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THE MECHANISM OF NOISE FORMATION AND CALCULATION OF NOISE CHARACTERISTICS OF UNDEREXPANDED STEAM JETS

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Abstract

In technological processes of various plants and facilities, steam and gas at excess pressure is often vented. As a result of such emissions, underexpanded supersonic turbulent jets are formed, which create a sound field exceeding background levels by up to 30...40 dBA within a radius of several kilometers. Forecasting noise characteristics of air venting of steam and gas is important even at the design stage, to facilitate the development of noise control measures. Here, on the basis of research led by the authors, results are presented for the numerical simulation of the venting of underexpanded steam and gas jets into the atmosphere. The specific mechanism of noise formation and a new method of predicting the noise characteristics of steam jets are also presented.

1. INTRODUCTION

In technological processes of various plants and facilities (thermal ower plants, metallurgical, chemical industries) , steam and gas at excess pressure is often vented. Emissions steam most typical for thermal power plants (TPP), also are connected, as a rule, with start-up and stops of blocks, emergencies. Emissions of gas are stipulated at stations of increase of pressure of the main gas mains, a various sort of the chemical enterprises, etc. Feature of the given emissions is that dump the steam or gas is made with superfluous pressure therefore there is a critical current in exhaust systems with formation on an output underexpanded turbulent jets. Such jets are sources of the raised radiation of the noise, exceeding levels of a sound on 30…40 dBA in radius of several kilometers [1]. The important problem reduction of noise of underexpanded turbulent jets is the knowledge of the mechanism of its formation, methods of their account noise characteristics that allow developing actions on struggle against noise on a design stage.

Not isobaric jets are characterized by a degree of underexpand (the relation of static pressure on a cut of the pipeline p_{cr} to atmospheric pressure p_{atm}):

$$n = p_{cr} / p_{atm} \tag{1}$$

The air venting of steam on TPP makes a degree of underexpand of jets, as a rule, $n > 2$, and in some cases can be and more than 20.

One of possible ways of studying of the mechanism of formation of noise of the turbulent expanded jets is numerical simulation.

2. NUMERICAL SIMULATION OF JET CURRENTS

Numerical simulation of jet currents at emissions the steam and gas represents important problem: it is better to present the mechanism noise and more precisely to calculate noise levels from a steam and gas jet.

Parameters of turbulent jets can be expressed equations Navier-Stokes which has been written down for turbulent currents in the form of Reynolds and describing in non-stationary statement laws of preservation of weight, an impulse and energy of the moving environment. Parities of energy of turbulence are applied to short circuit of system of the equations and it dissipation with use k - ε models of turbulence [3]. Simulating was carried out with use of a package of applied programs CosmosFlowWorks.

Further results of simulating of jets the steam expiring in surrounding space with superfluous pressure which are characteristic for steam power boilers are presented. Boundary conditions were parameters of steam on an output from the exhaust pipeline (static pressure, temperature, critical speed, parameters of turbulence) and parameters of atmospheric air.

In fig.1 and fig.2 fields of speeds and are accordingly presented to a trajectory of development of a jet on the initial site, received by results of simulating for a jet of steam with parameters on a cut of the exhaust pipeline: pressure $p_{cr} = 1{,}3$ MPa; temperature $t = 415$ °C; critical speed $w_{cr} = 633{,}8$ m/s.

The structure of a steam jet received by results of simulating shows the analysis of fig.1 that is similar to structures of not isobaric jets described in [4].

According to [4], process of the expiration of a steam jet following: the steam's jet, following the exhaust pipeline with superfluous pressure, starts to extend. The speed of steam increase up to supersonic values. Here on an initial site arises one "flank", having trailing, slanting jumps of condensation and a disk of the Mach. In "flank" huge losses on pressure take place. Behind a disk of the Mach pressure increases a little, and then becomes practically equal atmospheric and, hence, the jet becomes isobaric.

