SPECTRAL CHARACTERISTICS OF VORTICITY AND TEMPERATURE PULSATIONS IN TURBULENT FLOW WITH HEAT SOURCES

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We propose a mathematical model of the interaction of vorticity and temperature pulsations for turbulent flow in the mixing layer of wakes. We obtain the spectral characteristics of temperature and vorticity pulsations in the presence of heat release.

Instabilities have been observed in the working regimes of systems with intense energy release, which include combustion chambers of modern thermoenergetic devices, chemical reactors, and a number of plasma technology devices. These instabilities are directly connected with the physical processes which occur in the systems [1]. In this case the instabilities manifest themselves in the arisal and amplification of certain types of disturbances [2].

According to [3], any deviation of the thermodynamic parameters from their average values can be represented in the form of a superposition of acoustic, vortical and thermal perturbations. Acoustic-vortical and thermoacoustic interactions have been studied in detail, and the results have been generalized in monograph [1]. Thermo-vortical interactions have been studied to a lesser degree, although a series of experimental data indisputably establishes their existence during combustion [4].

The goal of this work is to establish a model of thermo-vortical interactions in the presence of volume heat release.

1. Mathematical Model

We examine plane, isobaric flow of a viscous heat-conducting gas in the mixing layer of two wakes and in the presence of volume heat sources. The average velocity of the flow is along the x-axis (see Fig. 1).

We write the basic system of conservation equations in the usual form [5], taking into account the presence of nonlinear volume heat source $Q(T, \mathbf{u})$:

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \mathbf{u}) = 0, \qquad (1)$$

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho(\mathbf{u}\nabla)\mathbf{u} = -\nabla p + \mu \nabla^2 \mathbf{u}, \qquad (2)$$

$$\rho c_p \left(\frac{\partial T}{\partial t} + \mathbf{u}\nabla T \right) = Q(T, \mathbf{u}) + \lambda \nabla^2 T. \qquad (3)$$

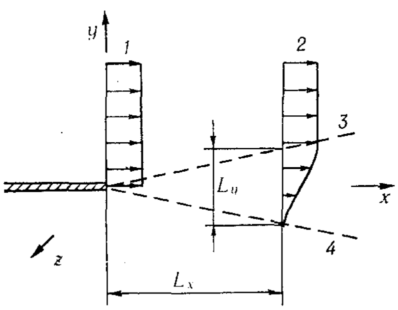

Fig. 1. Flow pattern in a mixing layer: 1, 2) averaged velocity u_0 profile at the burner nozzle edge and in a typical cross section; 3, 4) inner and outer boundaries of the mixing layer.

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For isobaric flow the equation of state takes the form

$$\rho T = \text{const.} \tag{4}$$

Applying the operator rot to (2), we obtain the vorticity equation [6]. We write this for small perturbations, using the previously estimated residence time $\tau_{res} = L_x/u_0$ and rise (induction) time $\tau_i = L_y/u_0$ for the perturbation in the mixing layer. Here L_x and L_y are the dimensions of the mixing layer along the x- and y-axes, $u_0 = (u_{x0} \equiv u_0, 0, 0)$ is the averaged flow velocity (see Fig. 1). In the future we assume that L_y is the dimension of the largest vortex, and that vorticity generation occurs as a result of flow velocity differences in the mixing layer $\Delta u_0 = u_{0max} - u_{0min}$, $\Delta u_0 \sim u_0$ for the discharge stream in the flooded space. In addition, for $Re = u_0 h/\nu \gg 1$ (h is the width of the nozzle outlet, $h \gg L_y$ [7]) $L_y/L_x \ll 1$ and correspondingly, $\tau_i/\tau_{res} \ll 1$.

