POSSIBILITIES OF SUPPRESSION TOXIC SUBSTANCES EMISSION BY NON-STATIONARY COMBUSTION

Vladimir G.Bazarov

Moscow State Aviation Institute
Moscow, Russia

The results of a theoretical study and the experimental data regarding the completeness of combustion and emission of nitrogen oxides under excitation of non-stationary fuel burning in the combustion chamber are presented. It has been shown that there is a frequency range of entropy oscillations excited in the combustion chamber in which the emission of nitrogen oxides significantly decreases, completeness of combustion increasing at that.

State of the problem.

The exhaust gases of engines, working on hydrocarbon fuels, contain as unburned hydrocarbons and products of their incomplete combustion, mainly carbon monoxide CO, and oxides of atmospheric and fuel nitrogen. Firsts are a corollary of a mixing imperfection. Their quantity can be reduced by increase of atomization quality and carefulness of mixing fuel with air, increase of an oxidizer excess coefficient, residence time of a combustible mixture in the combustion chamber. However, it is necessary to mark, that all these measures, directed on increase of combustion completeness, also increase nitrogen oxides emission because of increase of combustion zone temperature and residence time of combustion products in a high-temperature zone.

Widely used methods of nitrogen oxides emission suppression [1] consists, in basic, in reduction of temperature of combustion zone (water injection, cooled flue gases injection, organization of two- and multistage combustion). These measures, as a rule, will cause to reduction of combustion completeness and jet temperature, or require excessive complication and increase of metal consumption of the combustion chamber.

One of perspective methods of combustion, ensuring full elimination as NO_x and CO in combustion product was offered by the "Mitsubishi" company [2]. It provides separate incineration lean combustible mixture and enriched one at reduced temperatures, and then enriched and lean one in each other, i.e., application of the so-called gas-gas scheme, known in liquid-propellant rocket engines (LRE).

Thus the prevention of nitrogen oxides emission at afterburning of incomplete combustion products is provided by useful heat braid (with the help of heat exchanger), that is unacceptable in aviation gas-turbine engines (GTE). Thus, it is possible to consider, that the problem of simultaneous suppression of NO_x and CO emission in GTE is not solved, and the existing design of combustion chambers is rather not the result of scientific research, but mainly is a result of long operational development, so that elaboration the GTE combustion chamber is largely a kind of art, not of science.

Theoretical considerations.

It was noted that the concentration of nitrogen oxides formed during explosions is considerably lower than the equilibrium one [3]. Only during very powerful explosions, of a nuclear-bomb explosions type, these concentrations become equal [4]. The reason of the nitrogen oxides reduced quantity is in rapid cooling of the explosion products due to mixing with the atmospheric air.

Therefore a question arises: is it possible to achieve a similar effect in the GTB combustion chamber as well, having created a source of pulsating combustion in it?

Diagrammatically two zones can be distinguished in the combustion chamber (Fig.1): a combustion zone (1) and a zone of mixing combustion produces with cold air (2).

Suppose the combustion products to cool in mixing with the air by the same laws as the explosion products do. Then, for describing a process of cooling, the Ya.B. Zeldovich's mechanism should be applied [3]:

$$\frac{dT}{dt} = -AT^2,$$

where A is constant, characterizing the rate of cooling. In relation to the combustion chamber, within the frame of a one-dimension model, this mechanism can be written as:

$$\frac{\partial T}{\partial t} + U_{av} \cdot \frac{\partial T}{\partial x} = -AT^2, \tag{1}$$

where U_{av} is average rate of gases flow in the combustion chamber. To follow the process of temperature non-uniformities dissipation in detail, come over to the system of coordinates τ-X, moving in line with the gas flow.

$$\begin{cases} \tau = t - \dfrac{X}{U_{av}} \\ X = x \end{cases}$$

Then differential equation (1) will be

$$\frac{\partial T}{\partial X} = -aT^2, \qquad (2)$$

where $a = A / U_{av}$.

The following solution corresponds to differential equation (2)

$$\frac{1}{T} = \frac{1}{T_{\max}} + aX \qquad (3)$$

similar to that one for cooling the explosion products (see [3]).

