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Spectral analysis of high-speed flow at combustion of preliminary unprepared fuel-air mixture

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The results of the study of spectral characteristics of high-speed flow under conditions of autoignition of priliminary unprepared fuel-air mixture with intensive interaction of external acoustics and combustion are presented. As a result of thermoacoustic interaction, the power of pulsations increases by an order of magnitude or more compared to the case of „cold“flow, as a result of which mixing improves, combustion intensifies and heat release increases. At high levels of heat release, flow instability and the probability of transition to vibrational combustion occur. Keywords: supersonic flow, combustion, pressure pulsations, spectrum.

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Combustion-induced flow fluctuations, which are commonly known as combustion instability, induce an increase in pressure and heat fluxes, high-amplitude structural vibrations, and combustion failure. This may have disastrous consequences for combustion chambers and power devices. Although these phenomena have been studied extensively for a long time, supersonic reactive flows have remained virtually uninvestigated until recently. In the case of subsonic and transonic flows, the feedback mechanism appears obvious due simply to the possibility of propagation of disturbances upstream via large separation regions. It was assumed that such a mechanism is infeasible at local flow velocities corresponding to a Mach number of 2 (and certainly 3 or 4). However, it has recently become clear that upstream transmission of disturbances is possible at high flow velocities [1]. if ignition is initiated near the channel wall with intense combustion and an increase in the size of separation regions and the thickness of the subsonic flow part. The conditions at the channel inlet (pulsations of the main air flow and the high-pressure fuel jet) are the factors governing thermoacoustic oscillations of the reacting flow. The other factors are the ignition process instability, the interaction of flow aeroacoustics with flame-generated acoustics, and the enhancement of instability in back propagation of the flame. Acoustic instability emerges when acoustic waves start to interact with acoustic waves generated by combustion. As the pressure in the combustion zone increases, the separation of the boundary layer and the intensity of shock waves increase, inducing a change in the wave structure of flow in the channel and a mixing enhancement.

The aim of the present study is to examine the spectral characteristics of a combusting flow at high flow velocity and acoustic intensity at the channel inlet. Experiments were performed using a pulsed setup with a model of a rectangular channel with a constant cross-section of 100 × 100 mm that featured a supersonic nozzle, an insulator, and a flame stabilizer in the form of a step (Fig. 1, *a*). The model was fitted with optical glasses for flow visualization. Fuel was supplied in front of the step through eight round apertures on the upper and lower walls at an angle of 90°. The setup, the model, and the experimental procedure were discussed in detail in [2,3]. Tests were carried out at a static pressure of 0.08−0.12 MPa, a stagnation temperature of 1760 ± 35 K, and an overall fuel-air ratio $\beta = 0.5{-}0.985 \pm 0.016$. The fuel-air ratio was determined based on the conditions at the channel inlet within the entire operating time of the pulsed setup as the ratio of fuel and air masses divided by the stoichiometric ratio of these masses; i.e., $\beta = (m_f/m_a)/M_{0st}$.

The data in Fig. 1, *b* illustrate the change in pressure in the channel with an increase in the fuel-air ratio, which is accompanied by an increase in the pulsation amplitude. Here, X is the relative distance of the measurement point from the flame stabilizer step (in units of step height). Curve *1* corresponds to a flow without combustion, but with fuel supplied to a nitrogen atmosphere. The level of pulsations is minimal in this case, and they are caused exclusively by disturbances at the channel inlet. These data correspond to the initial pulsation level and are used to quantify combustion pulsations. Curves *2–4* illustrate the growth of pulsations with combustion intensification. At $\beta = 0.62$, pressure pulsations remain virtually unchanged, and the pressure value remains constant. It follows from the comparison of curves *2* and *3* that even a small increase in β induces an increase in pressure due to the intensification of pulsations before the pressure rise [2]. A further increase in the fuel-air ratio is accompanied by

