ISSN 0018-151X, High Temperature, 2024, Vol. 62, No. 1, pp. 128–131. © Pleiades Publishing, Ltd., 2024.
Russian Text © The Author(s), 2024, published in Teplofizika Vysokikh Temperatur, 2024, Vol. 62, No. 1, pp. 150–153.

SHORT COMMUNICATIONS

Self-Excitation of Gas Oscillations in a Tube with a Swirling Flame

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Received June 27, 2023; revised October 13, 2023; accepted December 4, 2023

Abstract—The article studies fluctuating combustion in a combustion chamber with a swirling flow. The excitation conditions and characteristics of acoustic oscillations of gas in a tube with tangential supply of a propane–butane fuel–air mixture were determined experimentally. An anomalous dependence of the gas oscillation frequency on the excess air coefficient α was discovered: a minimum at $\alpha = 1$ and a local maximum at $\alpha \approx 1.15$. At $\alpha = 1$, the gas oscillations have maximum amplitude. It is shown that the axial gradient of the sound speed in the tube and its dependence on the amplitude of gas oscillations significantly affect the oscillation frequency.

DOI: 10.1134/S0018151X2470007X

INTRODUCTION

It is known that in the combustion chambers of power plants, e.g., modern gas turbine plants (GTP) [1–4], the combustion process can become unstable. This excites acoustic oscillations of the gas, which destabilizes the operation of the entire plant and therefore should be eliminated.

In [5], self-excitation of gas oscillations in a tube with a swirling flame was studied. It was established that when the flow rate of the stoichiometric mixture changes from 10.2 to 32 L/min, a stable mode (without flame failure) of pulsating combustion with a frequency of 230–260 Hz and a sound pressure level (SPL) of 122–162 dB is observed.

A linear approximation was used to distribute the sound speed [6, 7]. In this case, the wave equation for gas velocity fluctuations has an analytical solution, which allows us to develop mathematical models of fluctuation combustion for a number of direct-flow combustion chambers. It is assumed that the temperature distribution for a fixed flow rate of the fuel–air mixture depends only on the combustion temperature and is the same at all stages of gas oscillation excitation. In reality, gas vibrations significantly accelerate heat transfer to the chamber walls. As a result, the gas temperature distribution in the steady-state oscillation mode differs from the distribution without oscillations or at the initial stage of oscillation excitation, when their amplitude is infinitely small.

The aim of this study is to determine the excitation conditions, frequency, and amplitude of gas oscillations as a function of the excess air coefficient in the mixture and the geometric parameters of the mixture feed device in the tube for combustion in a swirling flow.

RESULTS

The experiment was carried out on the setup used in [5, 8]. The combustion chamber is a cylindrical tube closed at the outlet; the mixture was supplied tangentially (Fig. 1).

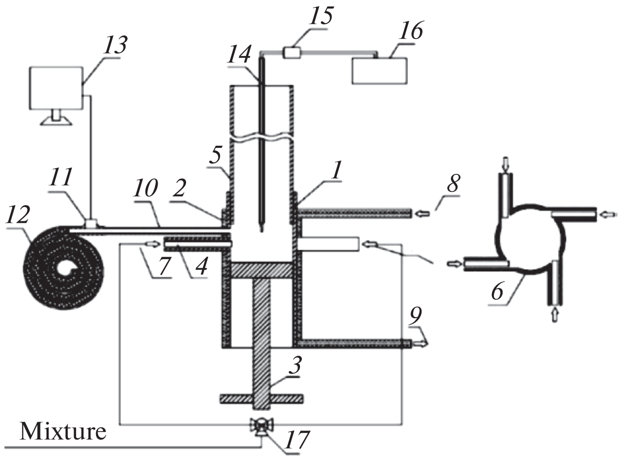

Fig. 1. Scheme of experimental setup: *1*, inlet chamber; 2, cooling circuit; *3*, screw piston; *4*, fuel–air mixture supply tube; *5*, cylindrical resonator tube; *6*, tube placement diagram; *7*, pipelines for supplying mixture to nozzles; *8*, *9*, cooling water inlet and outlet; *10*, acoustic probe, feeler gauge; *11*, microphone; *12*, helical sound-absorbing tube; *13*, computer; *14*, VR 5/20 thermocouple; *15*, cold junction compensator; *16*, F266 digital device; *17*, mixture distributor.

