed flame. It is found that with an increase in the frequency of perturbations, the acoustic effect decreases as a result of a decrease in the amplitude of the velocity fluctuation. It is also shown that with increasing fuel concentration in the mixture, the effect of external acoustic disturbances increases.

High-speed imaging of flame blow-off showed the following: without perturbations, the flame breaks asymmetrically, while the excitation leads to a more symmetrical flame detachment from the edge of the nozzle. The time intervals, during which flame blow-off occurs in the case of perturbations and without them, differ by almost two orders of magnitude.

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