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THE INFLUENCE OF TURBULENCE AND COMBUSTION INTENSITY ON THE NOISE OF TURBULENT GASEOUS PREMIXED FLAME

Summary. This paper presents the solution of Lighthills equation of the wave propagation in a non-homogenous environment for the disturbances generated by a turbulent gaseous flame. There is shown the possibility of diagnostic treating the flame noise spectrum as a resultant effect of two factors: the time-averaged chemical energy release intensity in the flame and the state of certain flame "turbulentness".

1. Flame noise intensity

In spite of the fact that a flame noise spectrum is difficult for analysis it can be measured comparatively easily. So the estimation and understanding of an interdependence between the noise and some flame parameters can give some information about the noise sources as well as about the quantities characterizing the turbulent reaction zone which is still neither known exactly nor described. Following Strahle [7], the considerations of flame noise are presented here on the basis of a general form of the Lighthill's equation [3] for a wave propagation in a non-homogenous environment:

$$\nabla^2 p_a - \frac{1}{a_\infty^2}\frac{\partial^2 p_a}{\partial t^2} = -\frac{\partial^2 (u_i u_j \varrho)}{\partial x_i \partial x_j} + \frac{\partial^2}{\partial t^2}\left(\varrho - \frac{p}{a_\infty^2}\right) \tag{1}$$

where:

- p_a - instantaneous acoustic pressure in medium of wave propagation,
- ϱ, p - density and pressure of medium which generates disturbances,
- a_∞ - sound velocity in the considered point in the medium which propagates the wave,
- x_i, x_j - space coordinates in i-th or j-th direction (i=1,2,3; j=1,2,3),
- u_i, u_j - velocity of medium which generates disturbances,
- t - time.

Left-hand side of equation (1) is determined by the acoustic parameters of wave, right side regards to the parameters of medium generating this wave. The first term of the right-hand side presents the quantity which does not take part in combustion noise generation, but it is the only source of an aerodynamic noise [3],[7].

Non-homogenous form of differential equation (1) possessing the source-terms, suggests the possibility of the use of Green's function for solution [2],[1]. Taking into account the fluctuations inside a turbulent flame as the wave sources, one obtains the following solution which determines the deviation Δp of acoustic pressure p_a from the static pressure p_∞:

$$\Delta p(\vec{x},t) = p_a(\vec{x},t) - p_\infty = \frac{1}{4\pi}\int_{-\infty}^{\infty}\int_V \frac{\partial^2}{\partial t^2}\left[\varrho(\vec{x},t_1) - \frac{p(\vec{x},t_1)}{a_\infty^2}\right] \cdot$$

$$\cdot\ G(\vec{x},\vec{y},t-t_1)\, dV(\vec{y})dt_1 \tag{2}$$

where Green's function satisfies the equation:

$$\left.\begin{aligned} &\nabla^2 G - \frac{1}{a_\infty^2}\frac{\partial^2 G}{\partial t^2} = 4\pi\delta(\vec{y}-\vec{x})\,\delta(t-t_1) \\ &G(\vec{y},0) = \frac{\partial G}{\partial t}(\vec{y},0) = 0 \end{aligned}\right\} \tag{3}$$

For free, unbounded space the Green's function is given by the Dirichlet's distribution [1]:

$$G(\vec{x},\vec{y},t_1-t) = \frac{\partial\left(t_1 - t - \frac{|\vec{x}-\vec{y}|}{a_\infty}\right)}{|\vec{x}-\vec{y}|} \tag{4}$$

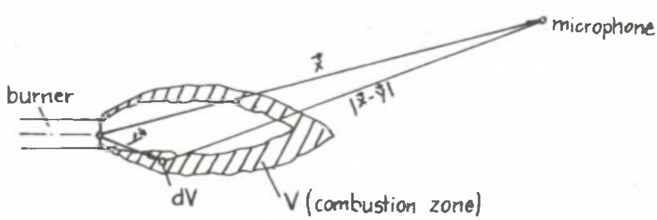

Fig. 1. Geometrical data for vector distances

For the acoustic pressure in so called "far field" $(\bar{x} \gg \bar{y},\ |\bar{x}-\bar{y}| \approx |\bar{x}|)$ after puting (4) to (2) and integrating in time t_1 with making use of the Dirac's delta δ properties, the following solution is obtained:

$$\Delta p(\bar{x},t) = \frac{1}{4\pi x} \int_V \frac{\partial^2}{\partial t^2} \left(\rho - \frac{p}{a_\infty^2}\right)_{\bar{y},t-\Delta t} dV(\bar{y}) \tag{5}$$

where time-delay

$$\Delta t \approx \frac{|\bar{x}|}{a_\infty} \tag{6}$$

Using the thermodynamic equations which are valid for a multicomponent mixture of reacting gases [8] and paying the attention only to the dominant term after re-formation of the integral in formula (5), one obtains [6]:

$$\Delta p(\bar{x},t) = \frac{1}{4\pi x} \int_V \frac{\partial}{\partial t} \left[\frac{1}{i_m} \sum_k i_k w_k \right] dV(\bar{y}) \tag{7}$$

where:

- w_k - rate of production of species k by chemical reactions (mass per unit volume per second),
- i_k, i_m - specific enthalpy of species k and mixture.

