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ACOUSTIC-TO-MECHANICAL EFFICIENCY OF TURBULENT JETS

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Abstract

In accordance to Lighthill's acoustic analogy the total acoustic power of turbulent jet is proportional to mechanical energy flux multiplied by M^5, where $M=U/a_0$, U – jet velocity, a_0 – ambient speed of sound. Hence acoustic efficiency of a jet (acoustical to mechanical energies ratio) can be expressed as $\eta=\beta*M^5$, where β is a constant. In presented work the relation between mechanical energy flux and jet acoustic power was investigated on the base of experimental tests and analysis of known data for different kind of turbulent jets.

It was shown that in the majority of cases the dependence of acoustic energy from Mach number keeps within the M^5 law. The reasons of deflection from M^5 low under some jet issue conditions (including main flow parameters and configurations of nozzle exit tip) were analyzed. Known devices for jet noise suppression (chevrons, lobed nozzles) reduce the acoustic efficiency (η) of jets due to longitudinal vorticity created at nozzle exit.

INTRODUCTION

In accordance to Lighthill's theory [1] the total acoustic power E_a (surface integral of acoustic radiation over sphere) of turbulent isothermal jet is proportional to mechanical energy flux $E_j=0.5\rho U^3F$ and M^5: $E_a=\beta*E_j*M^5$, where $M=U/a_0$, U – jet velocity, F – nozzle are, a_0 – ambient speed of sound. Factor β is almost constant up to $M\leq2$ for axisymmetric jets with uniform profiles of velocity and temperature at nozzle exit. In that way acoustic-to-mechanic efficiency of a jet, as a first approximation, can be expressed by a formula: $\eta=E_a/E_j=\beta*M^5$.

Fig.1 shows the acoustic efficiency of the different jets in dependence on jet Mach number from [2-6]. (Data [6] were obtained by authors of presented work at

CIAM open acoustic facility C-17-A4 for profiled convergent nozzle of 0.1m diameter). It can be seen that acoustic efficiency is proportional to M^5 within the range 0.5<M<2. At 2<M<4 the acoustic efficiency of the jets is almost invariable with growing of Mach number.

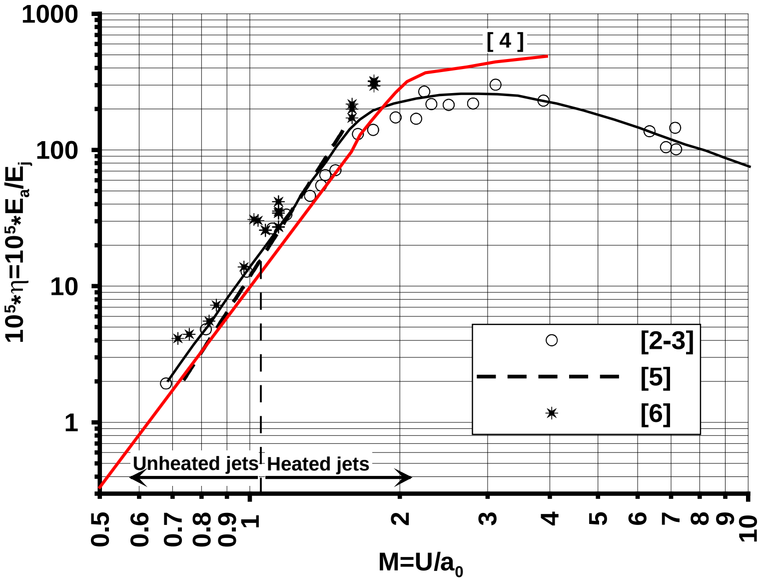


Fig.1 Acoustic-to-mechanical efficiency of a jets.

The coefficient of proportionality β for 0.5<M<2 is stay the constant as for unheated as for heated jets (at moderate jet temperatures T<900K) within each of experimental series. (Here by experimental series we understand different condition of experiment in [2, 3, 4, 6]: differences in nozzle profiles and model scales, initial turbulence, thicknesses of boundary layer). The discrepancy in β may reach value of 50% between different experimental series. However if we will correctly consider experimental condition at each acoustic test bench this discrepancy apparently will be substantially smaller.

In presented work on the base of experimental tests and analysis of known data the influence of different factors, which can change the jet structure and correspondingly change its acoustic efficiency (η) was investigated. The influences of initial boundary layer thickness, heating of a jet were analyzed. The co-axial jets with different velocity and temperature initial distributions were considered also. The result of experimental data analysis shows that only presence of longitudinal vorticity can break the relation between jet acoustical and mechanical energies obtained from Lighthill's analogy.

