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ABSTRACT

CONTRIBUŢII TEORETICE ŞI EXPERIMENTALE PRIVIND FILTRAREA GAZELOR NATURALE ÎN CÂMP ULTRASONIC

THEORETICAL AND EXPERIMENTAL CONTRIBUTIONS CONCERNING THE FILTERING OF NATURAL GASES IN ULTRASOUND FIELD

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CHAPTER I

NATURAL GASES AND THEIR QUALITY. THE NECESSITY OF USING AND PURIFYING THEM

The national system of natural gases transmission is presently made out of 13110 km of transmission mains and supply pipe connections, being foreseen with 21 command stations of the valves and/or technological nodes, 961 tuning-measuring and/or measuring of the processed gases from national exploitations stations, 3 stations for measuring gases taken from import, 6 measuring stations placed on the transit pipes, 6 stations for compressing gases, 857 stations for cathode protection of the pipes, 575 installations for gases odorization and millions of users.

For the good functioning of the entire SNTGN *(National System Of Natural Gases Transmission),* avoiding accidents in order to reduce the technical risk attached to the transmission and distribution of natural gases, for an efficient usage and processing, first, the natural gases need to be filtered and then purified or a logical combination of these operations required by the technological process.

Filtering is the operation by which the solid matter transmitted by the natural gases flow from the extraction point to the usage point is retained. The solid matters existing in the natural gas flow neither have the same shape or size nor the same chemical composition. The smallest suspended particles have a size of approximately 0,002 μm (meaning 2 nm) and the largest ones can measure millimeters or even tens of millimeters. Although only very few of the solid particles have a sphere-like-shape, further down in all demonstrations presented, they will be considered as sphere-shaped, their diameter being the main feature.

From this qualitative point of view, the individual particles are classified according to their diameter in gross (if their diameter is bigger than 2.5 μm) and fine (if their diameter is smaller than 2.5 μm). The fine particles represent a rather complicated technical problem regarding their retention because they remain suspended in the gas for an almost undetermined period.

Very small particles gather to form bigger particles, usually also from the category of those of fine size and they represent the same problem difficult to solve in certain situations

Sometimes, these fine particles can also be dangerous because they can contain toxic compounds, such as heavy metals (mercury) or their compounds with certain persistent organic pollutants (polynuclear aromatics), according to the granulation of the particles. This is due to the fact that many toxic compounds found as vapors in the natural gases condensate on the already present fine dust particles

That is why, in order to retain solid impurities from the natural gases, one uses dust separator filters which, based on their functioning principle can be:

- ✓ gravimetric separators;
- ✓ centrifugal separators;
- ✓ separators by abruptly reducing speed;
- ✓ separators by cleaning;
- ✓ filters;
- ✓ separators in electric field;
- ✓ separators by coalescence;
- ✓ special separators.

Along the solid particles of different shapes and sizes, natural gases also contain a series of gases such as hydrogen sulphide, ammoniac, carbon dioxide, sulphur alcohols, sulphur dioxide and others which, in order to prevent polluting the atmosphere, out of the necessity of accomplishing advanced purities for some reactant substances and for recovering some valuable compounds, require an appropriate purification.

The usual purification procedures of natural gases can be based on the following processes or unitary operations:

- ✓ absorption in a liquid called absorbent;
- ✓ absorption on a solid material called absorbent;
- ✓ fractionation;
- ✓ crystallization and filtering;
- ✓ chemical conversion of impurities;
- ✓ special procedures.

As a consequence, for an efficient usage, a risk free exploitation and a high maintenance of the entire system of natural gases transmission and distribution, the purification and filtering of the gases at the quality requested by the end consumer is necessary

CHAPTER II

FLOW STATE OF RESEARCHES REGARDING THE FILTERING OF NATURAL GASES

Solid impurities and their retention

Solid impurities are of different shapes and sizes, firstly depending on where the analysis of the transmissible natural gas is done, as follows:

- at the extraction point: sand, mud, rock fragments and different liquids;
- on the route of the transmission pipes: dust, liquid and solid particles, powders and oxides;
- before the end user: solid and liquid particles and micro-particles.

In order for these impurities to have an increasingly smaller negative effect on the efficiency of natural gases transmission and in order to reduce the technical risk attached to the transmission pipes their separation and filtering is done.

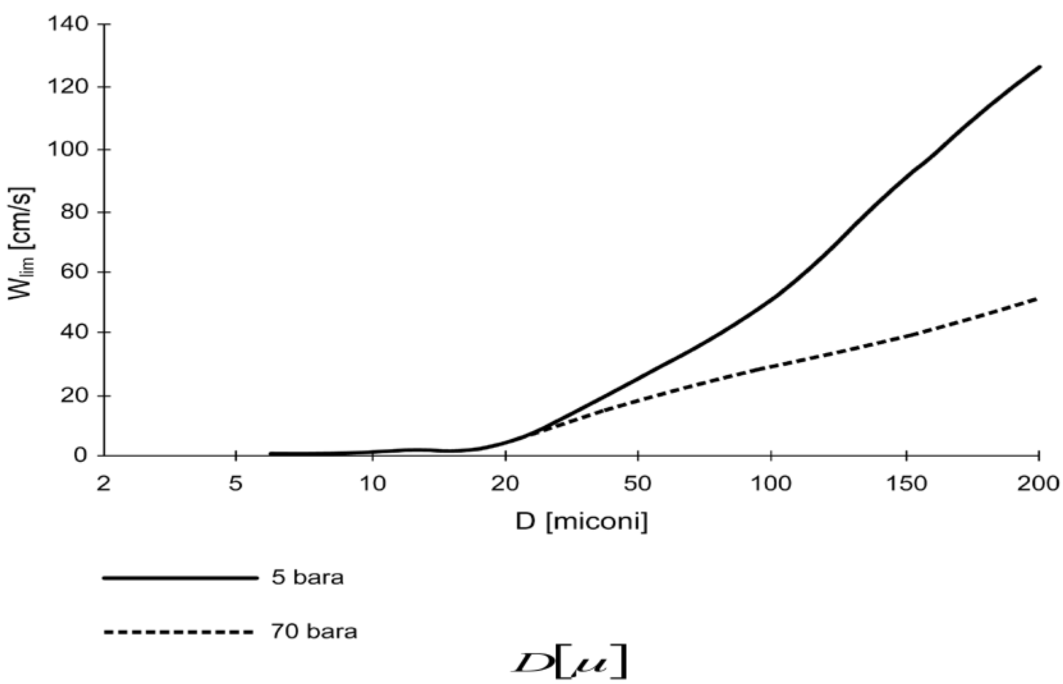


Fig.2.1 The minimum falling speed of dust particles

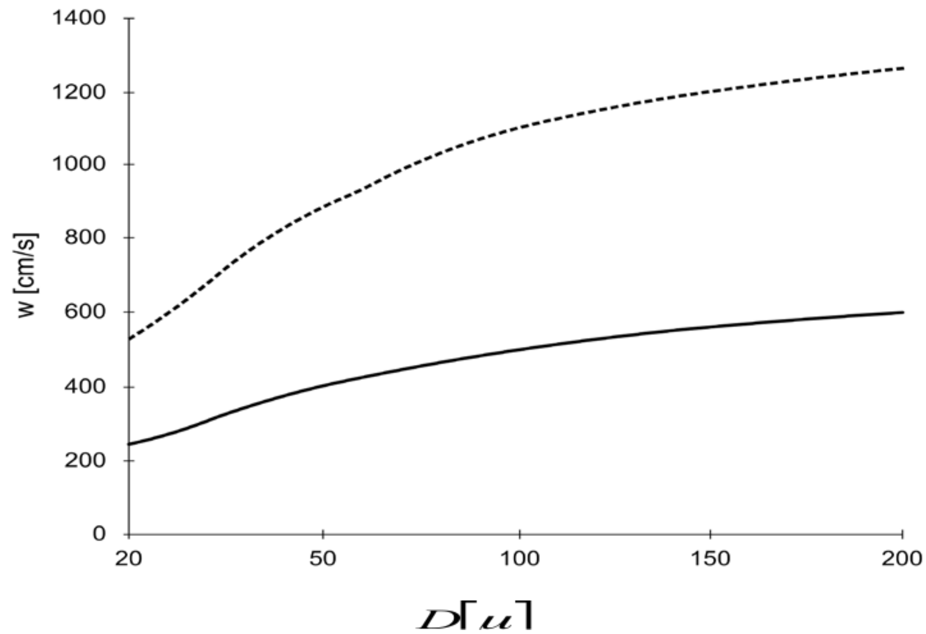


Fig.2.2 The entrainment and floating beginning speed of the dust particles

This separation and retention is done with the help of some filters which are characterized by:

- ✓ the flow of natural gases coming out from the extraction pump;
- ✓ the entrance pressure in the filter of the natural gases;
- ✓ the exit pressure from the filter of the natural gases;
- ✓ the diameter of the particles it can retain;
- ✓ the maximum temperature of gases when entering the filter;
- ✓ the retention degree or the filter efficiency;
- ✓ pressure loss in the filter;
- ✓ annual maintenance costs.

The solid impurities separators and the filters need to be installed at least in the following places on the natural gases exploitation system's route:

- ✓ in the production fields, if possible at the extraction point;
- ✓ before the natural gases' drying stations;
- ✓ after the natural gases' drying stations which use solid drying;
- ✓ before the natural gases' compression stations;
- ✓ before the tuning and measuring stations;
- ✓ at the natural gases users with pretentious technological processes (chemistry, thermal treatments, glass and porcelain industry, etc.)

The filtering operation consists in passing a fluid through a permeable medium (filter) in order to retain the impurities. As filtering material one can use for example, a textile material with fibers regularly (fabrics) or irregularly placed (fibers or felt), or a grained material in which the grains can be free and constitute the filter's stuffing.

The filtering mechanism in a filtering material is complex because inertia effects, adherence effects, diffusion effects, effects of an electrostatic nature and the griddle effect appear.

The image of the hydro-dynamic spectrum at small Reynolds numbers (of the unit order) to the movement around a cylinder (a fiber) is presented in figure 2.3.

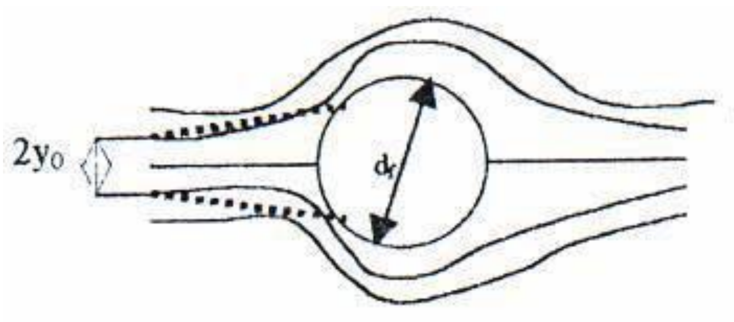


Fig. 2.1 The image of the hydro-dynamic spectrum at small Reynolds numbers at the movement around a cylinder (a fiber)

In the gas flow there are particles in suspension which are driven by the gas flow up close to the fiber of the filtering element where the flow lines bend.