As a result we obtain in place of (2) after straightforward transformations the equation for small perturbations in the vorticity Ω' in the case ρ = const:

$$\frac{\partial \Omega_z'}{\partial t} = -u_y' \frac{\partial \Omega_{z0}}{\partial y} + \nu \frac{\partial^2 \Omega_z'}{\partial y^2}, \tag{5}$$

where

$$\Omega_z' = \frac{\partial u_y'}{\partial x} - \frac{\partial u_x'}{\partial y}, \quad \Omega_{z0} = \frac{\partial u_{y0}}{\partial x} - \frac{\partial u_0}{\partial y}.$$

Velocity pulsations along the x-axis can be induced by either shear stresses in the mixing layer, or by density or temperature pulsations. In this connection, it is useful to represent the velocity as the sum of two components

$$u_y' = u_{yv}' + u_{yp}', \tag{6}$$

where u_{yv}' is the vortical component of the pulsation u_y', which is caused by pulsations in the shear stresses; and u_{yp}' is the potential component, due to density and temperature pulsations.

We know that for free vortex flow [7]

$$u_{yv}' = L\Omega_z', \quad L = \frac{\Delta u_0}{(\partial u_0/dy)_{\max}}, \quad \frac{d\Omega_{z0}}{dy} = -\frac{d^2 u_0}{dy^2}, \tag{7}$$

where $L \equiv L_y$ is the characteristic width of the mixing layer. Substituting (7) into (5) and using (6) we obtain

$$\frac{\partial \Omega_z'}{\partial t} = \frac{\Delta u_0}{(du_0/dy)_{\max}} \frac{d^2 u_0}{dy^2} \Omega_z' + \frac{d^2 u_0}{dy^2} u_{yp}' + \nu \frac{\partial^2 \Omega_z'}{\partial y^2}. \tag{8}$$

Equation (8) permits description of vorticity generation in the mixing layer with account taken of the transverse velocity gradient, the influence of density and temperature pulsations on the process, and also of vorticity decay as a consequence of viscous losses.

We now obtain the equation of energy (3) for small perturbations, which is derived from (6) and (7) in analogy to (8). We have in the end

$$\frac{\partial T'}{\partial t} = \left[\frac{1}{\rho_0 c_p}\left(\frac{\partial Q}{\partial u_0}\right)_T - \frac{\partial T_0}{\partial y}\right] \frac{\Delta u_0}{(du_0/dy)_{\max}} \Omega_z' + \frac{1}{\rho_0 c_p}\left(\frac{\partial Q}{\partial T}\right)_{u_0} T' + \frac{\partial T_0}{\partial y} u_{yp}' + a \frac{\partial^2 T'}{\partial y^2} \tag{9}$$

where we have taken into account

$$Q' = \left(\frac{\partial Q}{\partial T}\right)_{u_0} T' + \left(\frac{\partial Q}{\partial u_0}\right)_T u_y'.$$

Such a relation reflects the dependence of the heat-release perturbation on temperature, through the kinetics of chemical reactions, and also on the velocity pulsation. This holds, for example, close to the region of flame separation when the fuel mixture is strongly enriched or made lean by combustion and flashback occurs, due to insufficient stabilization [8].

It is evident from Eqs. (8) and (9) that vorticity perturbations influence the temperature pulsations through heat release rate perturbation. The inverse effect may exist if the width of the burner outlet is of the same order of magnitude as the dimension of the mixing layer; $h \sim L_y$. We consider this case as beyond the limits of this work.

We write Eqs. (8) and (9) in final form, which describes thermo-vortical interactions in the presence of heat release:

$$\frac{\partial \Omega_z'}{\partial t} = I_\Omega \Omega_z' + \nu \frac{\partial^2 \Omega_z'}{\partial y^2}, \tag{10}$$

$$\frac{\partial T'}{\partial t} = I_{T\Omega}\Omega_z' + I_T T' + a\frac{\partial^2 T'}{\partial y^2}. \tag{11}$$

Here $I_\Omega = \Delta u_0(d^2u_0/dy^2)/(du_0/dy)_{max}$ is the increment of the vorticity perturbation, a quantity inversely proportional to the characteristic induction time of the perturbed vorticity ($I_\Omega \sim \tau_{i\Omega}^{-1}$). The value I_Ω characterizes the vorticity perturbation source in the mixing layer as a consequence of the appearance of shear stresses at the outflux of the reacting mixture. The parameter $I_{T\Omega} = [(\partial Q/\partial u_0)_T/(\rho_0 c_p) - \partial T_0/\partial y]\Delta u_0/(\partial u_0/\partial y)_{max}$ characterizes the perturbation energy pumping in the temperature perturbation, caused by the vorticity perturbations. This mechanism is due to the sensitivity of the heat release rate to velocity pulsations and the nonisothermal nature of the flow in the transverse direction. As follows from an analysis of these quantities, the condition for the influence of the vorticity perturbation on heat release is the presence of shear stresses.