The combustion chamber consists of cylindrical tube *5* with an internal diameter of 34 mm and input chamber *1* with the same internal diameter with four inlet nozzles *4* and *6* 60 mm in length with an internal diameter of 3 mm. The mixture was supplied to the tubes from pipelines *7* having a length of 0.48 m and an internal diameter of 8 mm. Two opposite or four symmetrically placed nozzles were used. After preliminary tests, piston *3* was always at a distance of 10 mm below the tubes. There is water cooling at combustion chamber inlet *2*, which is necessary to prevent overheating of tubes *4* and stabilization of the temperature of the incoming gas mixture *7*. The length of the combustion chamber (the distance from the piston to the open outlet of the tube) is 0.45 m.

A mixture of cylinder propane–butane fuel and atmospheric air was used. The fuel composition was as follows [5, 8]: propane (74.36%), methane (5.2%), isobutane (8.77%), butane (6.9%), hydrogen sulfide (4.13%), and water (0.63%). Calculations have shown [8] that complete combustion of 1 m^3 of fuel requires 23.5 m^3 of air. If the fuel consumption is V_f and air consumption is V_α, the excess air coefficient is calculated by the formula

$$\alpha = V_\alpha/(23.5V_f).$$

The characteristics of gas oscillations—frequency and ultrasonic pressure at the combustion chamber inlet—were measured with an acoustic probe, including a computer electret microphone and aluminum probe with a length of 15 cm and an internal diameter of 3 mm.

The influence of the mixture flow rate on the frequency and amplitude of gas oscillations was investigated under the condition of a constant excess air coefficient. The data were obtained for the pipelines supplying the mixture to the nozzles, with a length of $l_t = 0.48$ m. If $\alpha = 1$, an increase in the mixture flow rate from 10.2 to 24 L/min causes an increase in the oscillation frequency to the maximum value 260 Hz (Fig. 2). Further change in the mixture flow to 32 L/min leads to a decrease in frequency. The nature of the dependence of the sound pressure level in the combustion zone on the mixture flow rate (Fig. 3) is the same as for the oscillation frequency. There is a maximum 162 dB which corresponds to the maximum frequency.

The measurement results showed that the stable pulsating combustion mode with the highest values of the gas oscillation amplitude corresponds to the stoichiometric composition of the mixture in the air flow range from 20 to 27 L/min.

The influence of the excess air coefficient on the characteristics of gas oscillations in a combustion chamber of length $l_c = 0.45$ m with a four-tube supply system $(n = 4,\ l_t = 0.48\ \text{m})$ was further investigated for fixed values of air flow (V_a=21, 25.8, 27 L/min). The data presented in Fig. 4 show that the frequency of gas oscillations is minimal for the stoichiometric composition of the mixture ($\alpha = 1$). A decrease or increase in α, i.e.. an increase or decrease in fuel consumption relative to the stoichiometric value, increases the oscillation frequency. This result is unexpected and anomalous.

The combustion temperature of the stoichiometric mixture and the sound speed at the inlet to the combustion chamber have maximum values. As is known, the frequency of acoustic oscillations of gas in a tube is directly proportional to the sound speed [9]. Therefore, it could be expected that for $\alpha = 1$, the gas oscillation frequency is maximum. Measurements of the amplitude of pressure oscillations at the inlet of the combustion chambers showed (Fig. 5) that this parameter, in contrast to the oscillation frequency, has a maximum value for $\alpha = 1$.

Further measurements were carried for the mixture fed through two tubes ($n = 2$) at a constant air flow rate of $V_\alpha = 25.8$ L/min and a length of supply tubelines $l_t = 0.48$ m. The dependences of the gas oscillation characteristics on the excess air coefficient were measured under the condition $l_c = 0.45$ m (Fig. 6, 7). Comparison of the data obtained for $n = 2$

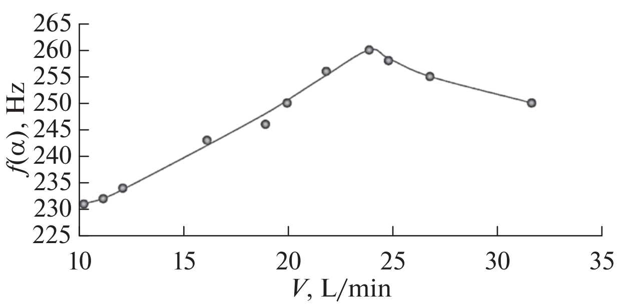

Fig. 2. Dependence of gas oscillation frequency on mixture flow rate.