From fig. 2 it is visible, that on an initial site within the limits of "flanks" mixture the steam with an atmosphere practically is absent. Active mixture begins after isobaric section where there are formations of coherent structures. As it was marked earlier, that the basic site of noise jets is the zone of mixture if to neglect mixture steam with air from a cut of the pipeline up to isobaric section inclusive it is quite possible to approve, that noise on this site of a jet does not arise. Hence, in the mechanism of generation of noise by not isobaric jets the important role belongs to parameters in isobaric section.

In fig. 3 the structure of not isobaric steam jet with a degree of underexpand $n = 3$, temperature $t = 400$ °C and critical speed $w_{cr} = 633{,}8$ 3 m/s in comparison with results of experiment is resulted. Fig. 3 shows correctness of the received results of simulating. It is visible, that on the schedule and in a photo of a jet the initial site contains to one "flank" with obviously expressed direct, trailing and slanting jumps of condensation which are characteristic for not isobaric jets.

3. CALCULATION NOISE CHARACTERISTICS OF UNDEREXPANDED JETS

The specified noise mechanism of underexpanded jets, received on the basis of numerical modelling and natural measurements, allows to offer a new method of calculation of acoustic capacity of the steam not isobaric jet, based on theory of Lighthill. With this theory sound capacity of a jet can be presented through parameters in isobaric section in the form of [5]:

$$P = k(\lambda) \cdot \frac{\rho_i^2 \cdot w_i^8 \cdot D_i^2}{\rho_0 \cdot c_0^5}, \tag{2}$$

where ρ_i – density of steam or of gas in isobaric section, kg/m^3; w_i – speed of its expiration, m/s; D_i – diameter of jet in isobaric section, m; λ – relative speed in isobaric section; ρ_0 – density of an environment, kg/m^3; c_0 – sound speed of an environment, m/s; $k(\lambda)$ – factor of proportionality which was defined by authors by results of experiments.

In connection with that the relative role of components of noise finally is not certain to write down expression for the total sound capacity in an exact kind without attraction of experimental data it is not possible.

The factor of proportionality $k(\lambda)$ depends on relative speed in isobaric section and by results of experiments for a steam jet [6]:

$$k(\lambda) = 10^{-(1,85\cdot\lambda+2,01)} \tag{3}$$

Parameters of a jet in isobaric section can be defined on following expressions of the one-dimensional theory [4]:

$$w_i = w_{cr} \cdot \lambda, \tag{4}$$

where $w_к$ – critical speed on a cut of the exhaust or blowing-off pipeline;

$$\lambda = \frac{G_0}{G_i} \cdot \left[1 + \lambda_0^2 - \frac{1}{n} \cdot \left(1 - \frac{k-1}{k+1} \cdot \lambda_0^2\right)\right] \cdot \frac{k+1}{2 \cdot k \cdot \lambda_0}, \tag{5}$$

where $G_0 / G_i = 1$ – the relation of the charge on a cut of the pipeline to the charge in isobaric section; $\lambda_0 = 1$ – the relation of speed on a cut of the pipeline to speed of a sound in jet; k – adiabatic exponent (for superheated steam $k = 1{,}3$); n – degree of underexpand.

In view of, that in many events the charge dumped the steam G depends on throughput of the valve.

The area of isobaric section of a jet:

$$S_i = S_{pipe} \cdot \frac{G_i}{G_0} \cdot \frac{\lambda_0}{\lambda} \cdot \frac{1 - \frac{k-1}{k+1} \cdot \lambda^2}{1 - \frac{k-1}{k+1} \cdot \lambda_0^2} \cdot n, \tag{6}$$

where S_{pipe} – the area of a cut section of the exhaust pipeline.

The density of steam in isobaric section is defined from the equation of indissolubility:

$$\rho_i = \frac{G_i}{S_i \cdot w_i}. \tag{7}$$

Steam or gas on a cut of the pipeline, it is possible to define critical pressure on following expression, Pa:

$$p_{cr} = m \cdot \frac{\sqrt{2 \cdot \frac{k}{k+1} \cdot p_0 \cdot \upsilon_o}}{k}, \tag{8}$$

where $m = G_0 / S_{pipe}$ – mass speed at the critical expiration, kg/(s·m^2); υ_0, p_0 – specific volume and pressure of steam at the speed close to zero.