The quantity $I_T = (\partial Q/\partial T)_{u_0}/(\rho_0 c_p)$ is the increment in the temperature perturbation. It is inversely proportional to the characteristic induction time of the temperature perturbation ($I_T \sim \tau_{it}^{-1}$). The terms $(d^2u_0/dy^2)u_{yp}'$ and $(dT_0/dy)u_{yp}'$ in Eqs. (8) and (9) were discarded in obtaining (10) and (11), since the value of u_{yp}' is, as is easily shown, proportional to the value of the averaged transverse velocity, which is negligibly small in the framework of the present problem. The effect of u_{yp}' is a subject for special study.

2. Spectral Characteristics of the Vorticity Fluctuations

We examine the spectrum of the vorticity perturbation in the mixing layer. Towards this end, we introduce into (10) the random pulsation source:

$$\frac{\partial \Omega_z'}{\partial t} = I_\Omega \Omega_z' + \nu \frac{\partial^2 \Omega_z'}{\partial y^2} + \xi(y, t), \tag{12}$$

$$\langle \xi(y, t) \rangle = 0, \quad \langle \xi(y, t)\xi(y', t') \rangle = \sigma_\Omega \delta(y' - y)\delta(t' - t). \tag{13}$$

Here $\xi(y, t)$ is the delta-correlated random vorticity pulsation source; σ_Ω is the vorticity perturbation intensity; the angular brackets denote averaging.

On the basis of (12) and (13) we can obtain the autocorrelation function for the vorticity perturbations:

$$R_\Omega(\Delta t) = \frac{\sigma_\Omega}{\nu k^2 - I_\Omega}\exp[-(\nu k^2 - I_\Omega)\Delta t], \quad \Delta t = t' - t. \tag{14}$$

It is easy to see that the presence of shear stresses in the mixing layer leads to an increase in the correlation time $\tau_c = (\nu k^2 - I_\Omega)^{-1}$ and to the corresponding growth in the intensity of the vorticity perturbations. Perturbations with scales less than $l^* = 2\pi/k_1^*$ prove to be unstable, where

$$k_1^* = (I_\Omega/\nu)^{1/2}. \tag{15}$$

In this way it is possible that "long-lived" structures with scales $l \geq l^*$ can arise and be amplified against a background of small-scale turbulence ($l < l^*$) [9].

We determine the spectral power density (SPD) S_Ω for the vorticity perturbation. To do this, following [10], we average the perturbations over the width of the mixing layer. The expression for $S_\Omega(\omega)$ takes the form (ω is the circular frequency)

$$S_\Omega(\omega) = (2\pi)^{-1} \int_{-\infty}^{\infty} \frac{\sin^2 kL}{(kL)^2} |D(k, \omega)|^2 S_\xi(k, \omega)\, dk. \tag{16}$$

Here $|D(k, \omega)| = [(\nu k^2 - I_\Omega)^2 + \omega^2]^{-1}$ is the modulus of the system transfer function; and $S_\xi(k, \omega) = \sigma_\Omega$ is the SPD of the random source. Direct integration of (16) gives

$$S_\Omega(\omega) = \frac{\sigma_\Omega}{4Lq^2}\left\{1 + \frac{1}{4\alpha_-}\left(\frac{4I_\Omega}{q} - 1\right) + \frac{1}{2}\exp(-\alpha_-) \times \right.$$

$$\left. \times \left[\frac{\cos\alpha_+}{\alpha_-}\left(1 - \frac{2I_\Omega}{Q}\right) - \frac{\sin\alpha_+}{\alpha_+}\left(1 + \frac{2I_\Omega}{q}\right)\right]\right\},$$

$$q = \sqrt{I_\Omega^2 + \omega^2},\ \alpha_\pm = \sqrt{\frac{2}{\nu_0}(q \pm I_\Omega)},\ \nu_0 = \nu / L^2. \tag{17}$$