Neglecting generation of nitrogen dioxide NO_2, the law of variations of NO concentration can be written in the following form

$$\frac{dC_{NO}}{dt} = K' \cdot C_{O_2} \cdot C_{N_2} \ , \qquad (4)$$

where K' is kinetic constant; K' greatly depends on the temperature of the process. This interconnection is described by Arrenius law:

$$K' = B \cdot e^{-E/RT} \ , \qquad (5)$$

where E is activation energy of NO generation process; R, T are gas constant and temperature of the process. In relation to the combustion chamber equation (4) will be

$$\frac{\partial C_{NO}}{\partial t} + U_{av} \cdot \frac{\partial C_{NO}}{\partial X} = K' \cdot C_{O_2} \cdot C_{N_2};$$

now coming over to a moving system of coordinates, we obtain:

$$\frac{\partial C_{NO}}{\partial X} = \frac{K'}{U_{av}} \cdot C_{O_2} \cdot C_{N_2} \, . \qquad (6)$$

Substituting expressions (5) and (3) into (6), we have

$$\frac{\partial C_{NO}}{\partial X} = \frac{K'_{\max}}{U_{av}} \cdot e^{-EaX/R} \cdot C_{O_2} \cdot C_{N_2} \ , \qquad (7)$$

where $K'_{\max} = B \cdot e^{-E/RT_{\max}}$.

We have obtained the equation describing the increase of nitrogen oxide concentration along the length of the combustion chamber in the zone of mixing (2) (see Fig.1).

The equilibrium concentration of nitrogen oxide corresponding to concentrations of C_{O_2} and C_{N_2} is determined by an equation of chemical equilibrium

$$K_P = \frac{[C_{NO}]}{\sqrt{C_{O_2} \cdot C_{N_2}}} \, .$$

Substituting it into equation (7), we obtain:

$$\frac{\partial \overline{C}}{\partial X} = \frac{K'_{\max}}{U_{av} \cdot K_P{}^2} [C_{NO}] \cdot e^{-EaX/R} \ . \qquad (8)$$

In this equation $\overline{C}$ is dimensionless concentration of nitrogen oxide, in relation to its equilibrium value

$$\overline{C} = C_{NO} \ / \ [C_{NO}].$$

From (8) it is seen that if we intensify heat exchange in the zone of mixing, i.e. increase coefficient a, this will result in lowering NO formation rate and, hence, NO concentration reduction in gases leaving the combustion chamber.

Assume the relative concentration of NO to be $\overline{C} = \overline{C}_o$ in the entrance plane to the zone of mixing at $X = 0$. Then the solution of differential equation (8) will be:

$$\overline{C} = \overline{C}_o + \frac{K'_{\max}[C_{NO}]}{U_{av} \cdot K_P^2} \cdot \frac{R}{Ea} \cdot \left(1 - e^{-EaX/R}\right). \qquad (9)$$

For infinitely long combustion chamber (X→∞) and $\overline{C}_0 << \overline{C}$, the relative limited concentration of NO is determined by the following correlation

$$\overline{C} = \frac{K'_{\max}[C_{NO}]}{U_{av} \cdot K_P^2} \cdot \frac{R}{Ea}$$

or, the higher the value of a, the lower is the value of $\overline{C}$:

$$\overline{C}' / \ \overline{C} = a / a' .$$

If the value of a is small (a ~0), i.e. , heat exchange in the zone of mixing is not intensified, the relative concentration of NO does not depend on the value of a, but does depend only on the length of the mixing zone x:

$$\overline{C} = \overline{C}_o \frac{K'_{\max}[C_{NO}]}{U_{av} \cdot K_P^2} \cdot X \, .$$

This asymptotic law being true is supported by measurements of the nitrogen oxide concentration carried out for the flame of an operating propane burner [5]. The corresponding experimental data are manifested in Fig.2. Heat exchange intensification by creating oscillations will result in reducing the content of NO only if the following condition is carried out:

$$a' > EX_k / R,$$

it seems that the higher the frequency of oscillations, the greater is coefficient a'.

To come to such a conclusion it is desirable to analyze how high frequency oscillations will effect the formation of NO in the combustion zone (see Fig.1). Consider a simplified model of the combustion zone. Suppose the dimensions of the combustion front can be neglected. Assume that within the combustion zone mixing with the outer cold air can be neglected too. Then at the exit of the combustion front with variation of fuel consumption we obtain the gas flow with fluctuating temperature. These fluctuations are known as entropy waves in the theory of rocket motors [6].