Here a solid particle having the diameter d, that moves with the speed v, equal to that of the gas flow (fig.2.4).

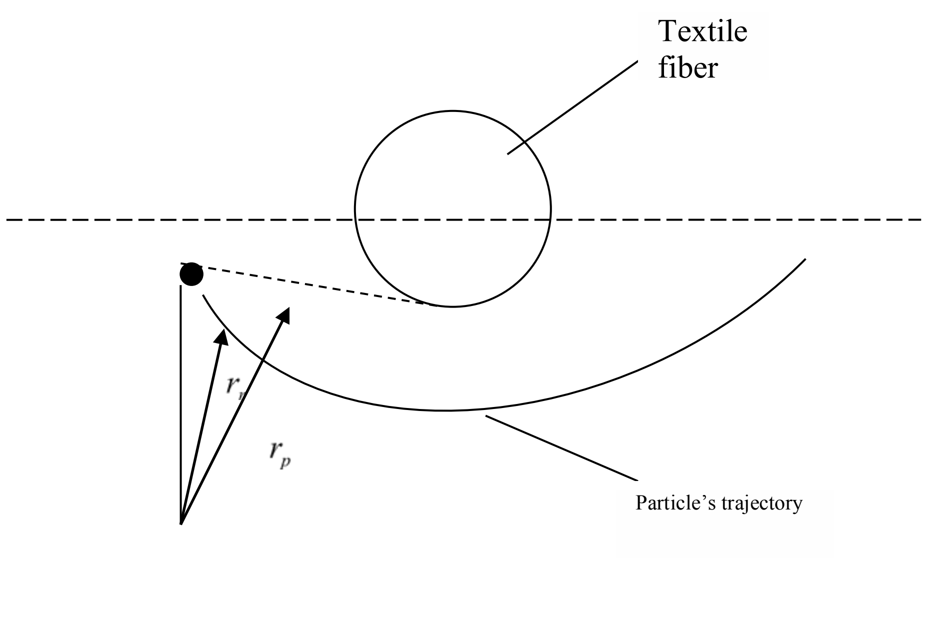


Fig. 2.2 Movement of the fluid particles around a textile material fiber

The centrifugal force which acts on the gas elements F_c, is given by the relation:

$$F_c = \rho_G \frac{\pi d^3}{6} \frac{v_c^2}{r_c} \quad , \tag{2.1}$$

In which:

r_c is the radius of the cylinder through which the gas circulates;

v_c – the flowing speed of the gas; ρ_G – gas density.

The centrifugal force which acts over the solid particles F_p, has the form:

$$F_p = \rho_p \frac{\pi d^3}{6} \frac{v_p^2}{r_p} \quad , \tag{2.2}$$

In which:

r_p - is the radius of the particle that exists in the carrier gas;

v_p – particle speed;

ρ_p – solid particle density.

If one considers that at the considered moment the two speeds are identical and that at the moment of bending the trajectory of the interior bending radius is the same, it results that the ratio F_p/F_c has the size order $\sim 10^3$, and $r_p > r_c$.

As a consequence, the solid particles found in the interval $2y_0$ will hit the fiber. In this manner, one can define a collision coefficient under the form:

$$\varphi_c = \frac{2y_0}{d_f} \ , \tag{2.15}$$

Part of the particles which are going to hit the fiber will stick to it and they will be retained by the fiber, and another part will slide on the surface of the fiber and they will be engaged by the particles' flow. The particles retained by the fiber are characterized by the adherence coefficient φ_i, under the form:

$$\phi_i = \phi_c \phi_a = f\left(\Psi, \mathrm{Re}, \rho_p / \rho_g\right) \quad , \tag{2.16}$$

where:

Ψ- is the number of Stockes;

Re- Reynolds number;

ρ_p/ρ_g- ratio of relative densities solid/gas particles.

The number of Stockes ψ has the formula:

$$\psi = \frac{v_p d^2 \rho_p c_u}{18\eta df} , \qquad (2.17)$$

In which:

C_u –is the number of Cunningham, which takes into consideration the effect of the Brownian movement;

Λ- the length which a molecule freely passes and the resulted formula is:

$$c_u = \frac{1}{1 + 2\Lambda / \ d}, \qquad (2.18)$$

The number of Stockes results from the ratio of the inertia forces:

$$\frac{F_{in}}{F_{visc}} = \frac{\rho_p\left(\pi d^3 16\right)\left(v_p^2/r_p\right)}{3\pi\eta R v_p} = \frac{\rho_p d^3 v_p^2}{18\eta \frac{d}{2} v_p \frac{df}{2}} = \frac{4\rho_p d^2 v_p}{18\eta df}; \quad (r_p\text{=df/2}) , \qquad (2.19)$$

The number ψ characterizes the ratio between the inertia F_{in} and the viscous friction forces F_{visc}.

From figure 2.5 one can see that the separation capacity, owed to inertia has increasing values when ψ increases, meaning when the values of the dp particle's diameter are high. This means that with dp>1 the effect of these inertia forces becomes special.

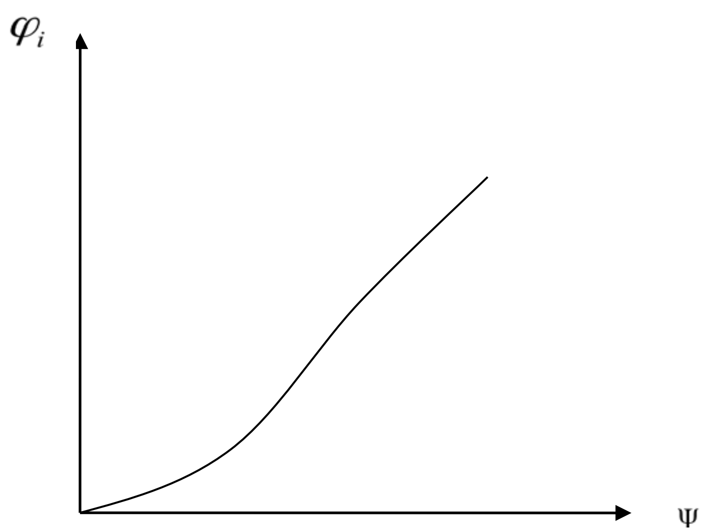


Fig. 2.3 The separation capacity

The influences of the Re number and the (ρ_p/ρ_g) ratio are defined by several authors. With Re numbers of the hundredth order, the hydro-dynamic spectrum looks like in figure 2.6.

Because in reality there are a number of fibers, the direction of the particles' carrier flow may not be the normal one, at the particle being able to be different

This means that the particles can enter in the areas behind the fiber and the secondary movements can engage the particle and hit it on the part behind the fiber and φ increases.

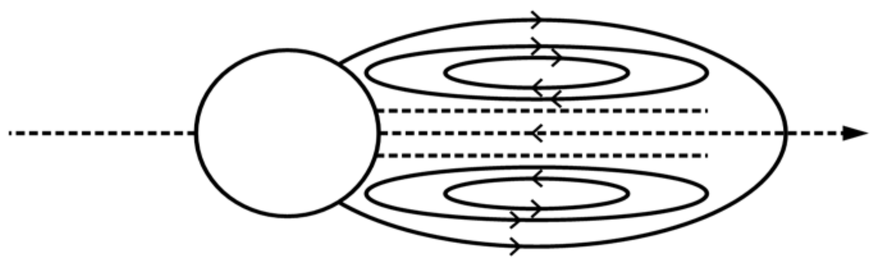


Fig. 2.4 The separation capacity in the case of the Re number of the hundredth order

The entrance in this back area can be done both because of the particles that enter behind another particle and because of some turbulent fluctuations. According to the chart $\varphi_i=f(\psi)$ in figure 2.5, it results that with small diameters of the dp particle, φ_i is reduced. Reality shows that with dp<1μm, φ_i increases again. This is owed to the diffusion effects. In this case, the particles being of small dimensions, one will consider that they are subject to the effects of the Brownian movement. Then, the probability of hitting the surface of the fiber increases and as a consequence the retention capacity also increases substantially. This random movement is characterized by a diffusion coefficient c_d, given by the formula:

$$cd = \frac{KT}{3\mu\pi d_f} c_u, \tag{2.20}$$

where:

K= $1.38\cdot10^{-23}$, in J/K;

K- Boltzmann's constant;

T- temperature of the carrier gas; d_f- fiber diameter.

The influence of the diffusion process on the separation capacity is presented in figure 2.7.

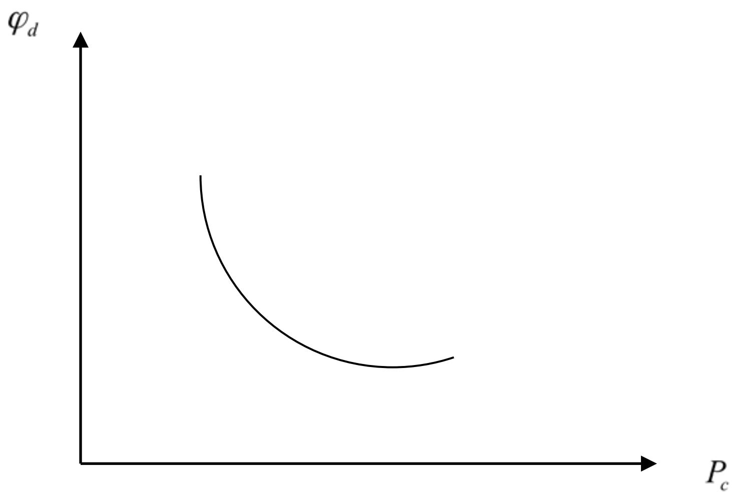


Fig. 2.5 The influence of the diffusion process on the seperation capacity

The separation ratio increases substantially through the effect of diffusion with small P_c numbers, meaning small flow values, small values of df and high diffusion coefficients, meaning small dps. P_c is Peclet's criteria and has the form:

$$P_c = \frac{v \cdot d_f}{D} \ , \tag{2.21}$$

On the particles which pass through the filter the electrostatic forces are present. This phenomenon is owed to the electrostatic charge of the particle and fiber due to the friction with the gas.