We obtain the asymptotes to $S_\Omega(\omega)$ for two cases of interest:

1) $I_\Omega > 0$; here

$$S_\Omega(\omega) = \frac{\sigma_\Omega}{4L^2}\left(\frac{\nu}{I_\Omega^3}\right)^{1/2}\left[\frac{3}{4} - \frac{1}{2}\cos\left(2L^2\frac{I_\Omega}{\nu}\right)\right]\omega^{-1},\ \omega \to 0; \tag{18}$$

$$S_\Omega(\omega) = \frac{\sigma_\Omega}{4L}\omega^{-2},\ \omega \to \infty; \tag{19}$$

2) $I_\Omega = 0$. In this case, in palce of (17) we have

$$S_\Omega(\omega) = \frac{\sigma_\Omega}{4L\omega^2}\left[1 - \frac{1}{\alpha_0} + \frac{1}{2}\exp(-\alpha_0)(\cos\alpha_0 - \sin\alpha_0)\right],$$

$$\alpha_0 = L(2\omega/\nu)^{1/2}.$$

Then the asymptotes take the form

$$S_\Omega(\omega) = \frac{\sigma_\Omega L}{8\sqrt{2\nu}}\omega^{-3/2},\ \omega \to 0, \tag{20}$$

$$S_\Omega(\omega) = \frac{\sigma_\Omega}{4L}\omega^{-2},\ \omega \to \infty. \tag{21}$$

By analyzing these asymptotes, we can draw the following conclusions:

1. A characteristic feature of this system for $I_\Omega > 0$ is the asymptotic form $S_Q(\omega) \sim \omega^{-1}$ for $\omega \to 0$ (or as will be shown below, in the more general case $S_\Omega \sim \omega^n$, where $n \geq -1$). Such a dependency in all likelihood is a characteristic peculiar to a nonequilibrium system [10].

2. The great sensitivity of the SPD to the width of the mixing layer ($S_\Omega \sim L^{-2}$) for $I_\Omega > 0$ as $\omega \to 0$ is notable. This is indicative of the determining influence of the initial section of the mixing layer on the generation of large-scale vortical structures, where the maximum transverse gradient in parameters is observed.

Figure 2 shows the characteristic form of the SPD of vorticity perturbations for various values $\bar{I}_\Omega = I_\Omega/\sigma_\Omega$ (Fig. 2a) and also the dependence of the power exponent n in the relation $S_\Omega(\omega) \sim \omega^n$ under similar conditions (Fig. 2b). It is apparent that:

$n = -1$ for $\omega = I_\Omega$, $n > -1$ for $\omega < I_\Omega$, $n < -1$ for $\omega > I_\Omega$.

For the purpose of interpreting our results, we examine (16). The product kL in the integrand characterizes the phase correlation of the dimensions of the perturbation and the width of the mixing layer. Here $k = 2\pi/\lambda_p$, where λ_p is the perturbation wavelength. As can be seen from (16), the integrand vanishes for $kL = 2\pi m$ (m = 0, 1, 2, 3, ...). We examine the characteristic values of the phases of the perturbations.

1) $kL_y \ll 1$. This condition is equivalent to $\omega \to 0$ ($\lambda_p \to \infty$). In this case, the perturbations are in a combustion zone that is "infinitely long" and their amplitude grows as a result of energy release. The perturbation energy is proportional to the characteristic residence time in the generation zone, which is in keeping with the dependency $S_\Omega \sim \omega^{-1}$.