Considering the turbulent field where fluctuating quantities are correlated only over the certian distance and using the equation for the noise intensity $I(\bar{x}) = \frac{\overline{\Delta p^2}}{\rho_\infty a_\infty}$ one obtains the intensity of flame noise:

$$I(\bar{x}) = \frac{1}{16\pi^2 x^2 \rho_\infty a_\infty} \int_V dV \int_{V_{Sk}} dV_{Sk} \overline{\left[\frac{\partial}{\partial t} \left(\frac{1}{i_m} \sum_k i_k w_k \right) \right]^2} \tag{8}$$

where:

- V_{Sk} - correlated volume, i.e. the smallest element of a flame in which the quantities changing in time are pulsating in the same phase.

2. Factors influencing the flame noise intensity

Analyzing equation (8), it should be emphesized that the flame noise intensity is generated not directly by an energy release rate $\sum_k i_k w_k$ in a reaction zone, but by the magnitude of an amplitude of its pulsations and deviations from the mean-time value.

The amplitude a_i of the i-th pulsating component of an arbitrary quantity $\tilde{f}$ in a turbulent field can be treated as a function depending on a time-mean value $\bar{f}$ and, for example, on the parameter "z", which characterizes a certain field "turbulentness"

$$a_i = a_i(\bar{f}, z) \tag{9}$$

when

$$\bar{f} = \tilde{f} - f' \tag{10}$$

and suggested parameter "z" should take into account as well the vortex configuration expressed with the use of an assumption of any scale, for example the Lagrange scale L_l, as a microstructure of vortices, - and particularly their activity expressed for example with the use of a turbulence intensity $\mathcal{E}$:

$$z = z(L_l, \mathcal{E}) \tag{11}$$

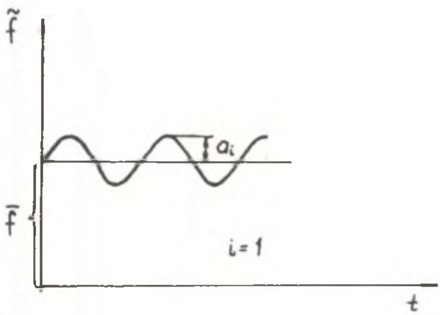

Fig. 2. Characteristic quantities of fluctuation

Pulsatory component f' can be approximated by means of the Fourier series or e.g. by simplified series (Fig. 2):

$$f' = \frac{1}{\pi} \sum_i a_i \sin\omega_i t \tag{12}$$

Using (12), the time-mean square of the rate of pulsatory component changes:

$$\overline{\left(\frac{\partial}{\partial t} f'\right)^2} = \frac{1}{2T} \int_{-T}^{T} \left(\frac{\partial f'}{\partial t}\right)^2 dt = \frac{1}{2\pi} \sum_i \omega_i^2 a_i^2 \tag{13}$$

where T - period of approximated pulsation.

On the basis of equations (8) (13) and (9) it appears that flame noise intensity depends on a volumetric energy release rate averaged in time and on the parameter z

$$I(\vec{x}) = I(\overline{\Delta p'^2}) = I\left\{\overline{\left[\frac{\partial}{\partial t}\left(\frac{1}{i_m}\sum_k i_k w_k\right)\right]^2}\right\} = I\left[\overline{\left(\frac{1}{i_m}\sum_k i_k w_k\right)}, z\right] \qquad (14)$$

So the flame noise intensity can increase due to the increase of a time-mean intensity of chemical energy release rate or due to the increase of a zone "turbulentness" or other way this effect can be the result of superposition of both factors. Now, the way of changing of a noise intensity with a certain substrate parameter should include the nature of changing of both factors mentioned above.