The electrostatic charge effect is present at a flowing speed of v = 1.5…2 m/s. Their effect is as high as the particles' dimensions are small. A determinant role in the functioning of the filters is the adherence of the fiber particles. In order to sometimes increase this retention capacity, one can additionally increase the adherence coefficient, either by moistening the fiber or by setting a layer of oil.

For the particles, if the condition s>3d is met, this effect does not occur. If the surfaces are active, these bridges can also appear in the case of s>3d but they are unstable, and the griddle effect is intermittent. This griddle effect can occur only on the exterior surfaces of the filters. Thus, a layer forms on the filter's surface which in return retains the particles with bigger diameters of solid impurities.

The thickness of this layer is fluctuant, in time leading to the increase of the pressure drop on the filtering element, given by the formula:

$$C_i \cdot v \cdot S \cdot t = (1 - \varepsilon) \cdot \rho_p \cdot S \cdot h \ , \tag{2.22}$$

Particule de praf - Dust particles

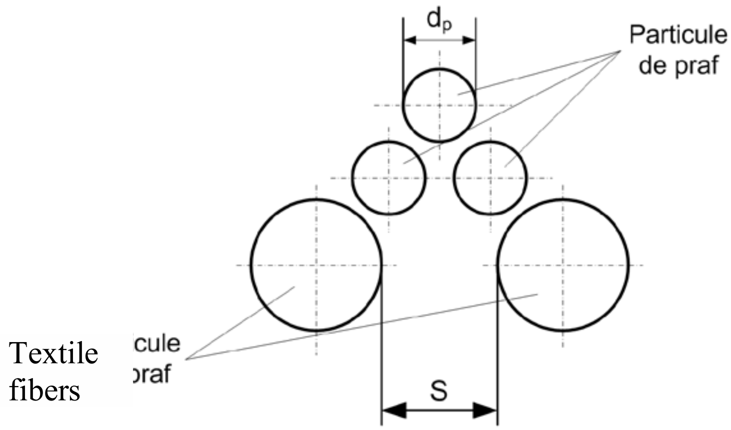


Fig. 2.6. Placement of textile material fibers and dust particles inside a filter; d_p diameter of solid particles; s-distance between two textile fibers

At the moment in which the pressure on the filtering layer reaches a certain value and the pressure drop increases, the dust layer is removed and the filter is regenerated. During regeneration it is considered advantageous to remove the entire dust quantity and to leave a dust layer which will induce and accelerate the formation of a filtering dust layer in order to retain smaller particles.

The variation of the pressure drop on a filtering element is presented in the chart in figure 2.9.

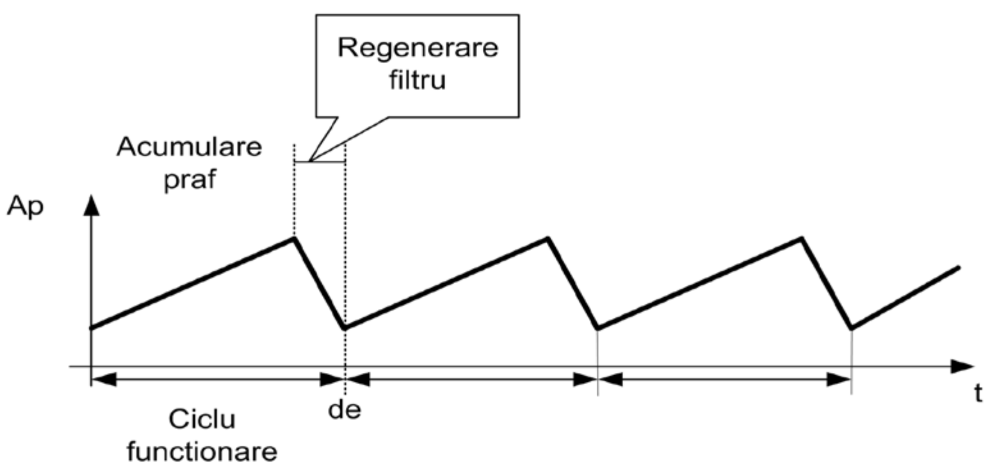


Fig. 2.7 The functioning cycles of the filtering device

Acumulare praf – dust accumulation

Regenerare filtru – filter regeneration

Ciclu de functionare – functioning cycle

Finally analyzing the global separation capacity, it results that with low speeds the diffusion effects are preponderant and the filters in this category work at very low speeds.

The inertia effects are specific to a category of filters that work at higher speeds.

At very high speeds, a blowing of the dust occurs and a reflection of the particles due to the collision with fibers (fig. 2.10), pressure losses being lower.

The dust collectors by cleaning have a very good separation capacity but they need to function in a strictly delimited regime of flows and speeds. In the case in which the speed of the gas surpasses the prescribed limit, the risk exists for the oil with the collected dust to be engaged beyond the de-oiling baffles, with oil losses and with decrease of the de-dusting efficiency. If the speed is below the foreseen limit, the cleaning, respectively the dust retention is done with an unsatisfactory capacity.

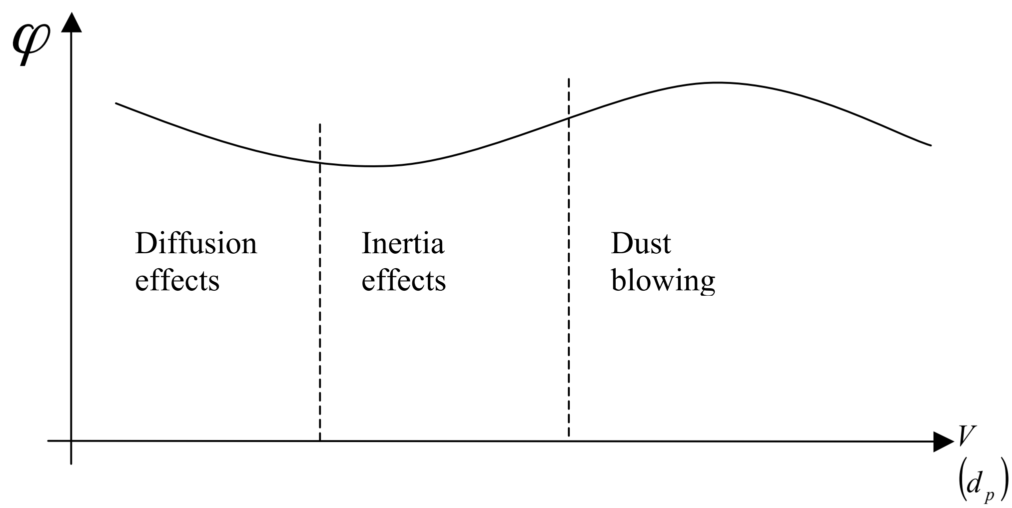


Fig. 2.8 Functioning cycles of the filtering device

CHAPTER III

THEORETICAL AND EXPERIMENTAL CONTRIBUTIONS REGARDING IMPROVING THE FILTERING OF NATURAL GASES USING THE ULTRASONIC FIELD

Theoretical and experimental contributions regarding the design requirements of a filtering installation

By analyzing the classical filtering methods and the equipment used for filtering and purifying gases, presented in the previous chapters, a series of limits of the methods used with a series of disadvantages have resulted out of which the most important ones are the following:

- ✓ the retention degree of the particles is variable during functioning, the danger of an incomplete separation especially of the particles with the diameter smaller than 5 μm existing;
- ✓ most of the times a gradual filtration, which implies several filtering devices and a more complicated pipe system with a reduced verification possibility, is necessary;
- ✓ pressure loss is variable, in several cases reaching the admitted minimum limit after a short functioning period, especially due to the clogging and blocking-up phenomenon of the filtering elements;
- ✓ the necessity of periodically cleaning the filtering elements and as a consequence the decrease of the efficiency of the natural gases utilization process and the complication of its transmission and distribution system by the parallel existence of two transmission paths which function in tandem;
- ✓ the impossibility of retaining all solid and liquid particles, those that remain constituting an aggressive corrosive agent of all parts that come in contact in the transmission pipes, in the measuring, control and downstream distribution devices;
- ✓ high energy consumption and pretty high maintenance cost in certain cases (cyclone filter, electrostatic filters);
- ✓ limiting the entrance speed and the flowing speed which during consumption peaks are always surpassed expressly leading to the erosion of the pipes, etc.

In order to reduce part of these disadvantages and in order to substantially improve the natural gases filtering process, the researches enclosed in this doctoral dissertation suggest the usage of ultrasound waves in the filtering and purification process, based on the analysis of the main phenomena which occur during ultrasound waves' propagation through a natural gases medium.

Stationary waves

In most filtering and purification cases, in order to retain the smallest solid particles, it is necessary to create stationary waves.

If in any medium several ultrasound waves are propagated then, in certain points of the medium the ultrasound waves intersect with one another thus the interference phenomena occurring. A particular case of waves' interference is constituted by the *stationary waves.* If one considers two waves with the same amplitude and frequency, which propagate in opposite ways between two perpendicular reflection planes on the propagation direction one can obtain the following movement equation:

$$y = A\sin(\omega t - kr_1) + A\sin(\omega t + kr_2)\ , \tag{3.91}$$

In which r_1 and r_2 are the distances from point M, to the vibration.

If one considers the separation surfaces of the perfectly reflecting mediums, the entire energy from the direct wave is found in the reflected wave, one can deduce the pressure equation p, in a point M, at a distance x, from the separation surface (fig. 3.6), with the relation.

$$p = 2A\sin\omega t\cos kx, \tag{3.92}$$

Corresponding one can determine the speed equation of the particle v, in the same point M, with the expression:

$$v = -\frac{2A}{\rho c}\cos\omega t\sin kx\,, \tag{3.93}$$

The pressure will be lowest in those points in which coskx = 0, which results:

$$x = (2n+1)\frac{\lambda}{4}\ (\mathrm{n} = 0, 1, 2, 3, \ldots), \tag{3.94}$$

The relation (3.92) shows that at distances equal to an odd number of wave lengths the acoustic pressure is null (pressure nodes), and the particle speed is maximum (speed antinodes). The pressure will be highest for any value of x, in which coskx=1, which results:

$$x = n\frac{\lambda}{2}\ (\mathrm{n} = 0, 1, 2, 3, \ldots), \tag{3.95}$$

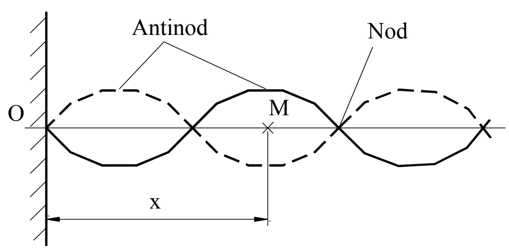


Fig. 3.6. Stationary waves.