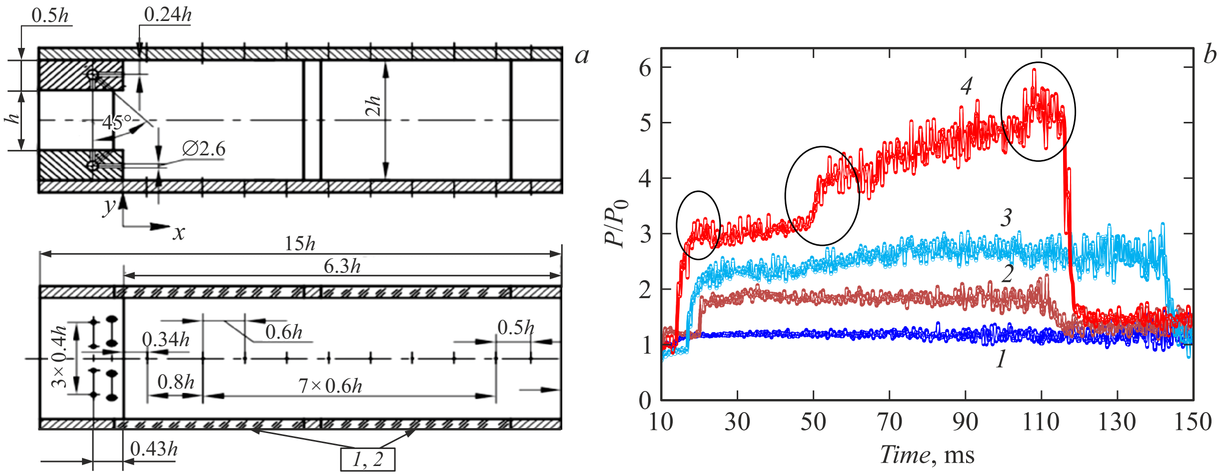

Figure 1. Schematic diagram of the model (*a*) and pressure pulsations observed with an increase in heat supply (*b*). *1* — $\beta = 0$, $X = 2.94h$; *2* — $\beta = 0.62$, $X = 2.94h$; *3* — $\beta = 0.68$, $X = 5.34h$; *4* — $\beta = 0.98$, $X = 5.34h$.

a significant variation of pressure and pulsations (curve *4*). Three characteristic regions of pressure pulsation growth are highlighted in the figure: ignition (10–18 ms), abrupt increase in pressure (48–55 ms), and transition to subsonic combustion (105–115 ms). Each of these regions precedes an increase in the average integral heat release within the corresponding time interval under quasi-stationary conditions (with the combustion efficiency taken into account).

In order to examine the amplitude-frequency parameters of pressure pulsations under significant non-stationarity of average values, the pulsation component was isolated by subtracting a smoothed function from the original signal. The averaged value was obtained using smoothing splines. Following the approach tested in [3], the original signal was approximated for this purpose by a cubic spline.

The quantitative change in the amplitude of pressure pulsations without and with combustion at $\beta = 0.98$ is illustrated by the measurement results presented in Fig. 2. Here, the pressure pulsation amplitudes are compared for a flow without combustion but with a hydrogen jet (curve *1* in Fig. 1) and a flow with intense combustion at $\beta = 0.98$ wherein the transition to subsonic combustion has occurred (curve *4* in Fig. 1). It is immediately obvious that the presented data differ qualitatively. The „cold" flow (Fig. 2, *a*) is characterized by a monotonic broadband spectrum of pulsations in the operating mode of the setup without any pronounced discrete values of amplitude. It follows from Fig. 2, *a* that this nature of pressure pulsations is preserved (with only minor deviations) throughout the entire length of the channel.