AN INFLUENCE OF INITIAL BOUNDARY LAYER

To investigate the influence of initial boundary layer on jet acoustic efficiency three models were used. These models were differing by length of cylindrical parts (L) at the nozzles exit – fig.2. Outlet diameters were the same for each tips: D=15mm. The thicknesses of initial boundary layer were equal δ=0.05D, 0.25D and 0.5D for L/D= 1, 10 and 30 correspondingly. These experiments were conducted in the small acoustic chamber (ACM) which was designed in CIAM for tests on models of nozzle diameter up to 20mm.

Experimental results are shown in the fig.2 as dependence of acoustic efficiency on maximal Mach number. (Here maximal Mach number is defined by maximal jet velocity at nozzle exit or (it is the same) by total pressure in the receiver). It can be seen that data for model 1 (empty circles) satisfy the known M^5 law (see fig.1). Data for models 2 and 3 are lying essentially lower than points for reference nozzle if we will use maximal Mach number as representative parameter. However if we will assume that characteristic value of Mach number should be calculated by averaged velocity ($U=I_j/G_j$), then points for model 2 and 3 will shift to general dependence (rows in the fig.2) and will lie at the common curve. (Here $I_j = \int_F \rho_j U^2 dF$ – jet impulse, G_j – jet mass flow rate, ρ - jet density, dF – element of nozzle area.)

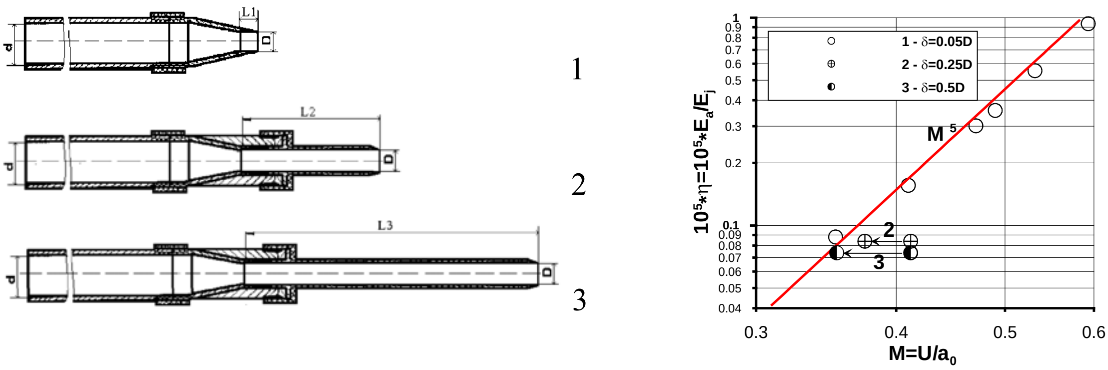


Fig.2. Acoustic efficiency of unheated jets with different initial boundary layer.

JETS WITH LOW DENCITY AND LOW VELOCITY.

An investigation of the influence of jet density on jet noise was carried out using model 1 described in previous section. Measurements were made in the same small acoustic chamber CIAM (ACM). To model the hot jet the mixture of helium (He) and air was used. The concentration of He in the mixture (κ) was varied in the range 0-100%.

It should be noted that profile of the mean values of temperature in heated jets and concentration in low density jets are similar, as well as there are similar the distributions of averaged instantaneous parameters [7]. In this way the mixture of different density gases can be used to model the aerodynamic and consequently acoustic fields of heated turbulent jets. The growth of concentration of He in the jet models the increasing of jet temperature. The jet of pure helium (ρ_j/ρ_a=0.138) is equivalent to hot jet at temperature about T^*=2175K.

Results of experiments are presented in the fig.3 as dependences of jet acoustical efficiency on Mach number. In addition, results for heated jets (from fig.1) obtained at open test bench C17-A4 for large scale models (D=100mm) are shown with symbols ⊕.

Results in the fig.3 display that at low Mach numbers the relation between mechanical and acoustical energies of a jet obtained from Lighthill's analogy ($\eta=E_a/E_j=\beta*M^5$) is failed. For M<1 data for He-air mixture are lying essentially higher than common theoretical relationship. In [8] it was shown that in jets of low density (heated jets) in addition to conventional quadrupole sources of sound there are appear the dipole and monopole sources. The intensities of these sources are proportional to M^3 and M^1 correspondently and they can dominate in common jet noise at low exhaust velocities. Data in the fig.3 confirm this supposition. For the jet of practically pure Helium (ρ_j/ρ_a=0.144) up to M=0.5 the acoustic efficiency is proportional to Mach number (M^1). Further, with growing of Mach number exponent increases and approaches to 5 at M≈1. For 1<κ<0 и M<0.5 the exponent has a values between 1 and 5.