3. Discussion of results of measurements

The parameter of substrates which had been changed during experiments was a primary excess air ratio λ. The time-mean chemical release rate E as a function of λ from theoretical point of view is shown in Figure 3 for kinetic combustion zone (solid line) and for after-burning diffusion zone (dotted line). The maximal value $E_{k\ max}$ for the kinetic front can be larger or smaller than the maximal value $E_{d\ max}$ for diffusion front of the flame:

$$E_{k\ max} \lessgtr E_{d\ max}$$

The diffusion zone disappeares at $\lambda = 1$, and at $\lambda = 0$ disappeares the kinetic front, so:

$$(E_d)_{\lambda=1} = (E_k)_{\lambda=0} = 0$$

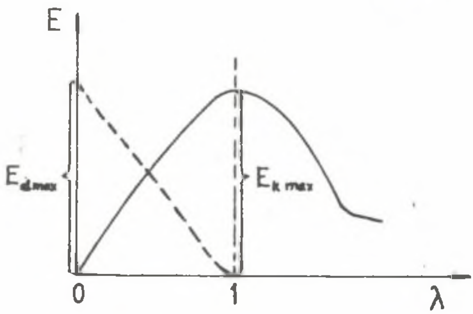

Fig. 3. Scheme of combustion intensity for premixed flame

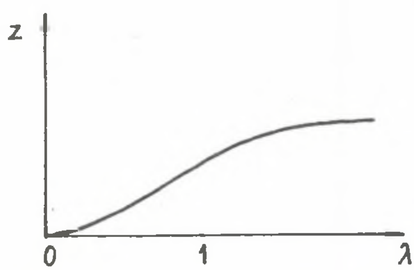

Fig. 4. Scheme of suggested flame turbulence characteristic

The Fig. 4 shows the parameter z, which is expected to increase monotonicaly with λ increase from very small value (close to zero): $z_{\lambda=0} \approx 0$.

On the basis of the changes of value z it is possible to justify the measurement results which show that the level of flame noise was incomparably higher at $\lambda = 1$ than for $\lambda = 0$. ($I_{\lambda=1} \gg I_{\lambda=0}$) in spite of the fact that the values of time-mean combustion intensity were of the same order for both cases.

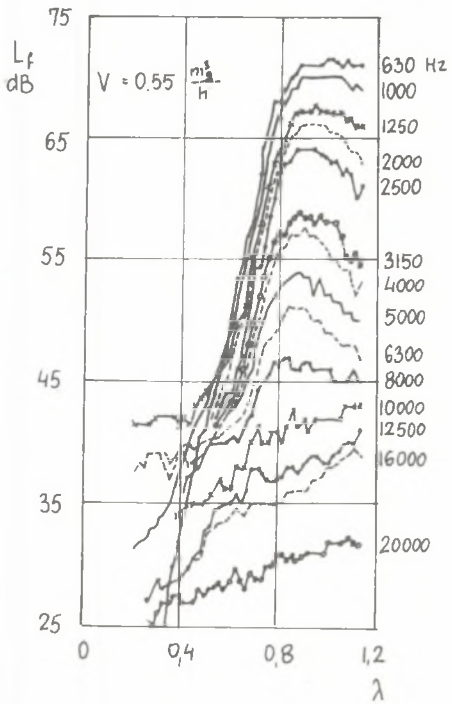

Fig. 5. Premixed flame noise spectrum

The results of flame noise spectral analysis in dependence on λ for two different types of gaseous flames are presented in Fig. 5 and 6. Fig. 5 (decibel level L_f proportional to the intensity of a noise component having frequency f vs λ, for the given gas flow rate $\dot{V}$ which is expressed in the standard cubic meters per hour remains constant), shows [4] the changes of noise level of a premixed flame for the small laboratory burner (gas nozzle diameter 2 mm, outlet burner diameter 13 mm) where the turbulence wasn't so much developed (Re 5470). The way of changes for the spectral components having comparatively low frequencies, has suggested the conclusion that in this case the time-mean combustion intensity was the factor which modulated the way of changes of flame noise level as λ function, and the kinetic flame front was the main source of noise generation.

Another analysis shown in Fig. 6 [5] was made for the diffusion industrial burner, in which could be achieved very high outlet velocities ($Re_{air} \leqslant 93\ 300$). In the range of λ up to about 1,1 there is an increase in the time-mean combustion intensity as well in the flame turbulence - so the noise increases very rapidly. For λ larger than about 1,1 there is the decrease of the time-mean volumetric combustion intensity but the flame turbulentness still increases. The interaction of these two factors changing contrariwisely results in very slight increase of flame noise level.