Critical speed w_{cr} (sound), m/s, currents the steam or gas is calculated under the known formula:

$$w_{cr} = \sqrt{2 \cdot \frac{k}{k+1} \cdot p_0 \cdot \upsilon_0}, \tag{9}$$

Then expression for a degree of underexpand can be written down jets in the form of:

$$n = \frac{w_{cr} \cdot G_0}{k \cdot S_{pipe} \cdot p_{atm}}, \tag{10}$$

Let's transform (2) in view of (3)-(10), and also that $G_i / G_0 = 1$ – the relation of the charge on a cut of the pipeline to the charge in isobaric section; $\lambda_0 = 1$ – the relation of speed on a cut of the pipeline to speed of a sound in jet. We receive the following new settlement formula of the total level of sound capacity underexpanded turbulent jets of steam and of gas:

$$L = 10 \cdot \lg\left(\frac{G_0^2}{S_{pipe}}\right) - 10 \cdot \lg n + P(w_{cr}) - K(n) - 23{,}2, \tag{11}$$

where $P(w_{cr})$ - parameter which depends on critical speed of the expiration $P(w_{cr}) = 60 \cdot \lg w_{cr}$; $K(n)$ – the correction factor which depends on a degree of underexpand n and is equal:

$$K(n) = 18{,}5 \cdot \lambda - 10 \cdot \lg\left(\frac{\lambda^7}{k + 1 - \lambda^2 (k-1)} \right), \tag{12}$$

where the relative speed λ, depending from n, is defined from (5):

$$\lambda = \frac{n \cdot (k+1) - 1}{n \cdot k} \tag{14}$$

For steam jets the formula (11) becomes simpler, considering the following: adiabatic exponent for superheated steam is equal $k = 1.3$; change of value of critical speed w_{cr} steam emissions on TPP in a range of temperatures 400 - 450 °C and a range of pressure steam 196,1 – 5736,8 kPa changes in small limits 609,5 - 658,1 m/s [7]. We use an average of value of critical speed $w_{cr} = 633{,}8$ m/s for the given range equal. Then (11) will become:

$$L_P = 10 \cdot \lg\left(\frac{G_0^2}{S_{pipe}} \right) - 10 \cdot \lg n + 144{,}9 - K(n) \tag{15}$$

Thus, the formula (15) allows to count the total level of sound capacity of air venting of steam on the power complexes, dumping steam with superfluous pressure. The total level of sound capacity depends on productivity of the valve of devices of air venting of steam, the areas of section of the exhaust pipeline and from a degree of underexpand jets of steam. It essentially simplifies carrying out of calculations in comparison with methods of calculation existed till now.

4. COMPARISON WITH RESULTS OF EXPERIMENT

Results of calculations under the formula (11) were compared about results of measurements for steam emissions for a range n =1,5 – 13,3. One of results of measurements for three modes of emission steam from the exhaust pipeline in internal diameter (tab.1) about results of calculation of noise level of emission steam are given on fig.4. Acoustic measurements were spent by a normative technique.

Table 1. Parameters of steam at realization of acoustic measurements in 15 m from the exhaust pipeline dumped

Parameter	Parameters of steam on a boiler		Parameters dumped of steam			The total level of sound capacity
	p_0, MPa	t_0, °C	G, kg/s	t, °C	n	L_P, dB
1	5,2	488	16,1	381	1,5	161,0
2	9.6	530	29,3	390	2,8	165,3
3	12,9	538	39,5	390	3,8	167,2

From fig.4 it is visible, that the levels of sound capacity certain by results of calculations under the formula (15) satisfy to results of measurements.

5. CONCLUSIONS

1. The design procedure of the expiration of steam jets with use of the theory of jets with the big degree of underexpand is specified.
2. The formula of calculation of the total level of sound capacity of air venting of steam (11), based on analogy by Lighthill, to a binding parameters to isobaric section of a jet is received.
3. The formula of calculation of the total level of sound capacity of emission of a stream (11) was checked experimentally up a degree of underexpand in a range n=1,5 - 13,3 of steam jets.