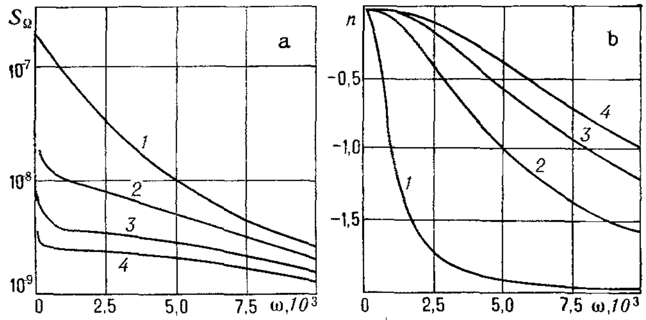

Fig. 2. Dependence of (a) SPD the vorticity perturbation and (b) the exponent index n on frequency ($\nu = 10^{-4}$ m²/sec, $L_y = 10^{-2}$ m). 1) $\bar{I}_\Omega = 10^3$ m/sec⁴; 2) $5 \cdot 10^3$; 3) $8 \cdot 10^3$; 4) 10^4. S_Ω is in units of sec^{-2}/Hz; ω in sec^{-1}.

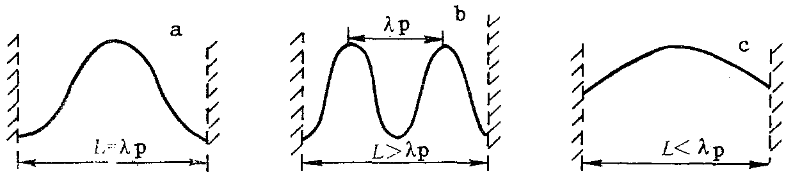

Fig. 3. Diagram illustrating the phase relationship between the dimensions of the perturbations and the width of the generation zone. a) boundary of the stability region, $kL = 2\pi$, $\tau_i = \tau_{res}$, $n = -1$; b) stability region, $kL > 2\pi$, $\tau_i > \tau_{res}$, $n < -1$; c) instability region, $kL < 2\pi$, $\tau_i < \tau_{res}$, $n > -1$.

Physically this signifies the onset of flicker noise [11], when in the mixing layer (or in the boundary layer) large-scale formations arise, which serve as the basis for coherent structure [10, 12].

2) $kL_y = 2\pi$. Under this condition, an entire perturbation period is reduced to the width of the mixing layer L_y (Fig. 3a). In other words, the characteristic dimension of the pulsation $\lambda_p = 2\pi/k$ coincides with the dimension L_y. This case corresponds to equality of the characteristic induction time of the perturbations and their residence time.

3) $kL_y < 2\pi$. Here the dimension of the perturbation exceeds L_y (Fig. 3c), and amplification of the perturbation takes place according to the "scenario" described in para 1, and $n \geq 1$.

Thus the power index n can serve as a criterion which characterizes the amplification or decay of vorticity or temperature perturbations [10].

3. Spectral Characteristics of Temperature Pulsations in the Presence of Vorticity Perturbations

Switching over to an analysis of the spectral characteristics of temperature puslations in the heat-release zone, we note that the conclusions inferred above for vorticity perturbations are valid for the temperature pulsations as well, if the characteristic induction time for the thermal perturbations τ_{it} is much less than the characteristic time of energy exchange between vorticity and temperature perturbations, that is,

$$I_T \gg |I_{T\Omega}|\, \Omega^0 / T^0, \tag{22}$$

where Ω^0, T^0 are the characteristic values for the amplitudes of the vorticity and temperature perturbations.

In this case, we represent Eq. (11) in analogy with (12), adding to the right hand side a random source of temperature perturbations $\eta(y, t)$:

$$\frac{\partial T'}{\partial t} = I_{T\Omega}\Omega_z' + I_T T' + a\,\frac{\partial^2 T'}{\partial y^2} + \eta(y,\ t). \tag{23}$$

We also assume that the properties of $\eta(y, t)$ are identical to those of $\xi(y, t)$, and furthermore assume that there is no correlation between them, that is:

$$\langle \eta(y, t) \rangle = 0, \quad \langle \eta(y, t)\eta(y', t') \rangle = \sigma_T \delta(y'-y)\delta(t'-t),$$
$$\langle \eta(y, t)\xi(y', t') \rangle = \langle \xi(y, t)\eta(y', t') \rangle = 0. \tag{24}$$

