Acoustic oscillations of the gas with axial distribution of average temperature in the vortex combustion chamber

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Abstract. Modern research of combustion processes affect a large number of combustion modes of gaseous fuel, but so far the effects associated with the occurrence of acoustic oscillations of the gas with a longitudinal temperature distribution have not been well considered. This article discusses the case of the occurrence of self-oscillations in a vortex combustion chamber.

1. Introduction
It is known [1,2] that in pulsating combustion chambers the longitudinal temperature gradient of the gas significantly affects the conditions of excitation, frequency and amplitude of oscillations. As you know, the rate of heat transfer to the walls of the combustion chamber depends on the amplitude of gas oscillations. This means that the distribution of the gas temperature and the speed of sound in the mode of vibration combustion differ significantly from the distribution in the absence of oscillations or when their amplitude is infinitely small. This factor is not taken into account in the available math models. In particular, in gas turbine units, in order to reduce the yield of nitrogen oxides, the gas stream is specially cooled before leaving the combustion chamber. As a result, there is a significant difference between the gas temperature at the inlet and outlet of the combustion chamber arises. However, in the available papers devoted to the theoretical research of vibration combustion in such combustion chambers, temperature and sound velocity gradients were not considered at all.

In the present article, an experimental research of vibration combustion in the vortex combustion chamber with a tangential supply of a mixture of propane-butane fuel with air was carried out [3,4]. It was found that the gas temperature distribution in the vibration combustion mode differs significantly from the distribution corresponding to the boundary of excitation of oscillations when their amplitude is infinitely small. This factor is not taken into account in the available math models.

This work objective is to determine the vibration frequencies of natural gas depending on the excess air ratio in the vortex combustion chamber, and to compare with experimental data.

2. Vibration frequency determining method
The schematic diagram of the vortex combustion chamber is shown in Figure 1. The mixture enters through 4 holes with area $S_1$ into a certain area at the initial end of the tube – the combustion chamber. In this area with the volume $V_c$, the mixture burns out and the amount of heat $Q$ is released per unit time. The excitation of longitudinal acoustic vibrations is investigated.
Consider the case where the total area of the inlets is much less than the cross-sectional area of the combustion chamber. Then, in the first approximation, we have a tube with a closed inlet and an open outlet. The equation of frequencies of gas oscillations with a temperature gradient is known [1] and has the form (1):

\[
\cos \left[ \frac{\omega \beta}{b} \ln \left( 1 - \frac{b l_c'}{a} \right) - \arctan \left( \frac{b}{2 \omega \beta} \right) \right] = 0, \quad \beta = \sqrt{1 - \left( \frac{b}{2 \omega} \right)^2},
\]

where \( \omega \) is the angular speed of sound; \( a, b \) is coefficients of sound speed distribution; at the outlet, the combustion chamber is open and the boundary condition is met:

\[
p_c'(l_c', t) = 0, \quad l_c' = l_c + 0.613 R_c,
\]

where \( R_c \) is the radius of the tube.

The sound velocity distribution is associated with a decrease in the average temperature of the gas along the combustion chamber.

In the oscillation mode with a frequency \( f_1 \) and an amplitude of pressure pulsations in the combustion chamber \( P_{c,1} \) appropriating to the excess air coefficient \( \alpha = 1 \), the gas temperature \( T_{l,1} \) at the end of the combustion chamber is measured. The most optimal method for calculating the theoretical flame temperature is set out in the dissertation work of V M Larionov. [5], where the calculation of the theoretical flame temperature \( T'_c \) is reduced to the universal formula (2), which takes into account the weight or volume fractions in the composition of the "technical propane" mixture, as well as all losses through the coefficient \( \phi = 0.238 \), for propane.

\[
T'_c = T_1 + \frac{10^3 k}{(m+na)},
\]

where \( k = \alpha \) for \( \alpha \leq 1 \), \( k = 1 \) for \( \alpha \geq 1 \), \( m = 0.084 \), \( n = 0.452 \).

In order not to measure the temperature \( T_0 \) for each new value of \( \alpha \), taking into account expression (2), we introduce a correction factor (3)

\[
\theta = \frac{T_c(\alpha)}{T'_c(\alpha)} = \frac{[T_c(\alpha)+T_0(\alpha)]}{2} T'_c(\alpha).
\]
We will assume that the coefficient $\theta$ does not depend on $\alpha$. Then the dependence of the temperature $T_c$ on $\alpha$, taking into account (3), can be described by the expression (4)

$$T_c(\alpha) = \theta T'_c(\alpha)$$

(4)

Further calculations in determining the temperature and sound velocity gradients inside the vortex combustion chamber were carried out taking into account the data obtained. According to the well-known formula (4), the combustion temperature $T_{c,1}$ is found for $\alpha = 1$. We use the formula:

$$c = c_0 \sqrt{\frac{T}{T_0}}$$

(5)

where $c_0 = 343$ and corresponds to $T_0 = 293K$.