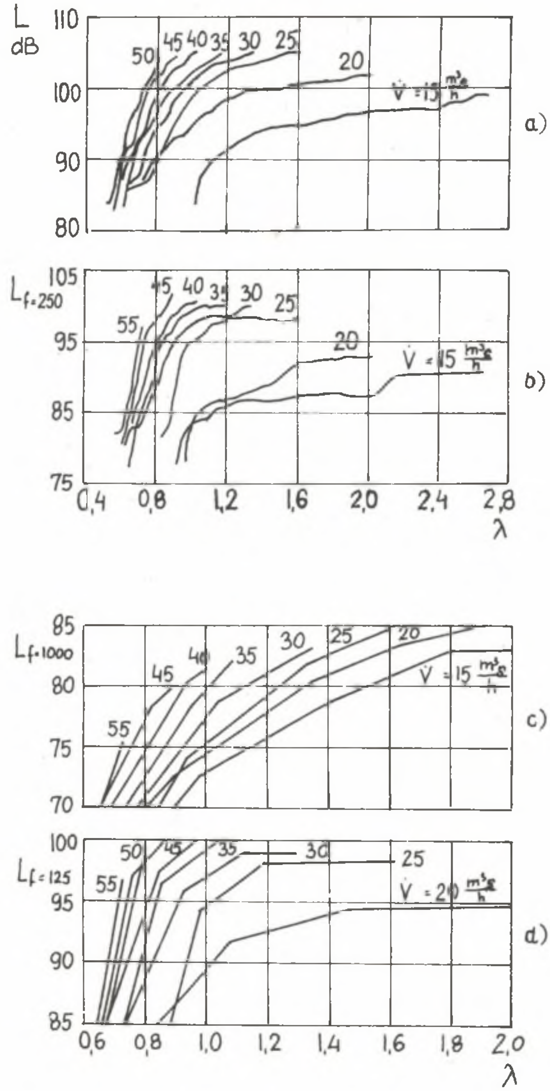

Fig. 6. Examples of noise spectra of industrial diffusion flames

a) the changes of overall flame noise level versus λ for various gas flow rates $\dot{V}$, b) the level of flame noise spectral component with frequency f = 250 Hz, c) the changes in the level of noise component from the frequency range which is already generated partially by aerodynamic noise, d) typical way of changes of noise components from the low frequency range which are generated by the combustion

4. Concluding remarks

1. On the basis of a level of flame noise spectral components it was possible to estimate the parameters at which the maximal volumetric energy release rate in a flame occurs, because at the same parameters was the maximum of the level of some flame noise components. This agreement between the maximum of combustion intensity and the flame noise intensity can be noticed even at a strongly developed flame turbulence,which however results in making this rule to appear not so explicit (for instance: on the basis of a noise spectrum measurements when the gas and air streams were not controlled it was possible to show out the state of λ = 1 in the kinetic flame front for a given gas flow rate).

2. The noise was generated mainly in a primary kinetic flame front and not in a diffusion after-burning zone.

3. Silencing of the burners noise ought to be achieved first by the reduction of a turbulentness z - where it is possible. Obviously, a high level of turbulence in industrial flames must be kept in order to ensure the intensive combustion, but there can exist some unwanted flow disturbances caused by the wrong burner constructive elements which should be improved. Frequently suggested methods of a noise reduction by means of the changes in mixture contents, burning velocity or decrease of λ result rather in the decrease of the time-mean combustion intensity and this reflects in the energetic parameters of a flame and its geometry.

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WPŁYW TURBULENCJI I INTENSYWNOŚCI SPALANIA NA SZUM TURBULENTNEGO, GAZOWEGO PŁOMIENIA KINETYCZNEGO

S t r e s z c z e n i e

Przedstawiono rozwiązanie równania Lighthilla opisującego rozchodzenie się zaburzenia w ośrodku niejednorodnym, a generowanego przez turbulentny płomień gazowy. Wskazano na możliwość diagnostycznego potraktowania widma szumu płomienia jako wypadkowego efektu dwóch przyczyn: średniej intensywności wyzwalania się energii w płomieniu oraz istnienia pewnej "turbulentności" płomienia.

ВЛИЯНИЕ ТУРБУЛЕНЦИИ И ИНТЕНСИВНОСТИ ГОРЕНИЯ НА ШУМ ТУРБУЛЕНТНОГО ГАЗОВОГО КИНЕТИЧЕСКОГО ПЛАМИ

Р е з ю м е

Представлено решение уравнения Лайтиля,которое описывает разпространение в негомогенной среде возмущения, которое генерует турбулентное газовое пламя. Показано различимость диагностической обработки спектра шума плами как результирующий эффект двох причин: средней интенсивности отключения энергии в плами и существования некоторой "турбулентности" плами.