Due to heat exchange under high frequency the entropy waves rapidly dissipate. Considering the ideal exchange law to be of the form suggested by Zeldovich for semi-waves of higher gas temperature in the moving system of coordinates we obtain the following dependence for describing the change of temperature

$$\frac{1}{T} = \frac{1}{T_{\max}} + aX$$

and for a semi-wave of lower temperature

$$\frac{1}{T} = \frac{1}{T_{\max}} - aX \cdot$$

In some distance of $-X_P$ the temperatures in semi-waves must be equal and achieve a nominal value - T_H. This allows to rewrite the laws of temperature change as:

a) for a "hot" semi-wave

$$\frac{1}{T} = \frac{1}{T_H} - a \cdot (X_P - X); \quad X \le X_P;$$

b) for a "cold" semi-wave

$$\frac{1}{T} = \frac{1}{T_H} + a \cdot (X_P - X); \quad X \ge X_P \cdot$$

Performing similar (6) - (8) transformations we obtain the following differential equation for NO generation in a "hot" semi-wave

$$\frac{\partial \overline{C}}{\partial X} = K_H \left[\overline{C}_{NO}\right] \cdot e^{Ea(X_P - X)/R};$$

and in a "cold" semi-wave

$$\frac{\partial \overline{C}}{\partial X} = K_H \left[\overline{C}_{NO}\right] \cdot e^{-Ea(X_P - X)/R}.$$

Their solutions will be the following functions under the boundary condition of X=0, $\overline{C}$=0:

$$\overline{C} = K_H [C_{NO}] \cdot e^{\frac{EaX_P}{R}} \cdot \frac{R}{Ea} \cdot \left(1 - e^{-\frac{EaX}{R}}\right);$$

$$\overline{C} = K_H [C_{NO}] \cdot e^{-\frac{EaX_P}{R}} \cdot \frac{R}{Ea} \cdot \left(e^{\frac{EaX}{R}} - 1\right) \cdot$$

The sign of K_H denotes the following complex in these formulae

$$K_H = \frac{K_H'}{U_{av} \cdot K_p^{2}},$$

where $K_H' = B \cdot e^{-\frac{E}{RT_H}}$, the coefficient of K_P and equilibrium content of NO have been determined for temperature of T_H.

As a result the quantity of NO formed in a single entropy wave can be determined by the following formula

$$\overline{C} = 2 K_H [C_{NO}] \frac{R}{Ea} \Delta h \frac{EaX}{R} c \cdot h \frac{Ea(2X_P - X)}{R} \cdot \quad (10)$$

For small values of a function (10) becomes as

$$\overline{C} = 2 \cdot K_H [C_{NO}] \cdot X, \qquad X \le X_P$$

but at greater a - this fast growing function occurs with the order of increment of $e^{\frac{EaX_P}{R}}$.

Therefore, the dependence of NO content reduction will not be likely of a monotone character by the rate of oscillation frequency increase, as beginning with some frequency threshold the member of C_0 will intensively grow in formula (9).

For every combustion chamber there must be certain frequency of its own, under which the content of NO achieves the minimum.

High-frequency instability and its influence to stationary parameters of combustion

Researches of high-frequency instability of combustion in LRE and methods of its suppression, spent since 1964 in Moscow aviation institute and a number of other organizations on model chambers with significant margin of safety for long-duration observation over processes happening in combustion chambers have shown, that at development of self-oscillation process at combustion heat- and mass-transfer processes are intensifying shortly, expansion of a combustion zone and especially pre-flame zone is reduced, completeness of combustion is increased. The combustion adjoins immediately to the firing bottom of the mixer head, those results in its burning. There was the supposition, that high-frequency instability and accompanying its non-stationary processes, inadmissible in high energy-release LRE combustion chambers, could be used in less energy-intensive GTE combustion chambers and industrial heat-energetic installations.

The instability of combustion, being self-oscillating process, in which a power source is heat release, with a feed-back - oscillation of pressure, excites oscillations of practically all thermo-gas-dynamic parameters in the combustion chamber.

- Oscillations in space of the combustion chamber, in basic transverse and combined acoustic modes.
- Oscillations of combustion products velocity as an acoustic medium.
- Oscillations of an air velocity going to the combustion chamber owing to oscillations of a pressure drop on an air channel.