The relation (3.93) shows that at a reflection surface distance equal to an even number of wave lengths quarters, the acoustic pressure is highest (pressure antinode), and particle speed is lowest (speed node).

As a consequence, from the interference of the incident wave with the reflected wave a stationary waves system takes place characterized by a series of pressure nodes and antinodes and respectively speed nodes and antinodes.

From an energetic point of view one observes that in a stationary wave system there must not be energy propagation, only a local energy exchange.

In the filtering and purification with ultrasounds technologies stationary waves are used because they lead to the coalescence phenomena which consists in grouping the fine particles (with dimensions smaller than 0.1 μm) in particles with smaller dimensions (even bigger than 10 μm) easy to separate by any filter. These big particles are formed in the pressure antinodes created by the stationary waves then being taken by the gases that circulate with a corresponding flowing speed and retained by the filtering element.

Diffraction and diffusion of ultra-acoustic waves

Ultra-acoustic waves have the property of going around obstacles they encounter on their way if the obstacles have dimensions of the same size or smaller than the wave length. Thus, the ***diffraction*** phenomenon occurs, the vibratory energy reaching points in the medium that are found behind the obstacle. As a consequence, diffraction is the phenomena of the propagation direction change of the ultra-acoustic wave as a consequence of its passing around an obstacle. In this case, the problem at hand is the distribution of the ultra-acoustic energy behind the obstacle (impurities).

Just as the interference phenomena, the diffraction phenomena can be explained through the wavelike nature of the ultrasonic waves.

According to Huygens' Principle, with any progressive wave, each point can be considered as a center of elementary waves, in any point of the vibratory field the vibration state resulting from the interference of these elementary waves.

Experimentally it has been noted that the manner in which the ultrasonic waves' field is deformed by introducing an obstacle largely depends on the ratio between the size of the obstacle and the wave length of the ultrasonic waves. In the case in which the wave length is neglectable in relation to the solid impurity's dimensions, the ultrasonic energy propagates rectilinear following the laws of reflection and refraction. In the case in which the wave length is high in relation to the impurity's dimension, the ultrasonic energy goes around the obstacle so that practically no shadow occurs starting from a certain distance behind the obstacle.

Aside from diffraction, the acoustic waves are distributed when encountering an obstacle, part of them interfering with the incident waves. In the case of some simple and regulated form types of obstacles (sphere, cylinder, disc) one can evaluate the diffraction and diffusion.

In the case of a plane circular-like obstacle which makes a θ angle with the beam's axis (fig. 3.7) part of the incident energy is diffused, and another part is propagated behind the obstacle. If one assumes that the beam's axis passes through the center of the obstacle, according to Huygens' Principle it becomes a new oscillation center, a new sphere-like wave being born. The speed of particle u, is under the form of:

$$u = U \sin \omega t \,, \tag{3.96}$$

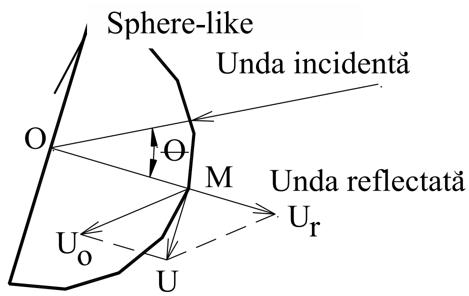


Fig. 3.7. Angular allocation of the particle's speeds at the diagonal incidence of an ultrasound beam on a circular obstacle

Unda incidenta – incident wave

Unde reflectata – reflected wave

and the corresponding acoustic pressure p, has the form:

$$p = \rho v U \sin \omega t \ , \tag{3.97}$$

In which: v is the oscillation velocity speed's module.

In a point M, on the circular obstacle found at distance r, from the center, the vibration speed of the particle u_r, is:

$$u_r = u_o \cos\theta \sin\left(\omega t - \frac{r}{v}\right) , \tag{3.98}$$

And the corresponding pressure p_r, is:

$$p_r = \frac{\rho \omega u \cos\theta}{\sqrt{\frac{1}{r_2} + \frac{\omega^2}{r^2}}} \sin\omega\left(t - \frac{r}{v}\right), \tag{3.99}$$

Since the incident wave and the reflected wave interfere in point M, a resulting pressure p_o, will exist under the form:

$$p_o = p + p_r , \tag{3.100}$$

Replacing (3.97) and (3.98) in (3.99) after processing the expression following results:

$$\frac{p_o}{p} = 1 + \frac{\omega \cos\theta \sin\left(t - \frac{r}{\vartheta}\right)}{v\sqrt{\frac{1}{r^2} + \frac{\omega^2}{\vartheta^2} \sin \omega t}} = 1 + \frac{2\pi \frac{r}{\lambda} \cos\theta \sin\omega\left(t - \frac{r}{v}\right)}{\sqrt{1 + \left(2\pi \frac{r}{\lambda}\right)^2 \sin \omega t}} \tag{3.101}$$

One can see that the ultra-acoustic pressure varies on the circumference of the radius circle equal to that of the obstacle according to the distance given by θ and the oscillation frequency. The value of the ratio p_o / p according to the ratio r/λ is presented in figure 3.8.

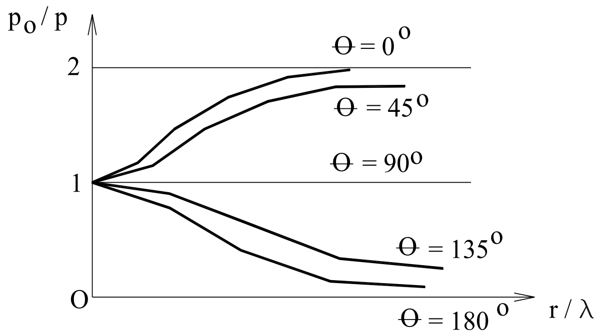


Fig. 3.8. The variation curves of the p_o / p ratio according to r / λ.

One can see that with $\theta = 0$ the pressure is highest and twice as high as the incident pressure; with $\theta = 90^0$ the total pressure is equal to the pressure of the incident beam, and with $\theta = 180^0$ behind the obstacle the pressure is zero when the incident beam falls normally on the obstacle. As a consequence, due to the interference phenomenon in front of the obstacle the pressure increases, while behind the obstacle the pressure decreases.

The variation of pressure p, in the shadow area of a circular obstacle found perpendicular on the beam's direction according to the distance from the obstacle1 is given in figure 3.10.

The diffraction and diffusion phenomena of the ultrasound waves play the most important role in the detection and characterization process of the solid impurities existing in the carrier gas, of their size and physical and mechanical properties of a medium through which they propagate.

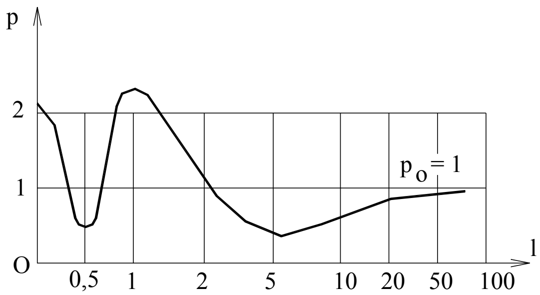


Fig. 3.10. Variation of the ultrasound pressure in the shadow area of a normal circular obstacle on the beam's direction

Attenuation of the ultra-acoustic energy

With the propagation of the acoustic waves through an elastic medium a gradual decrease of the oscillations' amplitude, of their intensity and thus, of the ultra-acoustic energy takes place. This attenuation is the result of dispersing the energy, caused by the energy's reflection and absorption phenomenon, and by a series of factors connected to the propagation medium. The losses caused by the reflection phenomenon can characterize the medium through which it propagates from the point of view of the structure's homogeneity, and the losses by absorption can give information regarding the medium's physical properties.

When the propagation of the ultra-sonic wave takes place in a medium in which energy losses occur, the movement equation becomes:

$$\frac{\partial^2 \xi}{\partial t^2} + \frac{R}{\rho_o}\frac{\partial \xi}{\partial t} = c^2 \frac{\partial^2 \xi}{\partial x^2} \ , \tag{3.102}$$

In which: R is the proportionality factor between the dissipation force and the speed of the particle in the considered medium.

The general solution of the equation (3.102) is under the form:

$$\xi = A \exp[j(\omega t + \gamma' x)] + B \exp[j(\omega t - \gamma' x)] \ , \tag{3.103}$$

Introducing (3.103) and its derivatives in (3.102) one obtains:

$$\gamma' = \pm \frac{\omega}{c}\sqrt{\left(1 - j\frac{R}{\rho_o \omega}\right)}, \tag{3.104}$$

If in the general solution of the equation (3.101) one notes with γ , the term $j\gamma'$ one obtains:

$$\gamma = j\gamma' = \pm \frac{R}{2\rho_o \omega} \pm j\frac{\omega}{c} = \alpha + j\beta \ , \tag{3.105}$$

In which γ is called waves' propagation constant.

As one can see, γ is a complex quantity whose real part α is called attenuation constant and it represents the decrease of the amplitude on distance unit, and the imaginary part β is called phase constant and it represents the change of the phase on distance unit. Taking into consideration (3.105), the solution of the differential equation of waves' propagation becomes:

$$\xi = A\exp(-\alpha x)\exp[j(\omega t - \beta x)] + B\exp(\alpha x)\exp[j(\omega t + \beta x)], \tag{3.106}$$

In which: the first term represents an attenuated plane wave which propagates in the direction of the positive x-s; the second term represents an attenuated plane wave which propagates in the direction of the negative x-s.

The acoustic impedance specific in the propagation of waves in a medium with energy dissipation Z_s is obtained by making the ratio between the ultra-acoustic pressure corresponding to the progressive plane wave and the particle's speed, meaning:

$$Z_s = \frac{p}{V} = \rho_o c\left(1 - j\frac{\alpha}{\beta}\right), \tag{3.107}$$

From (3.107) one can see that in the case of a medium in which the attenuation of the ultra-acoustic energy ($\alpha = 0$) does not occur, the acoustic impedance becomes $\rho_o c$, the impedance characteristic to the medium.

The attenuation thus has two main causes: dispersion and absorption. Dispersion takes place on the discreet structure of the medium, being influenced by the diverse non-homogeneities (solid and liquid impurities of different shapes and sizes). Absorption is owed to several causes, the most significant being: internal friction (viscosity), thermal conductibility, thermal radiation, the relaxation phenomenon and others, phenomena characteristic to the natural gases' transmission through pipes.

Having knowledge of these phenomena is very important especially for applying ultrasounds in the purification as well as the very fine filtering.