The pattern of temporal variation of pulsations in the reacting flow differs profoundly both quantitatively and qualitatively. It is evident that the amplitude of pulsations in time and space increases significantly (by a factor of 4–5); in extreme zones (ignition and combustion intensification, $\tau \approx 50$ and 110 ms), the increase factor is even higher and reaches 8–10. The enhancement of pulsations in the highlighted region is the result of intensification of heat release within the initial section of combustion during ignition and intensification of the thermoacoustic interaction. The patterns of pressure rise in the channel at $\beta = 0.68$ and 0.98 (curves *3* and *4* in Fig. 1) are qualitatively similar within the time interval of 0–50 ms. However, in the latter case, the average pressure is somewhat (10–15%) higher. This local pressure increase was sufficient to ensure that the interaction of external flow turbulence and acoustic waves generated during combustion resulted in improved mixing and upstream flame propagation. Owing to these processes, the pressure in the ignition zone increases, heat release intensifies, and an increase in pressure is established throughout the channel with a corresponding abrupt pressure buildup. These results indicate that pressure fluctuations under complex thermoacoustic interaction conditions differ greatly from those observed without combustion or with local combustion.

Fast Fourier transform was used to quantify the power spectral density (PSD) of isolated pulsations as a function of frequency (f). A set of 1024 samples (204 ms) was processed, which made it possible to examine frequencies up to 2.5 kHz. Figure 3 presents a comparison of the results of determining the PSD for two fuel-air ratios at the point corresponding to coordinate $X = 4.74h$, where the pressure rise reached its maximum. It can be seen that a 40 % increase in β leads to a 3–4-fold increase in spectral power and a change in position of the pulsation maximum (depending on the combustion intensity). As follows from Fig. 3, *a*, the maximum PSD values shift toward lower frequencies of 150–470 Hz when the combustion intensity increases. With a reduced β value (i.e., with a lower heat release), the PSD values are maximized at the frequencies of 620–800 Hz. This frequency level remains virtually unchanged throughout the combustion process. To illustrate the degree of variation of the pulsation level,

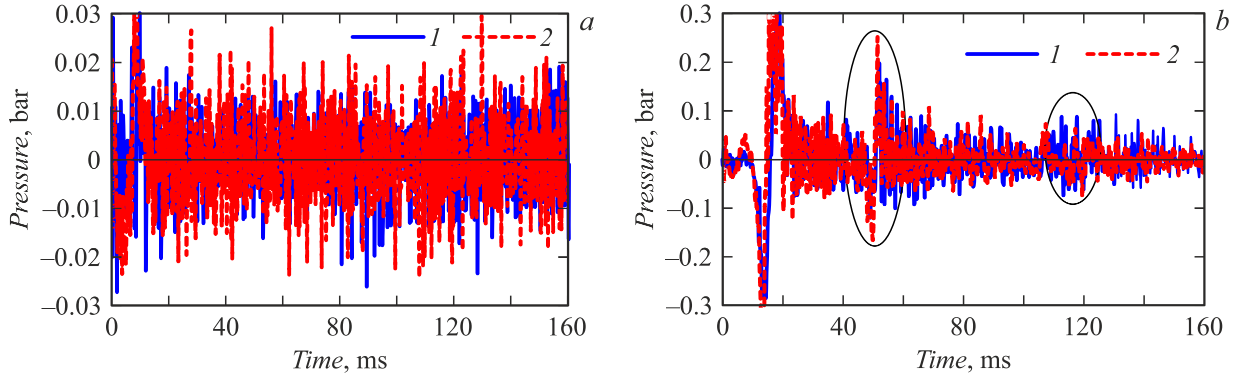

Figure 2. Pressure pulsations in flows without (*a*) and with (*b*) combustion. $X = 0.34h$ (*1*) and $5.34h$ (*2*).