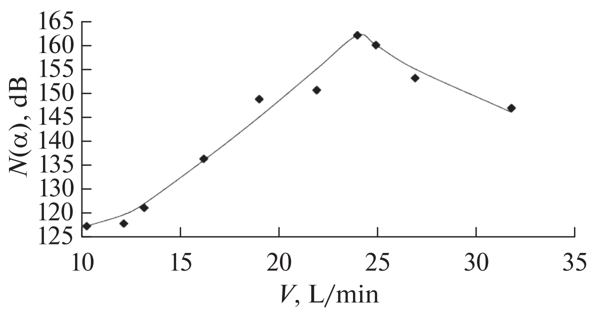

Fig. 3. Dependence of amplitude of gas oscillations on mixture flow rate.

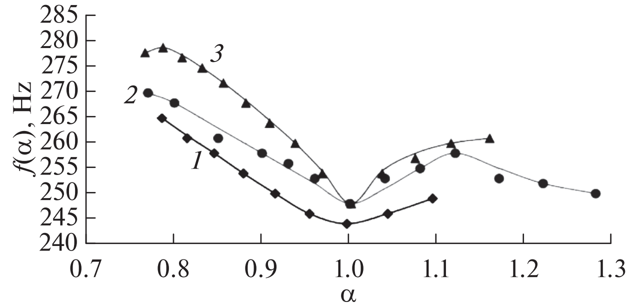

Fig. 4. Dependences of frequency of acoustic vibrations on excess air coefficient for three fixed air flow rates: *1*, V_a = 21 L/min; *2*, 25.8; *3*, 27.

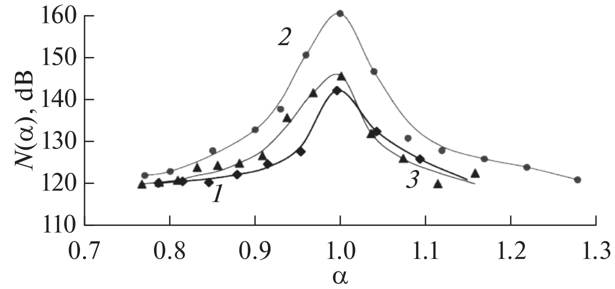

Fig. 5. Dependences of amplitude of acoustic vibrations on excess air coefficient: *1*, V_a = 21 l/min; *2*, 25.8; *3*, 27.

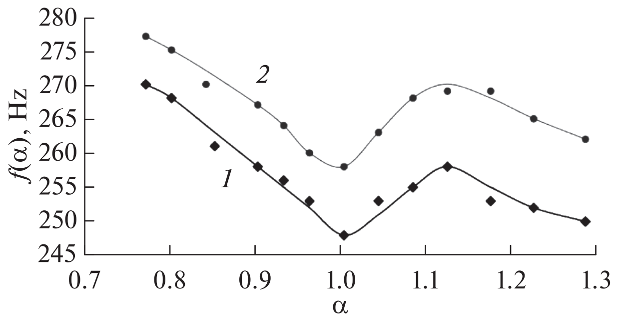

Fig. 6. Dependences of gas oscillation frequency on excess air coefficient for l_c = 0.45 m, l_t = 0.48 m: *1*, *n* = 4; *2*, 2.

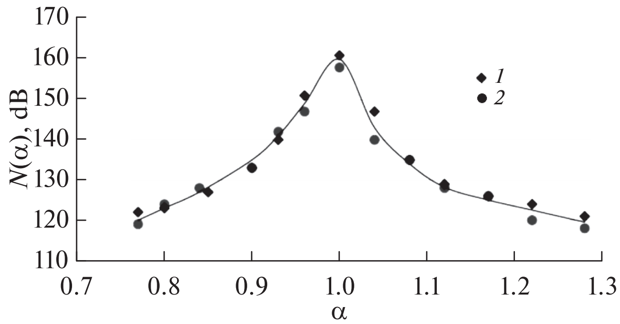

Fig. 7. Dependences of amplitude of gas oscillations on excess air coefficient for l_c = 0.45 m; l_t = 0.48 m: *1*, *n* = 4; *2*, 2.

and 4 showed that increasing the number of nozzles from two to four leads to a decrease in the gas oscillation frequency at the same α values (Fig. 6). In this case, the amplitude of gas oscillations in the combustion chamber remains almost unchanged (Fig. 7).