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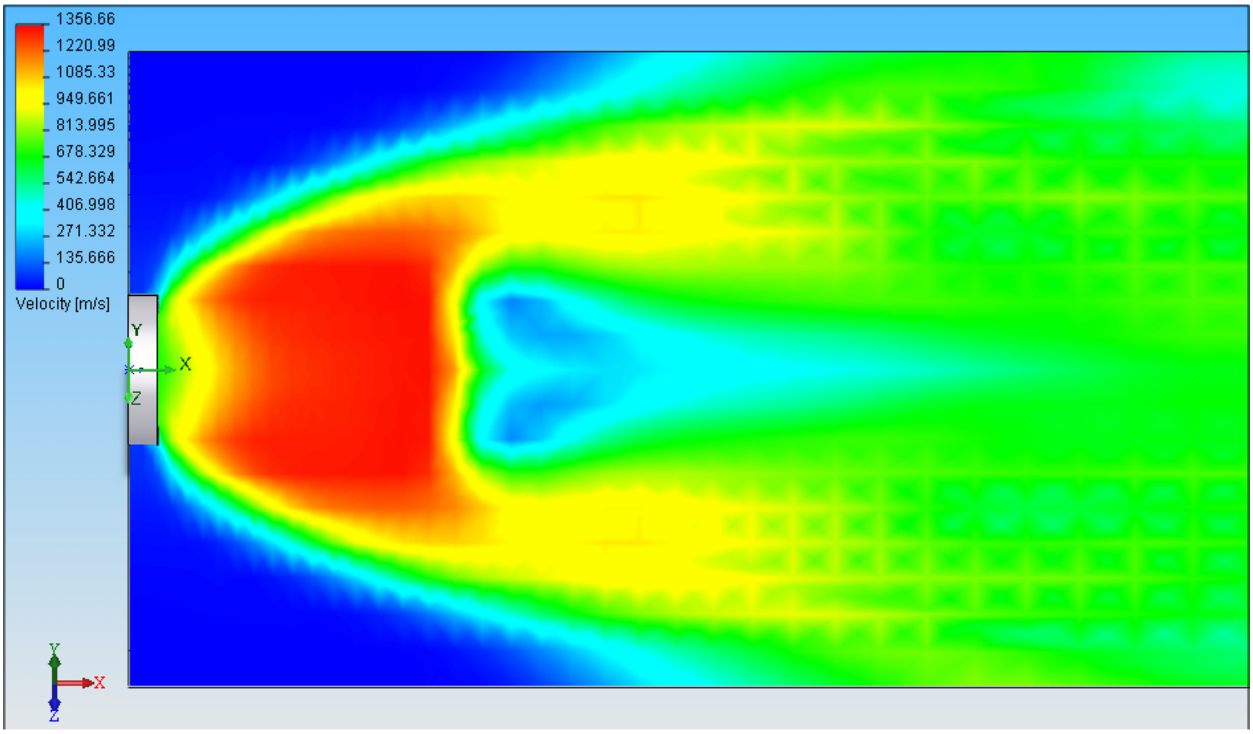