By formula (5), we calculate $c(0) = a_1$, corresponding to $T_{c,1}$, and $c_{l,1}$, corresponding to $T_{l,1}$. Then the distribution of the speed of sound has the form:

$$c_1(x) = a_1 - b_1 x, \quad b_1 = \frac{(a_1-c_{l,1})}{l_c}$$

(6)

For other $\alpha$, according to (5)

$$a(\alpha) = c_0 \sqrt{\frac{T_c(\alpha)}{T_0}},$$

(7)

where the combustion temperature $T_c(\alpha)$ is calculated using the well-known formula. Let's find the distance $L$, at which the speed of sound decreases to $c_0$, below which it cannot be. According to (6), we have:

$$c_0 = a_1 - b_1 L, \quad L = \frac{(a_1-c_0)}{b_1}$$

(8)

It follows from previous works that this distance is almost the same for other $\alpha$. Then $c_0 = a(\alpha) - b(\alpha)L$, where

$$b(\alpha) = \frac{(a(\alpha)-c_0)}{L}$$

(9)

The distribution of the speed of sound in the combustion chamber for any $\alpha$, but for oscillations with the amplitude $P_{c,1}$ has the form:

$$c_1(x, \alpha) = a(\alpha) - b(\alpha)x$$

(10)

Next, consider the case when there are no oscillations for $\alpha = 1$, i.e. $P_c = 0$. In this case, the combustion temperature $T_c(\alpha)$ and the value $a(\alpha)$ are the same as before. The experimental value of the gas temperature at the end of the combustion chamber is different, $T_l = T_{l,0}$. By formula (5) we calculate $c_{l,0}$, by (6) and (8)

$$b_0 = \frac{(a_1-c_{l,0})}{l_c}, \quad L_0 = \frac{(a_1-c_0)}{b_0}$$

(11)
Distribution of sound speed:

\[ c_0(x, \alpha) = a(\alpha) - b_0(\alpha)x, \quad b_0(\alpha) = \frac{(a(\alpha) - c_0)}{L_0} \]  \quad (12)

Let us determine the general form of the distribution of the speed of sound taking into account the influence of the amplitude of gas oscillations. Let us assume that the dependence of the sound speed gradient on the amplitude of pressure fluctuations in the combustion zone is linear: \( b(\alpha, P_c) = b_0(\alpha) + \xi P_c \). Then distribution (10) takes the form:

\[ c(x, \alpha, P_c) = a(\alpha) - (b_0(\alpha) + \xi P_c)x \]  \quad (13)

For \( \alpha = 1, \ P_c = P_{c,1} \), according to (6), (11) and (13) we have:

\[ c_1(x) = a_1 - b_1 x = a_1 - (b_0 + \xi P_{c,1})x \]

Hence:

\[ \xi = \frac{(b_1 - b_0)}{P_{c,1}} \]  \quad (14)

In the case \( P_c = 0 \), (13) implies (12).

3. Calculation results in comparison with experimental data

Measurements showed that for an air flow rate of 27.7 L / min, the experimental values at \( \alpha = 1 \) of the gas temperature at the outlet of the combustion chamber during oscillations, without fluctuations, and the temperature in the center of the combustion zone are respectively 376K, 553K, 1075K. The dependence of the gradient of the sound speed on the amplitude of gas oscillations was determined according to the experimental data, Figure 2. Figure 3 (1 - without oscillations, 2 - with oscillations, 3 - experiment) shows the results of calculation and measurement of gas oscillation frequencies. To calculate the coefficient \( \xi \), we used the value of the pressure pulsation amplitude corresponding to the measured value of the sound pressure level for \( \alpha = 1 \) (Fig. 2). The gradient of the speed of sound for other values of \( \alpha \) was calculated after substituting the corresponding values of the amplitude of pressure pulsations according to the experimental data, which are shown in Figure 2.
Based on the results of the calculation performed, it can be concluded that the frequencies obtained in the presence of gas self-oscillations decrease as the excess air ratio tends to unity on both sides (curve 2). This conclusion is confirmed by the results of experimental measurements of the gas vibration frequencies for different air excess ratios (curve 3). If we do not average the temperature of gases in the combustion zone and neglect the influence of the amplitude of gas oscillations on the gradient of the speed of sound, the results of the calculations are qualitatively and quantitatively inconsistent with the experimental data (curve 1).

4. Conclusion
The recognized effect is by its nature anomalous and sharply differs from the research of other authors, since during vibration combustion in a tube, the maximum gas temperature usually corresponds to the maximum frequency and amplitude of oscillations. In our case, the frequency of gas oscillations at maximum combustion temperatures has a minimum value. This is probably due to the combined combustion mode, where a vortex mode is added to the gas pulsations by means of tangential flow swirling.

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