- Oscillations of the mass flow rate, plume angle, thickness of a liquid-propellant sheet and atomization dispersibility of liquid fuel. The amplitude and shift angle of these pulsations, which caused by pressure differential oscillations, depend on dynamic characteristics of fuel injectors. For existing injectors these characteristics can be most various.

Besides excitation of combustion instability, sources of these non-stationarity can be:

- Oscillations of pressure, raised in the fuel supply system and air rendering system.
- Turbulence of a gas and liquid-propellant flow.
- Oscillations in a gas and liquid-propellant stage of injectors and at interaction of liquid-propellant and gas flows.

Experimental researches.

Experimental researches of influence of non-stationary processes on a mixing were conducted at the dynamic cold flow stand of Moscow aviation institute with application of water as a working skew field. For excitation of non-stationary processes the following means were used:

- Hydromechanical pulsator (7) at research of swirl and spray injectors.
- Electrodynamic pulsator - on supply line of a gaseous component (combustible gas, air).
- Rotation injector with generators of the various forms of non-stationarities: acoustic radiators of a type "Siren" - for excitation of oscillations of pressure and flow velocities, ring-type nozzle with bad streamlined skew fields - for creation of spiral Carman's vortexes [8] - nozzle with crossed channels - for formation of an intensive turbulent field round an atomization plume.
- Liquid-propellant swirl injectors with a self-oscillating mode of the efflux - for formation of mass flow rate oscillations and local oscillations of combustible mixture concentration.
- Swirl porous injectors for formation of oscillations of a two-phase flow in a mixing zone, including oscillations of fineness of atomization and plume angle in absence of oscillations of the fuel consumption.
- Pneumatic coaxial swirl-spray injectors with self-oscillating operational mode [8] - for creation of small-sized local oscillations of atomization dispersibility and fuel distribution in a mixing zone.

All above-stated devices should supply various kinds of heterogeneities in absence of instability of combustion.

The main result of these researches consists in following. Even weak oscillations about 6 % of a pressure differential on liquid-propellant injectors result in essential changes of the size of a atomization plume (at spray injectors width of a plume will increase in some times, at swirl - by 60-70 %), smoothing of mean non-uniformity of fluid separation on a plume radius. In an atomization plume, however, local non-uniformity occurs, the size of which is 25-80 mm depending on frequency of raised oscillations and velocity of a liquid-propellant flow.

Excitation of pressure oscillations in air flow, achievable by the ultrasonic Garthman and Gregush's generators, resulted to strong atomization intensification and various waves of pressure in the mixing zone. Thus, essential oscillations of a structure and of a combustible mixture flowrate were not marked.

The self-oscillations in liquid-propellant injectors had frequency not above than 750 Hz and were accompanied by intensive oscillations of the fuel flowrate and combustible mixture concentration in the chamber without essential influence to atomization quality.

The strongest influence to a structure of a mixing zone was exerted by pneumatic injectors.

The curl-shaped plume form of a swirl porous injector (Fig.2) has caused a strong ejection to plumes of ambient gas. The dispersibility of drops is improved with increase of flow rate of gas given through the porous insert.

The coaxial jets of gas and twisted fluid flow in vapor-liquid spray-swirl injector (Fig.3) provided both stationary, and self-oscillating mode of current at minor change of a pressure differential with strong change of mixing process.

Self-oscillations make strongest influence of liquid fuel distribution across plume radius. Emergence of self-oscillations results in strong reorganization of the plume form: from typical for a swirl injector up to a rectangular distribution of fluid on a plume and, in some cases, to spray roping. Structure heterogeneities zones with 25-40 mm in size are emerged on plume length, irrespective of a pressure differential, since the frequency of self-oscillations at growth of a pressure differential and velocity of two-phase flow will proportionally increase.

Rotation injectors, arranged with generators of non-stationarity in an air flow, surrounded a atomization plume, salutary work on a atomization dispersibility, especially on intermixing of fluid with air. Spectra of drops, formed by a nominal injector (1), equipped by the generator of Carman's vortexes (2) and siren (3), are presented on Fig. 4. It is visible, that the formation of a non-stationary flow has reduced mean-median diameter of drops in 1.5 time, from 300 down to 147 micron, that has reduced time of their burn-out more than twice. The plume angle at excitation of disturbances in air flow has increased.

Firing experiments.