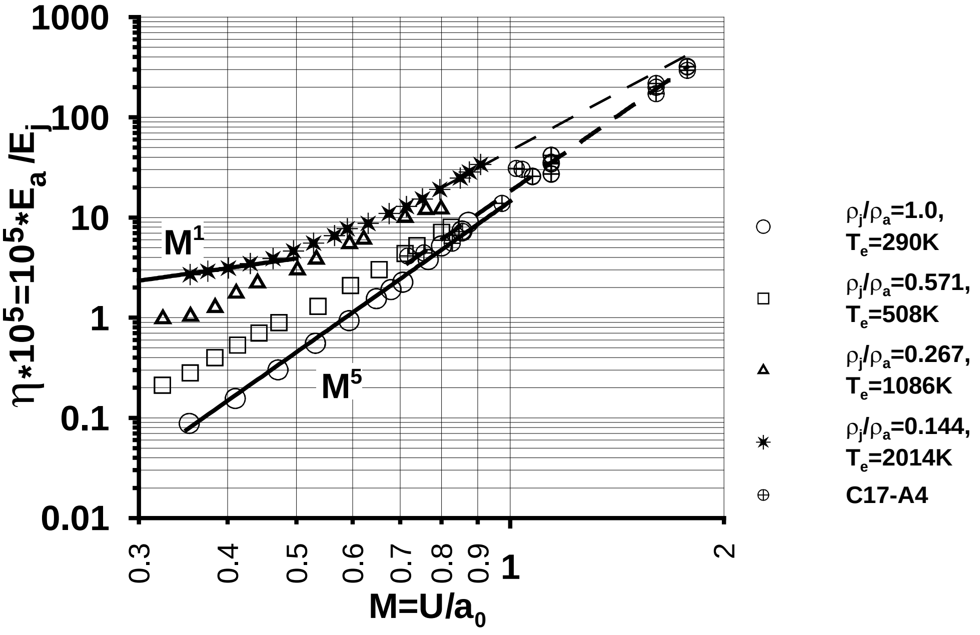


Fig. 3. An influence of jet density on acoustic efficiency of a jet.
(ρ_j- jet density, ρ_a-density of ambient air, T_e – temperature of equivalent heated jet).

The main result of this investigation is the fact that Lighthill's acoustic analogy, based on quadrupole mechanism of sound generation, cannot be applied to low density, low velocity jets. However in practice the using of low velocity jets of very small density (or very high temperature) is rare in occurrence. For example, the typical Mach numbers and temperatures of aviation engine jets are M=0.7-2, T=350-800K. Under such condition Lighthill's mechanism of noise generation is governed and sound sources of low order (dipole and monopole) can be neglected. Therefore for practical use relation between mechanical and acoustical energies ($\eta=E_a/E_j=\beta*M^5$) will be considered to be true also for heated and low density jets.

CO-AXIAL JETS

At open acoustic facility C17-A4 two series of experiments were carried out on coaxial jets. Convergent co-annular nozzles without plug were used. External nozzle has a diameter D_e=100mm, diameter of internal (central) nozzle was D_c=50mm. (Hereinafter index 'e' denotes external contour parameters, 'c' - internal). Exit sections of both nozzles lie in the same plane.

In the first experimental series under equal nozzle pressure ratios (NPR) in both contours the internal jet was stepwise heated from ambient temperature up to T_c=840K. NPR_c=NPR_e=1.6. External jet was unheated. In this way in the first experiment the jet velocities were equal: U_c=U_e=270m/s, in the last experiment of series U_c=468m/s, the velocity ratio was m= U_c/U_e=0.6.

In the second series internal nozzle pressure ratio and temperature were fixed (NPR_c=1.5, T_c=508K, U_c=337m/s). Velocity of external unheated jet was varied in the range U_e=0-364m/s.