Figure 1. Field of speeds on an initial of underexpanded jets

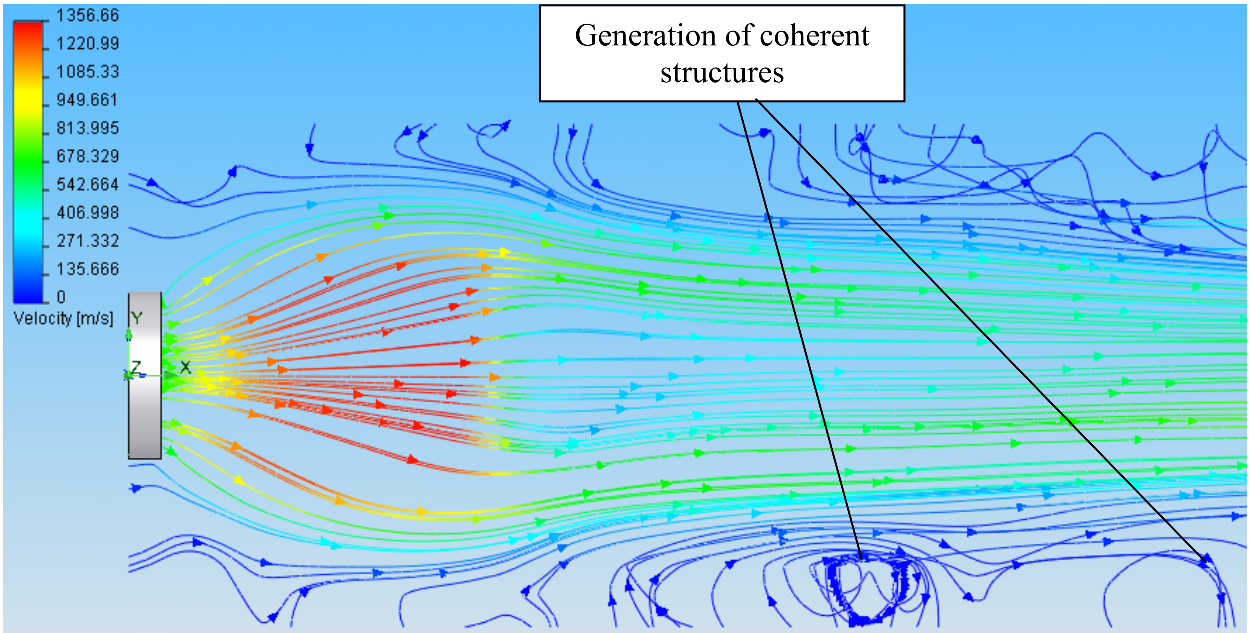

Figure 2. Trajectories of development underexpanded jets of steam