In the case in which attenuation is uniform in the ultrasound field, the variation of the ultrasound pressure p is proportional with the travelled distance d, meaning:

$$p = p_o \exp[-(\alpha_a + \alpha_d)]d \ , \tag{3.108}$$

and the variation of the intensity is proportional with p^2, so:

$$I = I_o \exp[-2(\alpha_a + \alpha_d)]d \ , \tag{3.109}$$

In which: p_o; I_o is the pressure and the initial intensity; α_a - an attenuation coefficient due to the absorption phenomenon; α_d - an attenuation coefficient due to the diffusion phenomenon.

In the case of gases, the absorption coefficient α_a can be considered as a sum of terms owed to the previously mentioned causes, so:

$$\alpha_a = \alpha_v + \alpha_{ct} + \alpha_r + \alpha_T \ , \tag{3.110}$$

In which: α_v is the attenuation through absorption coefficient owed to viscosity; α_{ct} - the attenuation through absorption coefficient owed to thermal conductibility; α_r - the attenuation through absorption coefficient owed to radiation; α_T - the attenuation through absorption coefficient owed to intermolecular energy exchange.

According to Stokes and Rayleigh, the attenuation coefficient α_v can be determined with the relation:

$$\alpha_v = \frac{8\pi^2 f^2}{3\rho_o c^3}\eta \ , \tag{3.111}$$

In which: η is the gas viscosity, which according to the kinetic theory of gases is:

$$\eta = \frac{lNmv_m}{3} \ , \tag{3.112}$$

where: N is the number of particles on volume unit; m – particle's mass; v_m – average speed of particles; l – average travelled free.

Introducing (3.109) in (3.108) one obtains:

$$\alpha_v = \frac{16\pi^2 Nmv_m}{15\rho c^2} f^2 \cdot L \ , \tag{3.113}$$

for kl < 1 and :

$$\alpha_v = \frac{\pi^2 Nmv_m}{3\rho_0 c^2} f \ , \tag{3.114}$$

for kl > 1.

One can observe that in both cases the attenuation constant varies with the frequency.

During propagation of the ultrasonic waves in the medium compressions and rarefactions occur and the temperature in the compression area becomes higher than that in the rarefaction area. Because of this a leakage of the heat takes place followed by the production of an entropy and an energy dissipation, from where an attenuation of the wave's amplitude results. Due to the thermal conductibility, the attenuation constant α_{ct} has the form:

$$\alpha_{ct} = \frac{2\pi^2}{c}\left(\frac{\chi - 1}{\chi}\right)\frac{c_T}{c_v \rho_o} , \tag{3.115}$$

In which: χ is the ratio of heats specific for constant pressure and constant volume; c_v - heat specific at constant volume; c_T – thermal conductibility coefficient.

Together with heating the gas layers which are compressed a radiation of this heat also takes place, fact which leads to a dissipation of the ultra-acoustic energy. The attenuation coefficient owed to radiation α_T, according to Stokes, can be calculated with the formula:

$$\alpha_T = \left(\frac{\chi - 1}{\chi}\right)\frac{q}{2c} , \tag{3.116}$$

In which: q is the coefficient characteristic from the law of gas mass cooling, which has the form:

$$\theta_t = \theta_o e^{-qt} , \tag{3.117}$$

where: θ_t is the excess of temperature at the time t; θ_0 – excess of temperature at time zero.

The attenuation constant due to the losses through diffusion α_d can be determined with the relation:

$$\alpha_d = \frac{8\pi^4 d^3 f^4}{9c^2}\delta , \tag{3.118}$$

In which: d is the average diameter of solid impurities; δ - the diffusion factor which depends on the material's anisotropy (δ = 6,7.10^{-3} – for steel; δ = 3.10^{-4} – for aluminum; δ = 7,4.10^{-3} – for copper).

With the propagation of ultrasonic waves in solid mediums other phenomena which lead to attenuation also appear, such as: the interaction between the ultrasound waves and electrons in metals, the interaction between the ultrasonic waves and the thermal waves and others, which are of smaller value and do not affect the relation substantially (3.105)

Along the volume absorption, in the field it is also necessary to know the absorption of the ultrasonic waves at the separation surface of two mediums, case which corresponds in most active applications of ultrasonic waves. Here, the notion of acoustic dissipation appears noted with δ_a, defined as the ratio between the dissipated energy flow Φ_d, from the separation surface and the incident energy flow Φ_I, meaning:

$$\delta_a = \frac{\Phi_d}{\Phi_i}, \tag{3.119}$$

Because in practice it is interesting to know what ultra-acoustic energy was sent in the second medium, the ultra-acoustic absorption coefficient is defined (noted α_a) as being the ratio between flow retained by the separation surface and the incident energy flow:

$$\alpha_a = \frac{\Phi_i - \Phi_r}{\Phi_i}, \tag{3.120}$$

In which: Φ_r is the ultra-acoustic energy flow reflected in the first medium.

The ultra-acoustic absorption coefficient α_a is tied to the specific acoustic impedance Zs, of the separation plan by the relation:

$$\alpha_a = 1 - \left| \frac{Z_s - \rho_o c}{Z_s + \rho_o c} \right|^2, \tag{3.121}$$

Replacing $Z_s / \rho_o c = r + jx$ in the relation (3.118) one obtains:

$$\alpha_a = \frac{4r}{(r+1)^2 + x^2}, \tag{3.122}$$

Out of which one can see that α is an r function (resistance to the normalized entrance to Z_s) and of x (normalized entrance reactance to Z_s).

In the complex plan, the equation (3.119) becomes:

$$r^2 + x^2 + 2\left(1 - \frac{2}{\alpha_o}\right)r + 1 = 0, \tag{3.123}$$

and it represents the equation of a family of circles having the centers on the abscissa axis and the radiuses equal to $2(1-\alpha_a)^{1/2}/\alpha_a$. Determining the ultra-acoustic absorption coefficient of a material can be calculated using charts such as the one presented in figure 3.11.

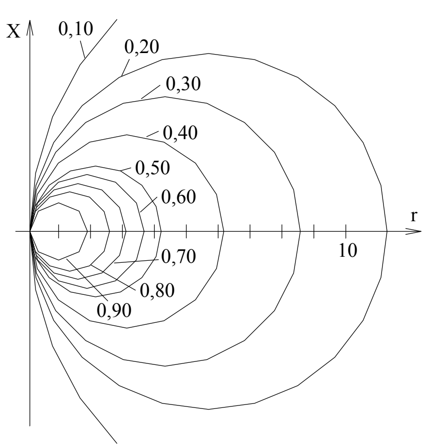


Fig. 3.11.
Chart for determining the ultra-acoustic absorption coefficient of a material

The absorption coefficient being a resistance function and the specific ultra-acoustic reactance of that particular material, the function peaks are defined by the relation:

$$\frac{\partial \alpha_a}{\partial r} = \frac{4\left[(r+1)^2 + x^2\right] - 4r\left[2(r+1)\right]}{\left[(r+1)^2 - x^2\right]^2} = 0 \ , \tag{3.124}$$

and

$$\frac{\partial \alpha_a}{\partial x} = -\frac{8rx}{\left[(r+1)^2 - x^2\right]^2} = 0 \ , \tag{3.125}$$

From (3.125) one concludes that x = 0, which introduced in (3.124) leads to r = 1, which proves that the absorption of an ultra-acoustic system is ultimate when the reactance is null, thus to resonance.

Experimentally it has been noted that the values of the ultra-acoustic absorption coefficient differs from one material to another and even with the same material they depend on its mechanical and geometrical characteristics, on frequency and on the formation manner of the separation plan by the impurities existing in the carrier gas in which the ultrasonic field was created.

CHAPTER IV
THEORETICAL AND EXPERIMENTAL CONTRIBUTIONS TO THE CALCULATION AND DESIGN OF ULTRA-ACOUSTIC SYSTEMS USED IN THE CONSTRUCTION OF FILTERS AND SEPARATORS FOR NATURAL GASES

Simple piezoceramic transducers and complex mechanical non-polarized piezoceramic transducers

The role of mechanical polarization is to strain the ceramics so that during operation the oscillations of the elastic tension would be calculated not around the null value, but according to value assigned by mechanically polarizing the transducer (fig. 4.12). Agreeing to associate the positive sign with mechanical expansion and the negative with compression, it follows that the mechanical polarization of the transducer is negative. Due to the polarization screw that induces a mechanical tension of compression T_0 , the transducer slightly changes its properties because the screw adds to it an additional mass and elasticity. Also, the piezoelectric constants of the ceramics are modified. The amplification factor G of the transducer is also modified, becoming G' and expressed as follows:

$$G' = 1 - 2/\sqrt{N} \quad , \tag{4.79}$$

where:

$$N = K_{ef}^2 Q_m Q_e \quad , \tag{4.80}$$

In order for the transducer to show optimum properties, the maximum domain of variation for the effective coupling coefficient K_{ef} is:

$$K_{33} \leq K_{ef} \leq \frac{2\sqrt{2}}{\pi} K_{33} \quad , \tag{4.81}$$

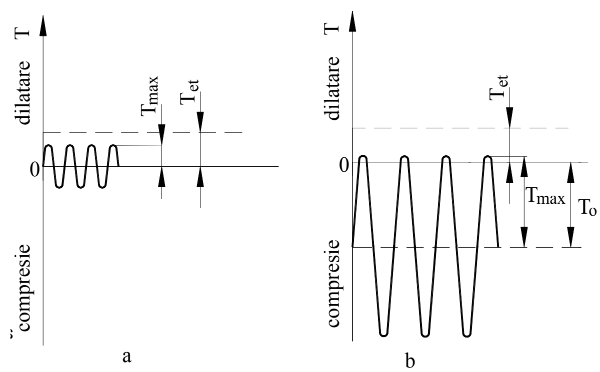


Fig.4.12. The influence of mechanical polarization T_0 over the maximum value of the mechanical tension T_{max}, which can be applied to the complex transducer during operation:

a – without mechanical polarization ($T_0 = 0$); T_{max} is limited by the resistance to the maximum mechanical expansion of the piezoelectric ceramics T_f; b – with mechanical polarization; T_{max}, is limited by the fatigue resistance of the mechanical polarization screw.

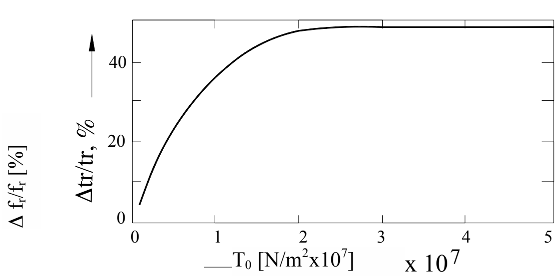


Fig. 4.13. The influence of the mechanical polarization tension T_0 over the resonance frequency of the transmitter

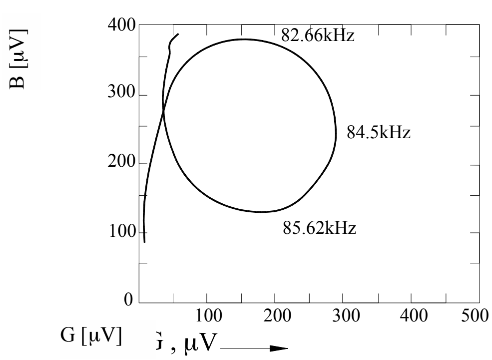


Fig. 4.14 Admission diagram of a piezoceramic complex transmitter G = f(B).