The experimental sites of the effect of the fuel mixture content variations and, accordingly, the entropy of combustion products, toxic substances on the combustion completeness were conducted in an industrial laboratory of Kazan Aviation Institute on a four-burner section of the AL-31 Su-27 engine circular combustion chamber. Firings were performed in model modes under atmospheric backpressure and the compressed air supply from an autonomous source, the consequence of which was low completeness of combustion of $\eta_t \cong 0,74$ with standard injectors and a fuel supply system applied. This allowed to study the effectiveness of different measures for increasing completeness of combustion that could not be studied under the design conditions of combustion chamber operation when completeness of combustion is $\eta_t = 0.95 - 0.97$. The fuel supply system was equipped with a described in [7] hydrodynamic pulsator installed before the fuel injector and generating pressure oscillations in frequency range from 294 Hz to 1800 KHz with the maximum amplitude in the range of 900 - 1100 Hz and being of 0.6 - 0.8 MPa. Hydraulic testing of fuel burners under a dynamic mode showed that pressure variations in pre-burner cavity cause changes in fuel consumption, the angle of flare taper, fine dissipation and density of the drop flow in the mixture formation zone [7]. Under the constant air consumption the fuel flame oscillations caused the formation of regions with time variable correlation of fuel mixture components in the zone of mixture formation.

The system of measurements, besides standard instrumentation for registering stationary and variable values of pressures and component consumption, included measurement instrumentation of combustion products temperature and their components, by which completeness of combustion was calculated.

Generalized results of a series of experiments are shown in the diagram of completeness of combustion dependence on frequency of excited oscillations (Fig.5).

Under low frequencies of excited oscillations (200 Hz) completeness of was considerably lower than under stationary conditions, which is explained by a greater volume of non-uniformities of the contents (the concentration wave length was ~ 40 cm, which is comparable with the length of the combustion chamber, the oxidizing and fuel-rich products of non-complete combustion formed during combustion of enhanced and poor fuel mixtures did not have time to mix and burn up in each other. The gas analysis showed the presence of both nitrogen oxides and nonburnt hydrocarbons, CO, etc. in the combustion products. By the increase of oscillation frequency the completeness of combustion grows up to maximum in the range of 400 - 450 Hz and then smoothly reduces asymptotically approximating its stationary value at $f \to 2000$ Hz. The content of nitrogen oxides is of a sloping minimum in the same frequency interval (Fig.5).

The obtained results can be only considered preliminary since the theoretical study has been conducted for a greatly diagrammaticalized model and the experimental one should be continued both in organizing careful physical studies of mechanisms of the non-stationary oscillating processes effect on averaged factors of combustion and in field firings. However, the manifested results show that the reduction of nitrogen oxide contents is possible without lowering the temperature of the combustion zone that usually results in prolonging the combustion process and reducing the completeness of combustion and, thus, unacceptable in GTE and heat-release industrial furnaces on account of organizing non-stationary combustion in them. This is supported by the results given in [8] of industrial tests of a fuel burner fitted with a generator of the air stream oscillations.

Conclusions.

Non-stationary processes of mixing and combustion intensify liquid fuel atomization and its mixing with air, heat-mass-transfer in a combustion zone, that reduces width of the combustion zone and increases completeness of combustion.

Thus, emerging oscillations of combustible mixture structure can exert as negative effects, resulting to emission of incomplete combustion products, and positive, reducing the contents of nitrogen oxides in combustion products due to the drop of combustion zone temperature. The intensity of this effect depends on frequency, form and amplitude of excited oscillations.

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Figure Captions

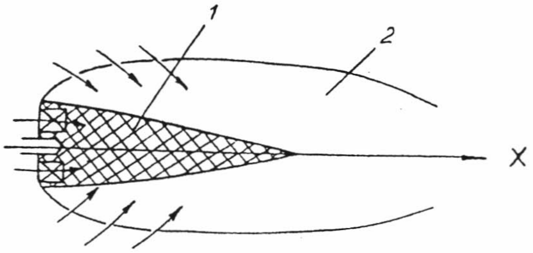

Fig.1. The layout of main zones in the combustion chamber.