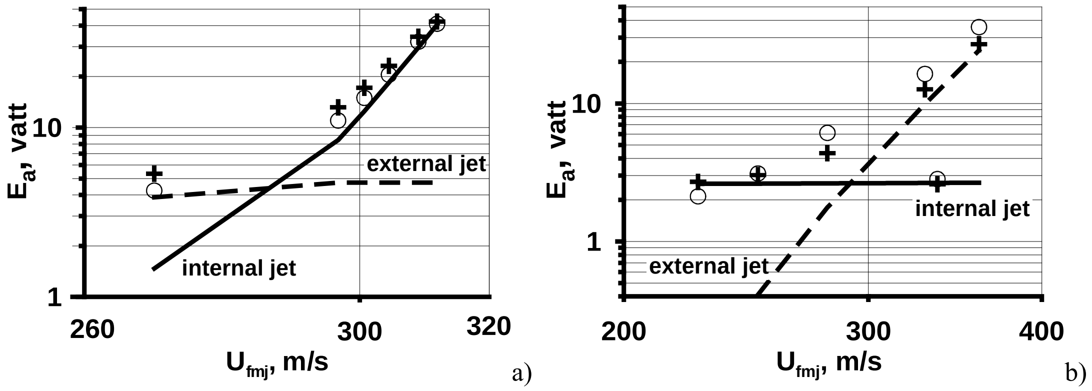
These parameters of experiments were chosen to cover the wide range of mechanical energies ratio E_{j_c}/ E_{j_e} and Mach numbers of internal and external jets.

Results of preliminary analysis show that using of Mach number calculated by averaged co-axial jet velocity ($U=I_j/G_j$) as a basis for generalization of experimental data cannot lead to any useful and comprehensible results. In this way the analysis of acoustic efficiency of co-axial jets was done in some different way then for simple single-contour jets.

The main points of this analysis are:

- keeping in the mind that sound generation is complicated mechanism connected with turbulent processes in mixing layers (internal and external one), let us assume to a first approximation that the acoustic energy is a function of mechanical energy flux coming throughout nozzle exit plane;
- let us consider that mechanical energy is converting to acoustical energy in both contours of co-axial jets independently, it corresponds to assumption that we can divide the common acoustic energy in two parts – external contour and internal contour energies;
- the acoustic energy of each contour can be calculated according to Lighthill's acoustic analogy: $E_a=\beta*E_j*M^5$, β is a constant, M and E_j should be taken for corresponded contour values;
- coefficient β should be obtained from the results of experiments on single-contour jets at the same facility where experiments on co-axial jets were conducted;
- common acoustic energy can be obtained as sum of acoustic energies of contours: $E_a=E_{a\_c}+E_{a\_e}=\beta*E_{j\_c}*M_c^5+\beta*E_{j\_e}*M_e^5$.

Results for single-contour jets gave the β value equals $\beta=19.8*10^{-5}$. For each of experimental regimes the mechanical (and correspondently acoustic) energy were calculated for both contours. These calculations are compared with experimental data in the fig.4. Fig.4.a presents results of the first series of experiments, fig.4.b – second series. The calculated acoustic energies of separate contours are presented in the fig.4 by solid and dashed lines. The data are presented as dependence of acoustic energy on velocity of "fully mixed jet" (U_{fmj}). Here "fully mixed jet" is single contour jet with the same impulse mass-flow rate and exit area as co-axial jet.



○ - E_a, *experiments;* + - E_a, *calculations*

Fig.4. Acoustic efficiency of co-axial jets.

Data in the fig.4 show that in wide range of axisymmetric co-axial jets jet exhaust conditions correlation between acoustic and mechanical energy stay the same as for Lighthill's analogy. Difference between experimental data and results of calculations lies within the limits of 1dB.

The typical experimental spectra of co-axial jet noise is shown in the fig.5. Here NPR_c=1.6, T_c=840K, U_c=468m/s, NPR_e=1.6, T_e=300K, U_e=270m/s, observation angle is θ=30° relatively to jet axis. Jet noise spectra of internal and external jets were calculated separately with a help of semi-experimental method [5]. These data corresponded to acoustic radiation of internal jet in the absence of external flow and acoustic radiation of external jet in the absence of internal flow. Results of calculations are shown in the fig.5. In the same figure the calculated spectra of "fully mixed jet" is presented also.