The uncharged mechanical quality factor Q_m is given by the equation:

$$Q_m = \frac{\omega_0}{R_m}\frac{m_2}{m_1}(m_1 + m_2) \quad , \tag{4.82}$$

where: R_m is the mechanical resistance (due to internal losses, friction, etc.), and m_1 and m_2 represent the masses of the reflector element and the radiant element respectively.

The piezoceramic element does not contribute significantly to the equivalent mass $M_{ech.}$ $(M_{ech} = m_1 + m_2 / m_1 m_2)$ of the vibrant system. The electrical quality factor Q_e is typical for piezoelectric ceramics and it depends on the action level of the transducer. Its variation domain is of 400…200 for a low level and it decreases to 50 for a high level.

Due to the mechanical polarization, the acoustic power per unit volume P_{av} , emitted by the complex mechanically polarized transducer increases with the square value of the mechanical tension of polarization T_0 , being expressed as follows:

$$P_{av} = \frac{d_{33}^2}{K_{33}^2}(T + T_0)^2 Q_m \omega_0 \eta \quad , \tag{4.83}$$

where: T is the operating mechanical tension.

Figure 4.13 represents the influence of the polarization tension over the resonance frequency of the mechanical polarized transmitter. For lower values of T_0 , the relation $\Delta f_r / f_r$ is very high (f_r is the resonance frequency of the non-polarized transducer) until it reaches a certain value over which the resonance frequency remains constant.

The material of the polarization screw must have similar characteristics to those that make up the reflector element. The screw must ensure the mechanical polarization tension and must present high compliance. Thus, by applying the mechanical polarization tension, great intensities and acoustic powers may be obtained from the same acoustic structure. On the other hand, the tuning to the same frequency of the transducers making up an assembly (for example, an acoustic siren) may be realized, in the case of a fine tuning, not by machining the mechanical parts, which is an irreversible method, but through the process of differential mechanical polarization of the transducers.

Experimental studies conducted on polarized transducers in which the direction of mechanical polarization coincides with the direction of electrical polarization have shown the changes in properties when passing from a state of null mechanical polarization $(T_0 = 0)$, called the minus state, to a state of non-null tension $\frac{T_0}{(0)}$ called the plus state, as well as in the reverse scenario.

The behavior of the complex transducer exposed to mechanical polarization has been studied in the following hypotheses: plane elastic waves; infinitely rigid metallic masses; the mechanical polarization direction the same with the electrical polarization direction and with the axis of symmetry of the transducers; the domain of the frequencies of experimentation set around the resonance frequency; the negligible ceramics mass in relation to the metallic masses.

Under these conditions the equivalent impedance of transmitter Z_t is given by the equation:

$$Z_t = R_m + j\left(L_m\omega + 1/\omega C_m\right), \tag{4.84}$$

The Z_t impedance is represented by a series resonant circuit R_m, L_m, C_m, parallel with the static capacity C_0 ; the R$_2$ component is the sum of two terms $R_1 + R_2$, where R_1 is the mechanical loss resistance, and R_s is the load resistance. Parallel with C_1 there is always an electrical loss resistance R_d in the system.

Figure 4.14 represents the diagram $G = f(B)$ of a transmitter, G and B being the conductance, respectively the susceptance, of the transmitter. If a change is introduced in the axial polarization state, different effects emerge and, in particular, the parameters that characterize the equivalent circuit of the transmitter change. These variations have been measured, as well as their variation in time. From the moment of inducing mechanical polarization and with the help of a previously established program, the diagrams of the corresponding admittance have been graphically recorded with the help of an automatic device for measuring a $x-y$ recorder, determining:

- the resonance frequency f_r (at the point of maximum conductance G_m ;
- the frequencies which limit the band width (to 3 dB), f_1, f_2 (conductance $G_m/2$);
- the mechanical resonance frequency f_0 (zero susceptance) when the losses are low, which results from:

$$\omega_0^2 = \frac{C_m + C_1}{L_m C_m C_1}, \tag{4.85}$$

With the help of these parameters and the graphical representation of the electrical admittance, the following parameters have been calculated:

- band width $\Delta f = f_2 - f_1$, (4.86)
- the mechanical quality factor $Q_m = f_r/\Delta f$,
- the capacity $C_1 = (C_a + C_b)/2$, (4.87)

Capacities C_a and C_b correspond to the frequencies f_1 and f_2 respectively:

- dynamic capacity C_m , represented as:

$$C_m = (C_a - C_b)/Q , \tag{4.88}$$

- coupling coefficient k_t , represented as:

$$k_t = \pi/2\sqrt{C_m/\left[2(C_1 + C_m)\right]} \quad , \tag{4.89}$$

Figure 4.15 presents the reverse diameter of the circle of admittances, thus the values of the R_m resistance. It may be observed that the resistance R_m , by passing from the "-" state to the "+" state, increases considerably and after 10^4 minutes reaches 210 W. After the change in the axial polarization state (''+'' becomes "-") and at the end of one week, the value of R_m decreases to 200 W, an approximate value obtained in the reverse process. The change of the resonance frequency of complex transducers was of approximately ±4% compared to the initial value. Figure 4.15 represents the variation of the Q_m· factor. Its form is similar to that of R_m , from figure 4.14. The Q_m· factor decreases when passing from "- " to "+" due to the effect of the mechanical polarization acoustic charge, while during the reverse process of passing from "+" to "-", Q_m· presents a very rapid increase (fig 4.16).

The k_t variation between the two processes of tensioning and de-tensioning during a period of two months is given by the equation:

$$\frac{k_{t^2}^{'}}{1 + k_t^{'}} = \frac{a}{a+1}\,\frac{k_t^2}{1 + k_t} \quad , \tag{4.90}$$

where: $k_t^{'}$ and k_t represent the coupling coefficients with polarization and without mechanical polarization and in which a is a constant related to the compliance of the ceramic element and of the mechanical polarization screw.

The state of mechanical polarization considerably influences the transducer's electro-acoustic behavior, which is in its turn dependent on the time elapsed from the changing of the polarization state, as well as on the mechanical polarization value.

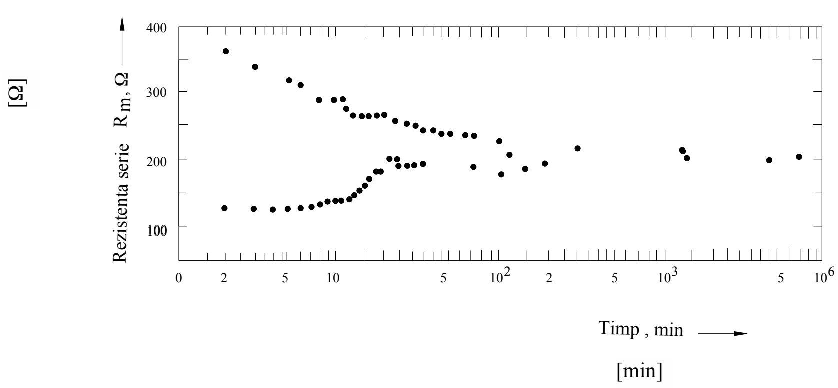
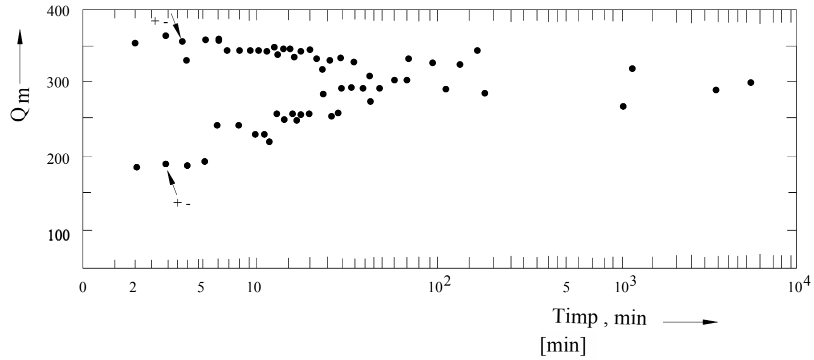


Fig.4.15. The variation of serial resistance R_m, during the time elapsed from the change of the axial mechanical polarization state.



Timp-time

Fig. 4.16. The variation of the mechanical quality factor Q_m, during the time elapsed from the change of the axial mechanical polarization.

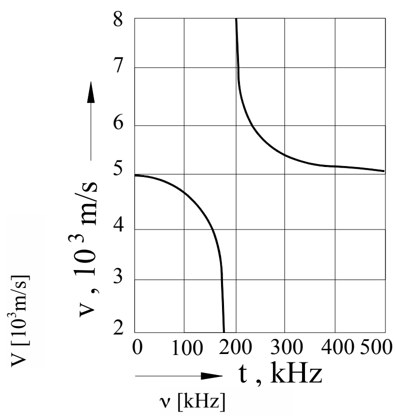


Fig. 4.17. The geometrical dispersion of longitudinal waves in a nickel rod of 100 mm length, an exterior diameter of 8,6 mm and an interior diameter of 8,3 mm.

Same frequency tuning of an ensemble of transducers in a network is practically achievable with the help of the adequate mechanical polarization (within the limit of small deviations). The correction of high variations is not recommended because it involves high variations of other parameters.

In designing piezoceramic transducers with the purpose of obtaining a certain frequency resonance, it is observed that the use of the results of the simplified mathematical model leads to large frequency deviations, which may be explained by using the longitudinal wave approximation without considering the existence of the transverse coupling in the case of simple piezoceramic elements, as well as in that of complex transducers, in the case of active elements, as well as in that of passive ones. For the vibrations wave length that is much larger than the dimensions of the transverse section, in the case of the propagation of vibrations through a rod, the speed of the elastic waves in the rod v_{long} is given by the well-known equation:

$$v_{long} = \sqrt{Y/\rho} \quad , \qquad (4.91)$$

When the wave length is much smaller than the diameter of the rod, it acts as an unlimited solid medium and the speed of elastic waves v_{ν} will be:

$$v_v = \frac{\sqrt{E(1-\sigma)}}{\sqrt{\rho(1+\sigma)(1-2\sigma)}} \quad , \tag{4.92}$$

where: σ is the Poisson coefficient, and v_v is also called the speed of volumetric waves.