1. Combustion zone. 2. Zone of mixing.

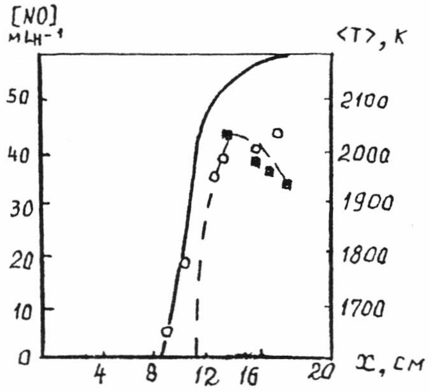

Fig.2. Distribution of temperature (- - - -) and NO concentration (——) along the flame of natural gas in air according to [5].

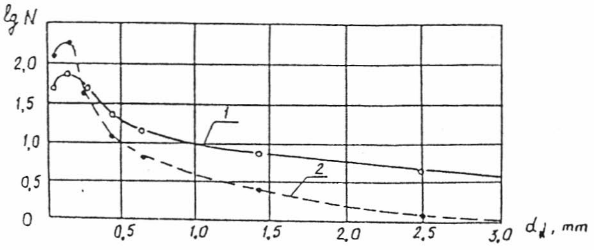

Fig.4. Influence non-stationary processes in an injector on a spray dispersibility. (——) stationary mode, (----) self-oscillating mode.

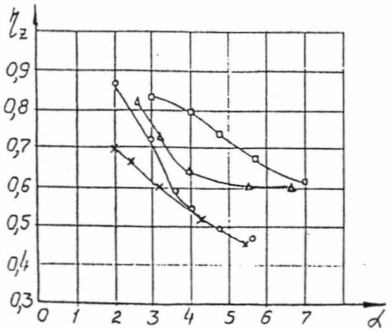

Fig.5. Influence of pressure fluctuations frequency on combustion efficiency. o - stationary operation; × -f=340 Hz; Δ - f=400 Hz; □ - f=750 Hz.

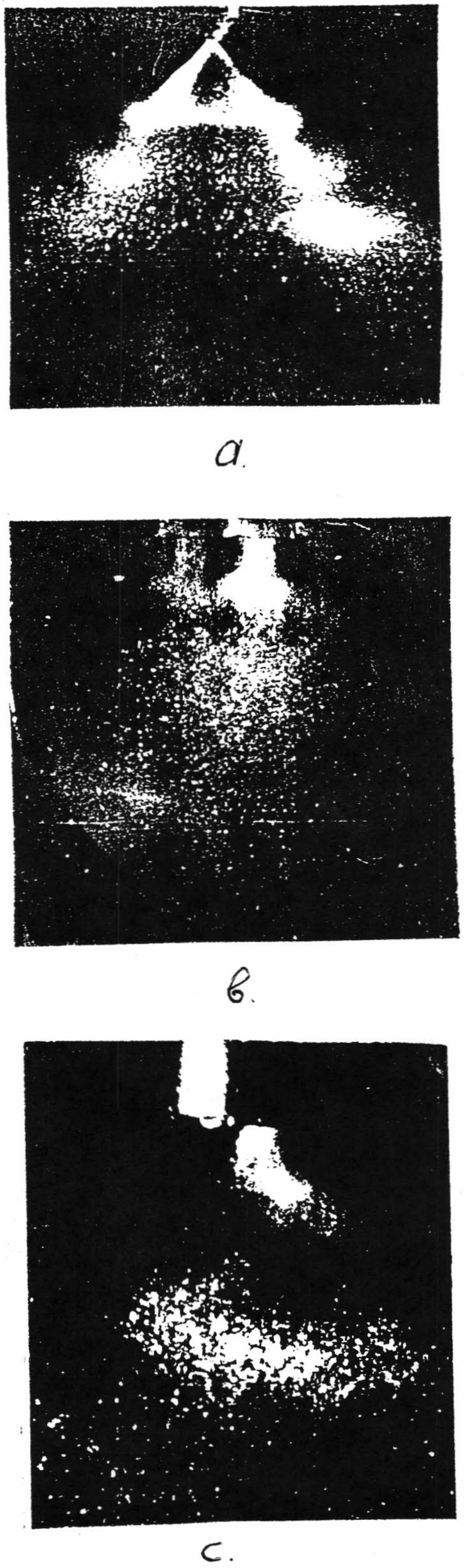

Fig.3 Spray plumes form of various injectors on non-stationary mode.

a - Induced oscillations in a spray-swirl injector f=1100 Hz

b - Self-oscillations in coaxial gas-liquid injector

c - Precesing self-oscillations in a swirl injector with the porous insert.