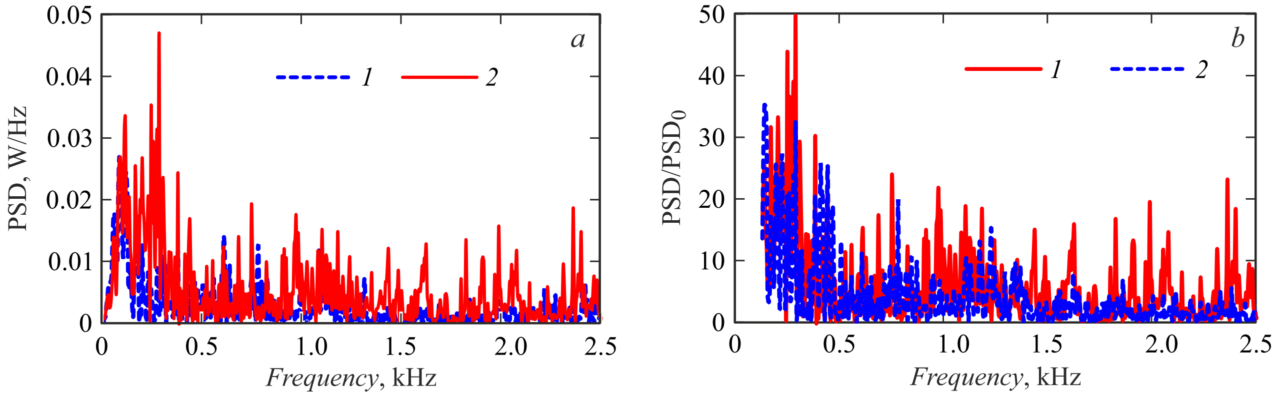

Figure 3. Power spectral density for a flow with heat supply at different combustion intensities. $\beta = 0.68$ (*1*) and 0.98 (*2*).

Fig. 3, *b* presents the normalized power spectral density for the same PSD values that are shown in Fig. 3, *a*.

The corresponding PSD value (denoted as PSD_0) for a flow without combustion at the channel inlet was used as a reference for normalizing the $\mathrm{PSD}(f)$ dependence. The presented data indicate that the interaction of external flow acoustics with combustion-induced acoustics leads to a significant enhancement of pressure pulsations; the power spectral density may increase by a factor up to 40–50 with a stoichiometric composition of the mixture and by a factor of 10–20 with moderate heat release. The obtained data are consistent with the results for reacting flows at supersonic flow speeds [4].

The above data correspond to the points at which the maximum heat release was achieved in the operating mode of the setup. Such dependences were obtained at various points along the entire length of the channel and are typical of a combusting flow. However, quantitative changes depend on the overall fuel-air ratio and the initial flow parameters at the channel inlet. Therefore, the presented results should be regarded as data close to the maximum values that were obtained under different conditions at the measuring channel inlet, but remained constant throughout a single experiment.

The results of studies of the spectral characteristics of high-speed reactive suggest the following conclusion. Although the processes of pulsation intensification are investigated primarily in the context of flow instability and the emergence of unsafe resonant modes, one cannot exclude the possibility of their use to improve mixing and increase effectively the enthalpy of a high-speed flow.

The process of transition to intense combustion is two-stage in nature and is driven by the enhancement of pulsations in the combustion initiation area. An abrupt increase in pressure is due to the enhancement of pressure pulsations upon local intensification of combustion. The results of spectral analysis of the flow indicate that an increase in heat release during combustion (e.g., with an increase in fuel-air ratio, fuel feed pressure, or combustion efficiency) leads to an intensification of thermoacoustic interaction and, consequently, to an extreme amplification of pressure pulsations to the point of transition to vibrational combustion.

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Conflict of interest

The author declares that he has no conflict of interest.

References

[1] H.T. Luong, Y. Wang, H.S. Han, C.H. Sohn, Aerospace Sci. Technol., **118**, 106994 (2021). DOI: 10.1016/j.ast.2021.106994

[2] M.A. Goldfeld, Int. J. Hydrogen Energy, **48** (53), 20483 (2023). DOI: 10.1016/j.ijhydene.2023.02.114

[3] N.N. Fedorova, M.A. Goldfeld, V.V. Pickalov, Combustion, Explosion, Shock Waves, **58** (5), 536 (2022). DOI: 10.1134/S0010508222050057.

[4] M. Sun, H. Wang, Z. Cai, J. Zhu, *Unsteady supersonic combustion* (Springer, Singapore, 2020). DOI: 10.1007/978-981-15-3595-6

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