Experience has shown that in the case of wave lengths comparable to the dimensions of the cross section of the rod there is a dispersion field, in which the speed of longitudinal waves depends on the wave length. In figure 4.17 the propagation speed of longitudinal waves in a nickel rod is presented. It is observed that in the bandwith 150 - 250 kHz, when the wave length is comparable with the diameter of the rod, the dispersion of vibrations occurs (called geometrical dispersion because it is not determined by the internal structure of the material, but by geometrical factors).

For the propagation of longitudinal waves in an infinitely long rod, the frequency equation is:

$$2\mu \frac{\partial^2 J_0(ha)}{\partial a^2} = p^2 \frac{\rho \wedge ¿}{+2\mu} J_0(ha)$$

¿

¿

$$2\mu k \frac{\partial J_1(\gamma a)}{\partial a} = 0 \, , \tag{4.93}$$

¿¿

$$2k \frac{\partial J_0(ha)}{\partial a} \qquad 2k^2 \frac{\omega^2 \rho}{\mu} J_0(\gamma a)$$

which, through certain replacements and calculations, is reduced to the equation:

$$(x-1)^2 \phi(ha) - (\beta x - 1)[x - \phi(\gamma a)] = 0 \quad , \tag{4.94}$$

In equations (4.93) and (4.94) the factors signify the following: $, \mu$ are the Lame constants; $\omega -$ angular frequency; $\beta = (1-2\sigma)/(1-\sigma)$; σ - Poisson coefficient; $x = (v/v_{long})^2 (1+\sigma)$; λ - wave length; a - rod radius; v_{long} - ultrasound speed inside the rod; v - wave speed;

$$h = k\sqrt{\beta x - 1}; \quad \gamma = k\sqrt{2x - 1}; \quad k = 2\pi/\lambda; \quad \phi(y) = yJ_0(y)/J_1(y) \quad , \tag{4.95}$$

The equation (4.94) has the following form:

$$F(x, \beta, ka) = 0 \quad , \tag{4.96}$$

The properties of the function $\phi(y)$ are:

$$\phi(y) = \phi(-y), \quad \phi(0) = 2, \quad \lim_{n-\infty}(iy) = y \quad , \tag{4.97}$$

The zero points and the poles of function ϕ correspond with those of functions J_0, J_1 respectively.

Supposing that (4.94) may be explicitly solved for x, x may be expressed under the following form:

$$x = x(\beta, ka)\ , \tag{4.98}$$

which represents a family of surfaces. Among these surfaces, the most important is the first surface that corresponds to the ordinary propagation of longitudinal waves. The dependent variable is v/v_{long}, and the independent variables are σ and $2a/\lambda$. In figure 4.18 the v/v_{long} curves are represented according to the $2a/\lambda$ ratio, for various values of σ. The analysis of the experimental data has demonstrated the existence of several types of vibrations in a rod simultaneous with or excluding the longitudinal mode. This suggests the expansion of the theoretical treatment to superior vibration modes, to obtain the dispersion curves for the associated elastic waves. Such calculations are extremely common for the study of stability and interaction of different vibration modes.

Figure 4.19 presents the dispersion curves of the longitudinal and bending modes for different values of the Poisson coefficient. The bending vibration modes also present a similar dispersion.

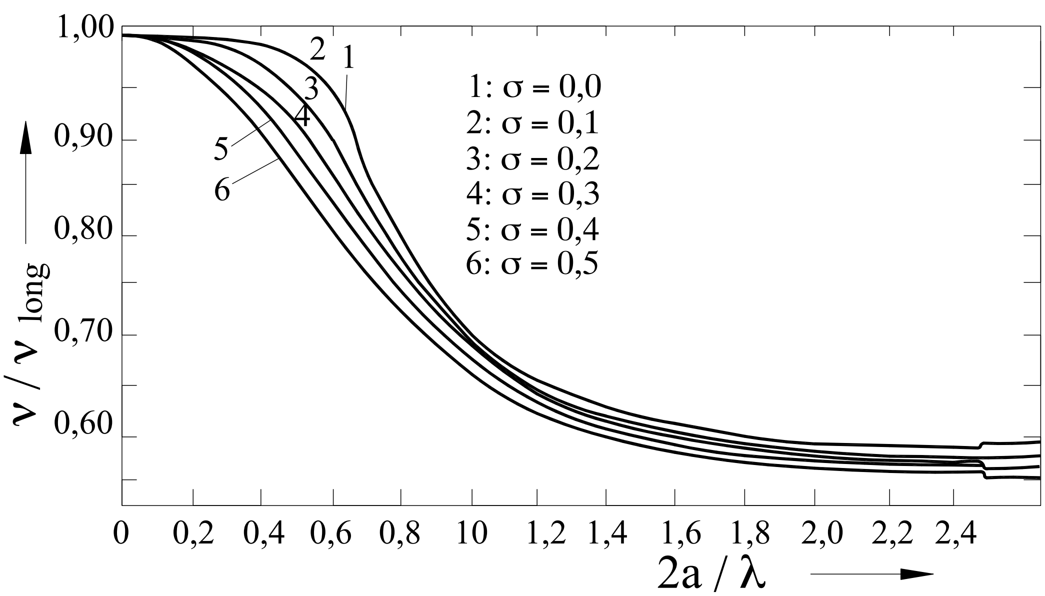


Fig. 4.18. The dependency of the v/v$_{long}$ coefficient, of 2a/l size, for different values of the Poisson s ratio.

In solid mediums, four fundamental types of waves may be propagated, each of them having different speeds. The highest speed is that of volumetric waves v_v, followed by the speed of longitudinal waves inside a thin rod at low frequencies v_{long} (wave length much larger than the diameter). The shear waves are propagated at an even lower speed v_s. The lowest speeds are associated with the bending waves. Longitudinal waves, as well as bending ones in rods and plates are dispersive. When the frequency increases the values of longitudinal and bending speeds, it asymptotically approaches the value of the speed of shear waves. In this transit area there is a coupling between the various types of movement: shearing movement, compression movement and the transverse movements. The relations tension – deformation in this area are very hard to express, especially in the case of anisotropic bodies. Nevertheless, in general it is possible to express the effective elasticity for any type of wave.

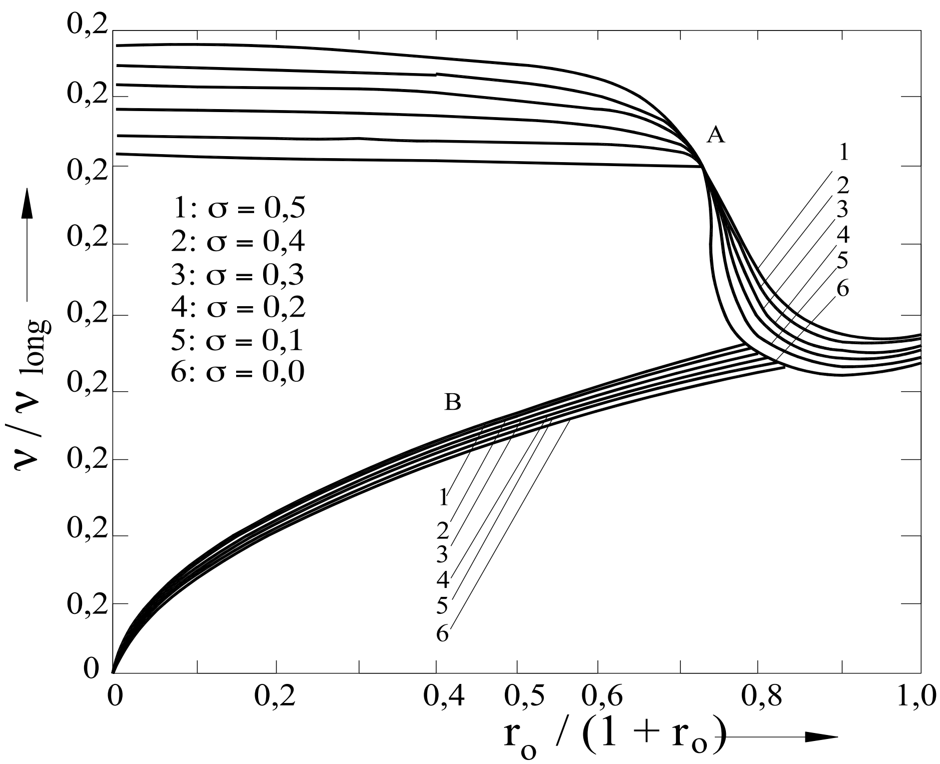


Fig. 4.19. The theoretical dispersion curves of longitudinal waves A and shear waves B

Thus, the fundamental modes of coupled tridimensional vibrations, of different piezoceramic ultrasonic transducers including rods with rectangular sections, rectangular plates, full and empty cylinder, of complex piezoceramic transducer, may be analyzed using the method of apparent elasticity (other methods employed in the analysis are: the finite differences method, the finite elements method and the Ritz variation method).

Using this method simple analytic formulas are obtained for resonance frequencies, by calculating the frequency constants of the vibrations according to the geometrical dimensions of vibrators. Thus, the form of the frequency dispersion has been obtained for the phase velocity of longitudinal waves in finite cylinders that is presented in comparison with that for infinite cylinders.