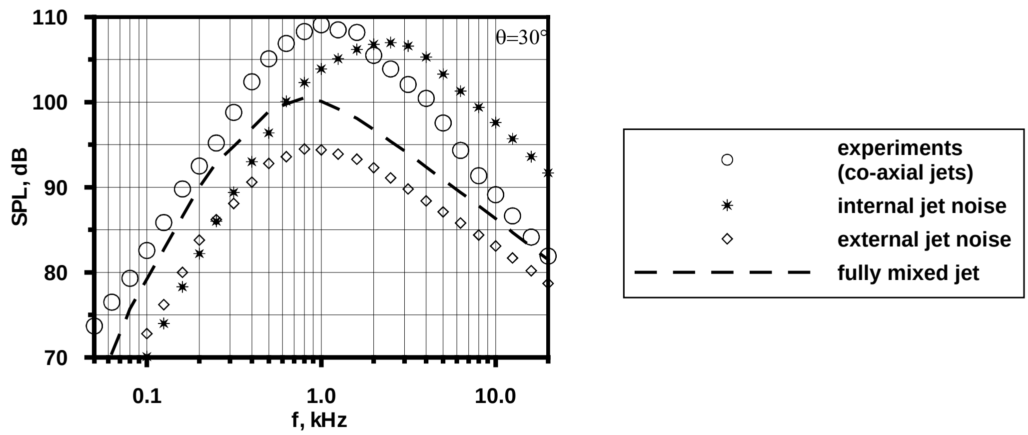
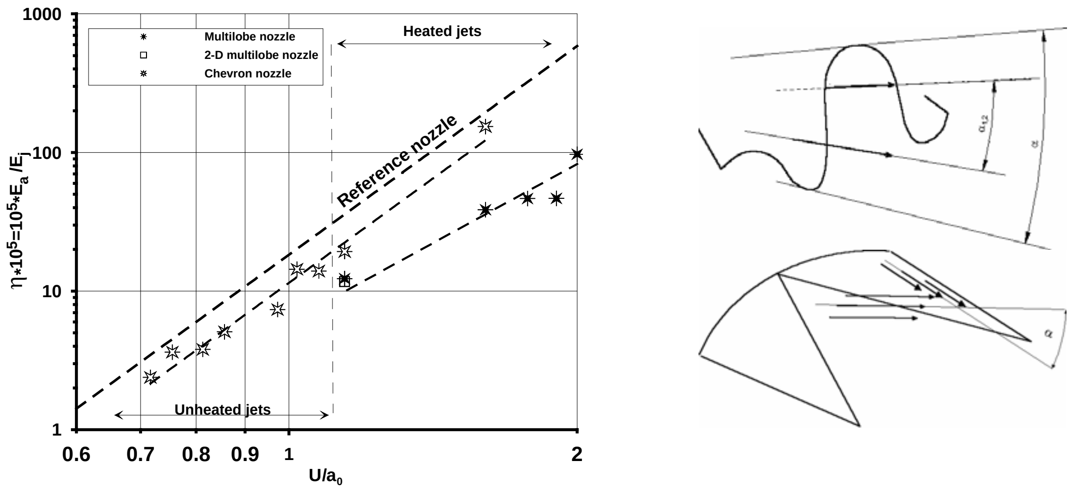


Fig.5. Acoustical spectra of co-axial jets.

It can be seen that maximum of calculated spectrum of internal jet is close (by amplitude) to maximum of experimental spectrum of co-axial jets. It proves the fact that in this case acoustic energy of co-axial jets governs by mechanical energy of internal high speed jet only (see also the last points in the fig.4a). However, the position of co-axial jet spectrum maximum does not correspond with position of maximum of internal jet spectra. It strongly shifted to the maximum of external jet spectrum. It means that internal high speed jet transmits its energy to mixing layer of external jet.

AN INFLUENCE OF LONGITUDINAL VORTICITY

The influence of longitudinal vorticity on jet noise was investigated in detail in [6, 9]. It was shown that as a first approximation the jet noise reduction is proportional to value of longitudinal vorticity created at nozzle exit. Vorticity can be induced by different noise suppression devices: multilobe, multitube nozzles, chevrons. As example of results of previous investigations the decreasing of acoustic efficiency of a jet using multilobe and chevron nozzles is shown in the fig.6.



a) acoustic efficiency versus Mach number

b) creation of longitudinal vorticity at lobed and chevron nozzle exit

Fig.6. The influence of longitudinal vorticity on jet noise.

The estimation of mechanical energy flux for multilobe nozzles were performed on the base of mass-flow and thrust measurements conducted in [10, 11]. E_j of chevron nozzle was obtained numerically [12]. Data in the fig.6 show that presence of longitudinal vorticity breaks the relation between jet acoustical and mechanical energies obtained from Lighthill's analogy.

CONCLUSIONS

Analysis of experimental results showed that in wide range of axisymmetric jet exhaust conditions (including co-axial jets) correlation between acoustic and mechanical energy stay the same as in Lighthill's acoustic analogy. In particular in the case of co-axial jets the transmitting of mechanical energy from internal to external jets leads to the strong spectra changing. In spite of that the relation between E_j and E_a stay the same. Discrepancy in experimental data and Lighthill's theory was been marked only at low density single jets for M<0.7. Known devices for jet noise reduction (chevrons, lobed nozzles) decrease the acoustic efficiency of jets on account of longitudinal vorticity created at nozzle exit. The presence of longitudinal vorticity breaks the relation between jet acoustical and mechanical energies obtained from Lighthill's analogy.

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