As a result, for a combustion chamber with a length $l_c = 0.45$ m, the most favorable conditions for the fluctuation combustion mode are as follows: air flow rate – 25.8 l/min and excess air coefficient in the mixture α from 0.77 to 1.22.

As a result of the experiment, an anomalous dependence of the gas oscillation frequency on the excess air coefficient was discovered: there is a minimum at $\alpha = 1$ and a local maximum at $\alpha \approx 1.15$. This peculiarity can be explained as follows. Due to heat transfer to the walls, the gas flow cools and the gradients of the average gas temperature and sound speed appear along the tube. In [6, 7, 10, 11], it was shown that the longitudinal distribution of the gas temperature, and consequently, density and sound speed significantly influences the excitation conditions, frequency, and amplitude of gas oscillations. In [8], the axial distribution of the gas temperature was measured and the corresponding sound speed distribution in a tube with a swirling flame was calculated:

$$c(x) = a - bx, \quad 0 \le x \le l_c,$$
$$a = a(\alpha) = c_1\sqrt{\frac{T_c(\alpha)}{T_1}}, \quad b = \frac{(a - c_l)}{l_0}, \tag{1}$$

where l_c is the tube length; $T_c(\alpha)$ is the gas temperature at the tube inlet; c_1, T_1 are the sound speed and ambient temperature; c_l is the sound speed at the tube outlet.

It has been established that for values of α close to unity, the value of $a(\alpha)$ remains almost unchanged. At the same time, the modulus of the sound speed gradient b increases rapidly and at $\alpha = 1$ reaches its maximum value, just like the amplitude of gas oscillations. These data allow us to explain the nature of the dependence $f(\alpha)$. For a linear sound speed distribution along the tube, to conduct a qualitative analysis, one can take the arithmetic mean of the sound speeds at the ends of the tube:

$$\bar{c} = (a + c_l)/2 = a - bl_c/2. \tag{2}$$

As α changes from 0.7 to 1, there is a slow increase in the gas temperature and, consequently, the sound speed at the tube inlet. It is known that gas oscillations significantly accelerate heat transfer from the gas to the walls. This means that, at the same input temperature, the gas temperature at the tube outlet decreases as the amplitude of gas oscillations increases. According to the experimental data, the amplitude of gas oscillations increases rapidly as α approaches unity. For a constant sound speed at the tube inlet, according to (1), the modulus of the sound speed gradient also increases, and in such a way that the average sound speed, according to (2), decreases, leading to a decrease in the oscillation frequency. For $\alpha = 1$, b reaches its maximum value, which corresponds to the minimum frequency. For $\alpha > 1$ there is a rapid decrease in b, which not only compensates for the decrease in the sound speed at the tube inlet, but also leads to a slight increase in the average sound speed and oscillation frequency. However, a further increase in the excess air coefficient causes a rapid decrease in the gas temperature and sound speed at the combustion chamber inlet. As well, the rate of change in b slows. As a result, the gas oscillation frequency, having reached a certain local maximum, begins to gradually decrease.

CONCLUSIONS

A study of the combustion process of a propane–butane fue–air mixture in an experimental combustion chamber with the mixture tangentially supplied showed that under certain conditions, combustion takes on a fluctuating character. In a tube with a length of 0.45 m, self-excitation of gas oscillations occurs with frequencies from 230 to 260 Hz and an SPL up to 162 dB. An anomalous dependence of the gas oscillation frequency on the excess air coefficient was revealed: a minimum at $\alpha = 1$ and a local maximum at $\alpha \approx 1.15$. The anomalous dependence of the gas oscillation frequency on the excess air coefficient is explained by the presence of a variable axial sound speed distribution, which depends not only on the excess air coefficient, but also on the amplitude of gas oscillations in the fluctuating combustion mode. When $\alpha = 1$, gas oscillations have the maximum amplitude.

FUNDING

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CONFLICT OF INTEREST

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