Representing the solution to system (12) and (23) in the form $T'(y, t) = T(t)\exp(-iky)$, we obtain

$$\ddot{T}' + \chi(k)\dot{T}' + \omega_0^2(k)T' = \varphi_T(k, t), \tag{25}$$

where

$$\chi(k) = (a+\nu)k^2 - (I_\Omega + I_T); \quad \omega_0(k) = [a\nu k^4 - (aI_\Omega + \nu I_T) + I_\Omega I_T]^{1/2};$$
$$\varphi_T(k, t) = \dot{\eta} + (\nu k^2 - I_\Omega)\eta + I_{T\Omega}\xi; \quad S_\varphi(k, \omega) = [(\nu k^2 - I_\Omega)^2 + \omega^2]\sigma_T + I_{T\Omega}^2\sigma_\Omega. \tag{26}$$

In these equations, χ, ω_0, φ_T, S_φ are the decrement and resonance frequency of the thermovortical interactions, the random source and its SPD, respectively.

If large-scale perturbations predominate in the mixing layer, whose evolution is determined solely by the action of the nonlinear sources, then the dissipation terms in the expression for ω_0 can be neglected. Then in place of ω_0 we obtain a relation for some effective frequency ω_e, averaged over the scale of the perturbations:

$$\omega_0 \simeq \omega_e = (I_\Omega I_T)^{1/2} = \left[\frac{\Delta u_0}{\rho_0 c_p (du_0/dy)_{\max}} \frac{\partial^2 u_0}{\partial y^2} \left(\frac{\partial Q}{\partial T}\right)_{u_0}\right]^{1/2}. \tag{27}$$

The modulus of the transfer function for temperature fluctuations in analogy to (16) takes the form

$$|D_T(k, \omega)| = \left\{\omega^2\left[(\varepsilon k^2 - I_0)^2 + \left(\frac{\omega_e^2}{\omega^2} - 1\right)\omega^2\right]\right\}^{-1}, \quad \varepsilon = a + \nu, \ I_0 = I_\Omega + I_T. \tag{28}$$

Using (27) and (28) in analogy to (16), we write an expression defining the SPD for temperature pulsations, which after integration yields:

$$S_T(\omega) = \frac{a_0^2\sigma_\Omega}{8\varepsilon_0^2 L\omega^2}\left[\frac{1}{\alpha_-} - \exp(-\alpha_-)\left(\frac{\cos\alpha_+}{\alpha_-} + \frac{\sin\alpha_+}{\alpha_+}\right)\right] -$$
$$- \frac{a_0 I_T \sigma_\Omega}{2q_s L\omega^2}\left[\frac{\alpha_+}{2\omega_s} - \frac{1}{\varepsilon_0}\exp(-\alpha_-)\left(\frac{\cos\alpha_+}{\alpha_-} + \frac{\sin\alpha_+}{\alpha_+}\right)\right] +$$
$$+ \frac{(I_T^2 + \omega^2)\sigma_\Omega}{4q_s^2 L\omega^2}\left\{1 + \frac{1}{4\alpha_-}\left(\frac{4q}{q_s} - 1\right) +\right.$$
$$\left. + \frac{1}{2}\exp(-\alpha_-)\left[\frac{\cos\alpha_+}{\alpha_-}\left(1 - \frac{2q}{q_s}\right) - \frac{\sin\alpha_+}{\alpha_+}\left(1 + \frac{2q}{q_s}\right)\right]\right\}, \tag{29}$$
$$\omega_s^2 = [(\omega_e/\omega)^2 - 1]^2\omega^2, \quad \varepsilon_0 = (\nu + a)/L^2, \quad q_s = (\omega_s^2 + I_0^2)^{1/2},$$
$$\alpha_\pm = \left[\frac{2}{\varepsilon_0}(q_s \pm I_0)\right]^{1/2}.$$

Figure 4 shows the characteristic SPD form for temperature pulsations for various values of ω_e and $\bar{I}_T$ ($\bar{I}_T/\sigma_\Omega$, $I_T = I_\Omega$).