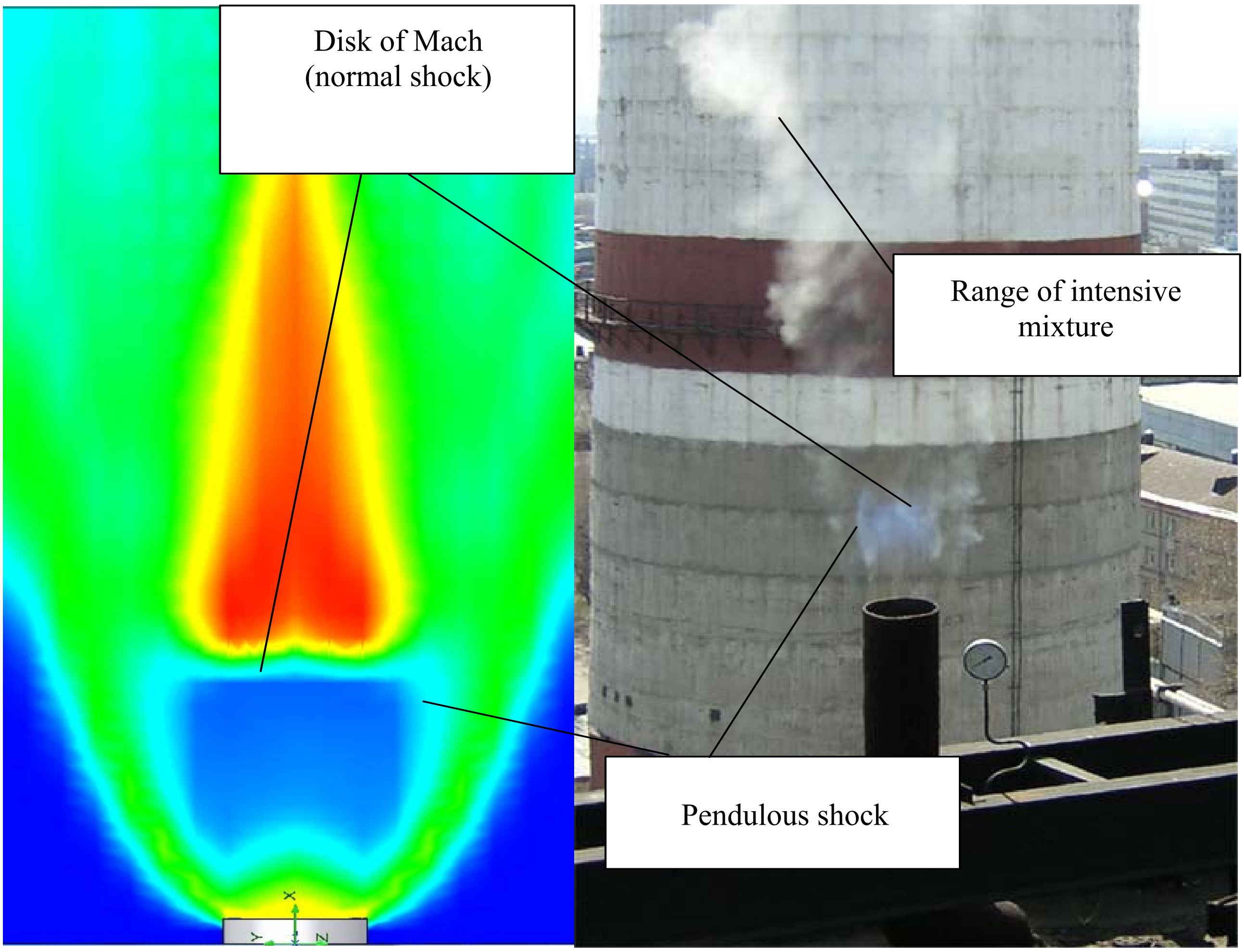

Figure 3.

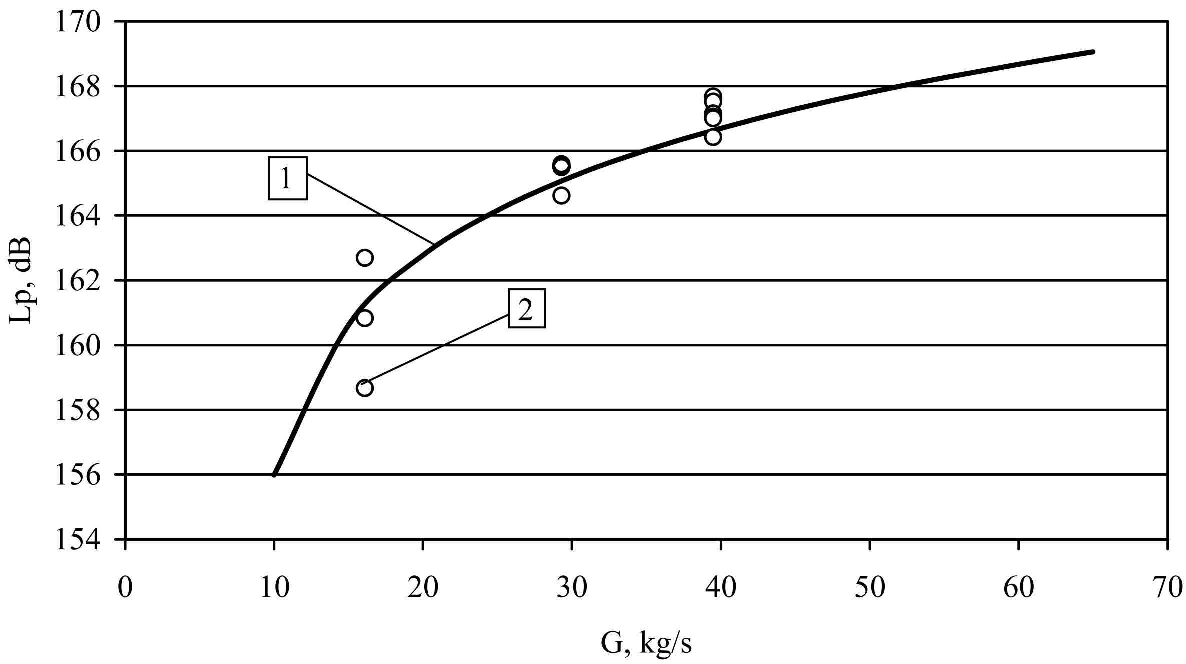

Figure 4. Comparison: 1 - results of calculations, 2 - results of measurements.