Once again we find the asymptotes to the SPD:

$$S_T(\omega) \to \frac{a_0^2\sigma_\Omega}{8\sqrt{2}\omega_e\varepsilon^{3/2}L}\omega^{-3/2} \sim \omega^{-3/2}, \quad \omega \to 0;$$
$$S_T(\omega) \to \frac{a_0^2\sigma_\Omega}{8\sqrt{2}\varepsilon_0^{3/2}L}\omega^{-5/2} \sim \omega^{-5/2}, \quad \omega \to \infty; \tag{30}$$
$$S_T(\omega) \to \frac{(I_T^2 + \omega_e^2)\sigma_\Omega\varepsilon_0^{1/2}}{32\omega_e^2 I_0^{3/2}L}|\psi|^{-1} \sim \omega^{-1}, \quad \omega \to \omega_e, \qquad \psi = \frac{\omega - \omega_e}{\omega_e}.$$

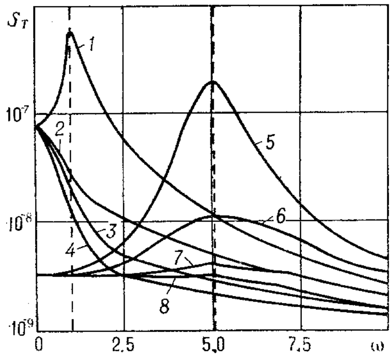

Fig. 4. Representative SPD forms for the temperature perturbations. $\omega_e = 10^3$ sec^{-1}: 1) $\bar{I}_T = 10^3$ sec^2/m; 2) $5 \cdot 10^3$; 3) $8 \cdot 10^3$; 4) 10^4. $\omega_e = 5 \cdot 10^3$ sec^{-1}: 5) $\bar{I}_T = 10^3$; 6) $5 \cdot 10^3$; 7) $8 \cdot 10^3$; 8) 10^4. S_T is in units of deg^2/Hz.

As follows from (30), flicker noise ($S_T \sim \omega^{-1}$) is already observed in the neighborhood of $\omega = \omega_e$, which indicates the arisal of nonequilibrium dynamic structure for $\omega \to \omega_e$.

The appearance of a characteristic resonance frequency ω_e described above in the temperature pulsation spectrum was, in all probability, observed by Abugov and Obrezkov [4] in their experimental investigation of the spectra of open propane—air flames. They observed the characteristic break in the radiation fluctuation spectrum, which with increasing oxygen content in the fuel mixture degenerated to a "peak."

4. Conclusions

1) It has been shown that the arisal of flicker-noise during turbulent flow with volume heat release in the mixing layer is indicative of amplification of perturbations due to nonequilibrium and of the probable appearance of ordered structures; 2) we have established that in the absence of interaction between vorticity and temperature perturbations, the range of frequencies in which pulsation amplification occurs corresponds to $n \geq -1$, where n is the power exponent in the relation $S(\omega) \sim \omega^n$; 3) in the presence of interaction between vorticity and temperature perturbations there is a certain isolated resonance frequency ω_e, which grows with intensification of the interaction, and flicker-noise arises in the neighborhood of this frequency.

NOTATION

u is the gas velocity; ρ, T, p are the density, temperature, and pressure of the gas; μ, ν are the coefficients of dynamic and kinematic viscosity; λ, a are the coefficients of thermal conductivity and thermal diffusivity; c_p is the heat capacity at constant pressure; L is a characteristic dimension; h is the width of the burner outlet; τ is the characteristic time; k, λ_p are the wavenumber and wavelength of the perturbation; ω is the frequency; Ω is the vorticity; χ is the attenuation of the thermo-vortical interactions; I_Ω, I_T are the vorticity and temperature perturbation increments; σ is the power of the random perturbation source; ξ, η, φ are the random perturbation sources; S is the spectral power density of the pulsations; D(k, ω) is the system transfer function; δ is the Dirac delta function. Indices: ' and 0 correspond to pulsation and averaged values.

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