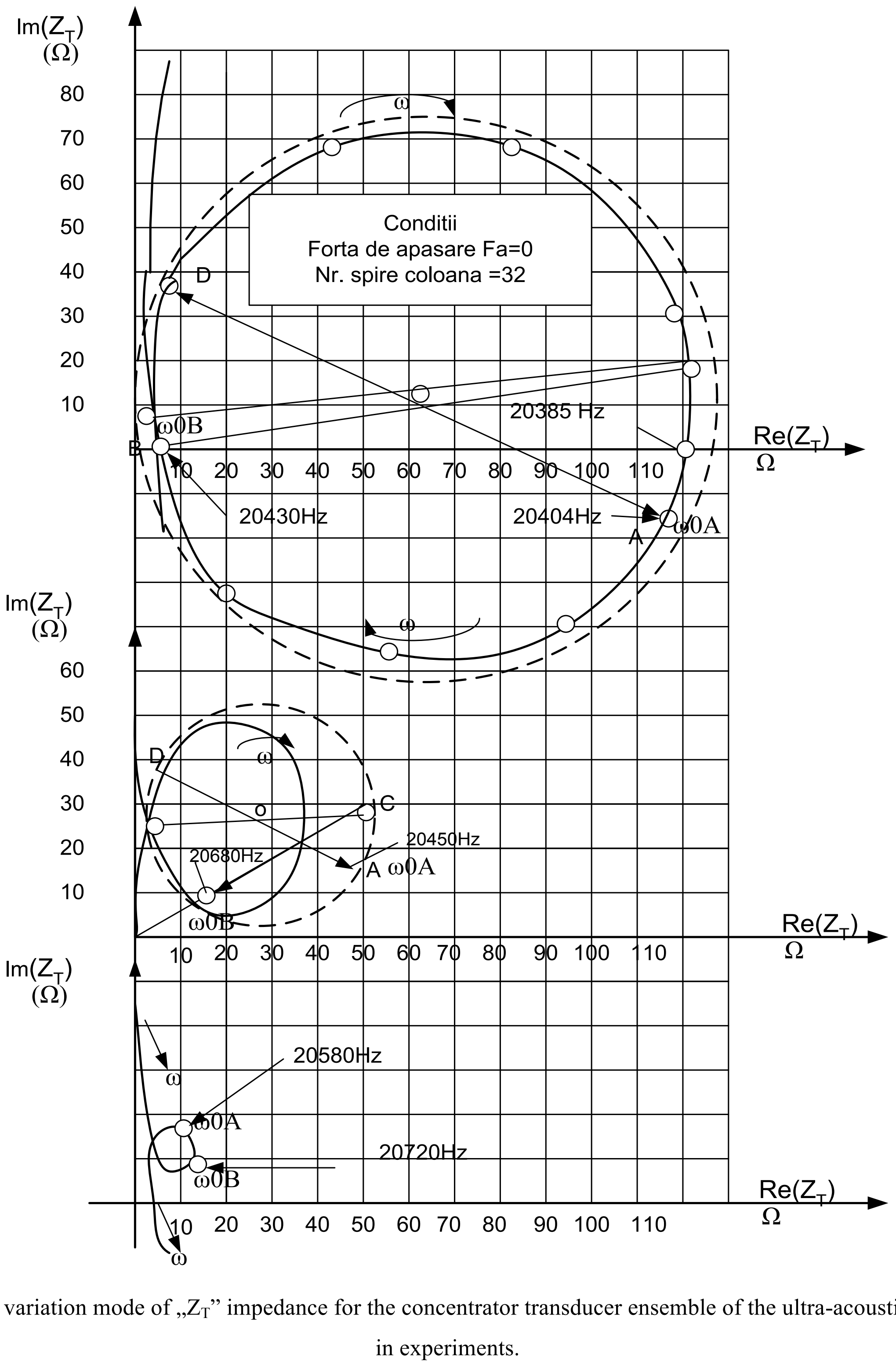


Fig. 4.20. The variation mode of „Z_T" impedance for the concentrator transducer ensemble of the ultra-acoustic system used in experiments.

Conditii - Conditions

Forta de apasare - Down force Fa = 0

Nr. spirale coloane - No. column coils = 32

Thus, for a rectangular rod with L, W, T dimensions, with L>>T and L>>W, the elasticity equations are expressed under the following form:

$$z$$

$$S_y = s_{11}^E T_x + s_{12}^E T_y + s_{13}^E T align l \quad S_z = s_{21}^E T_x + s_{22}^E T_y + s_{23} T_z \quad , \tag{4.99}$$

$$0 = S_{11}^E T_x + s_{12}^E T_y + s_{13}^E T_z \quad ,$$

Using the notations:

$$\nu_{12} = -\frac{s_{12}^E}{s_{11}^E}; \quad \nu_{13} = -\frac{s_{13}^E}{s_{11}^E}; \quad \nu_{32} = -\frac{s_{13}^E}{s_{33}^E} \quad ; \quad n = -\frac{T_z}{T_y} \quad , \tag{4.100}$$

the (4.99) equations are expressed under the following form:

$$S_y = s_{11}^E \left[\left(1 - \nu_{12}^2\right) + \nu_{13} \left(1 + \nu_{12}\right) n \right] T_y$$

,

$$S_z = s_{33}^E \left[\left(1 - \nu_{31} \nu_{13}\right) + \frac{\nu_{31} \left(1 + \nu_{12}\right)}{n} \right] T_z \tag{4.101}$$

and the elasticity modules Y_y and Y_z are:

$$Y_y = \left\{ s_{11}^E \left[\left(1 - \nu_{12}^2\right) \nu_{13} \left(1 + \nu_{12}\right) n \right] \right\}^{-1} \quad , \tag{4.102}$$

$$Y_z = \left\{ s_{33}^E \left[\left(1 - \nu_{13} \nu_{31}\right) + \frac{\nu_{31} \left(1 + \nu_{12}\right)}{n} \right] \right\}^{-1} \quad , \tag{4.103}$$

The vibrations resonance conditions for the secondary dimensions are offered by the following expressions:

$$k_y W = \pi; \quad k_z T = \pi \quad , \tag{4.104}$$

thus:

$$k_{oy} W = \pi \left[\left(1 - \nu_{12}^2\right) + \nu_{13} \left(1 + \nu_{12}\right) n \right]^{-\frac{1}{2}} \quad , \tag{4.105}$$

$$k_{oz} T = \pi \left[\left(1 - \nu_{13} \nu_{31}\right) + \frac{\nu_{31} \left(1 + \nu_{12}\right)}{n} \right]^{-\frac{1}{2}} \quad , \tag{4.106}$$

where:

$$k_y = \frac{\omega_0}{v_y}; \quad k_z = \frac{\omega_0}{v_z}; \quad v_y = \sqrt{\frac{Y_y}{\rho}}; \quad v_t = \sqrt{\frac{Y_z}{\rho}} \quad , \tag{4.107}$$

$$k_{oy} = \omega_0 \sqrt{\rho s_{11}^E} \quad k_{oz} = \omega_0 \sqrt{\rho s_{33}^E}; \quad \omega_0 = 2\pi f_0 \quad , \tag{4.108}$$

and f_0 is the resonance frequency.

From the (4.105) and (4.106) relations, the following expression is obtained:

$$\frac{W}{T}=\sqrt{\frac{s_{33}^{E}}{s_{11}^{E}}\cdot\sqrt{\frac{(1-\nu_{13}\nu_{31})+\nu_{31}\left(1+\frac{\nu_{12}}{n}\right)}{(1-\nu_{12})^{2}+\nu_{13}(1+\nu_{12})n}}} \quad , \tag{4.109}$$

In the case of a rectangular plate, when the tension is $T_z=0$, we get:

$$Y_x=\left[s_{11}^{E}\left(1+\frac{\nu_{12}}{n}\right)\right]^{-1};\quad Y_y=\left[s_{11}^{E}(1+\nu_{12}n)\right]^{-1} ,$$

(4.110)

and

$$k_{0x}L=\pi\left(1+\frac{\nu_{12}}{n}\right)^{-\frac{1}{2}};\quad k_{0y}W=\pi(1+\nu_{12}n)^{-\frac{1}{2}} \quad , \tag{4.111}$$

where:

$$k_x=\frac{\omega_0}{v_x};\quad k_y=\frac{\omega_0}{v_y};\quad v_x=\sqrt{\frac{Y_x}{\rho}};\quad v_y=\sqrt{\frac{Y_y}{\rho}} \quad , \tag{4.112}$$

$$k_{0x}=k_{0y}=\omega_0\sqrt{\rho s_{11}^{E}} \quad , \tag{4.113}$$

From the relations at (4.111) the following expression is obtained:

$$\frac{W}{L}=\sqrt{\frac{1+\frac{\nu_{12}}{n}}{1+\nu_{12}n}} \quad , \tag{4.114}$$

In the case of a finite full cylinder, of a dimension of 2*l* (*l* expressing its length) and 2*a* (*a* being its diameter) – the most common case in ultrasound filtering, the elasticity equations in cylindrical coordinates take the following form:

$$\begin{aligned} S_z&=s_{13}^{E}T_r+s_{13}^{E}T_\theta+s_{33}^{E}T_z\\ S_r&=s_{11}^{E}T_r+s_{12}^{E}T_\theta+s_{13}^{E}T_z\\ S_\theta&=s_{12}^{E}T_r+s_{11}^{E}T_\theta+s_{13}^{E}T_z \end{aligned} \quad , \tag{4.115}$$

Under the cylindrical symmetry condition $T_r=T_\theta$ and with the notation:

$$\frac{T_z}{T_r}=\frac{T_z}{T_\theta}=-n \quad , \tag{4.116}$$

the elasticity modules may be expressed under the following form:

$$Y_z = \left[s_{33}^E\left(1+\frac{2\nu_{31}}{n}\right)\right]^{-1};\quad Y_r = s_{33}^E\left[\left(1-\nu_{12}^2\right)+\nu_{13}\left(1+\nu_{12}n\right)\right]^{-1}, \tag{4.117}$$

By placing the longitudinal resonance condition, we get:

$$k_{0z}\cdot l = \frac{\pi}{2}\left(1+\frac{2\nu_{31}}{n}\right)^{-\frac{1}{2}}, \tag{4.118}$$

and the radial resonance condition becomes:

$$k_r a J_0\left(k_r a\right) = \left(1-\nu_{12}\right)J_1\left(k_r a\right), \tag{4.119}$$

where: $k_{0z} = \omega_0\sqrt{\rho s_{33}^E}$

If the following notation is made:

$$k_r\cdot a = R_1, \tag{4.120}$$

the (4.119) relation becomes:

$$k_{\theta r}\cdot a = R_1\left(1-\nu_{12}^2\right)+n\nu_{13}\left(1+\nu_{12}\right)^{-\frac{1}{2}}, \tag{4.121}$$

In these relations, the following has also been noted:

$$k_r = \frac{\omega_0}{\sqrt{Y_r/\rho}};\quad k_{\theta r} = \omega_0\sqrt{\rho s_{11}^E}, \tag{4.122}$$

Making the ratio between relations (4.118) and (4.121) the following expression is obtained:

$$\frac{l}{a} = \frac{\pi}{2R_1}\cdot\sqrt{\frac{s_{11}^E}{s_{13}^E}\cdot\frac{\left(1-\nu_{12}^2\right)+n\nu_{13}\left(1+\nu_{12}\right)}{1+2\nu_{13}/n}}, \tag{4.123}$$

an extremely important ratio in the dimensioning of any final active element of an ultra-acoustic system used in the construction of ultrasonic filters.

In the case of an empty cylinder of a 2*l* length, with the exterior diameter *a* and the interior diameter *b*, the elasticity modules are:

$$Y_z\left[s_{33}^E\left(1+2\frac{\nu_{31}}{n}\right)\right]^{-1};\quad Y_r = \left\{s_{11}^E\left[\left(1-\nu_{12}^2\right)+\nu_{13}\left(1+\nu_{12}\right)n\right]\right\}^{-1}, \tag{4.124}$$

The longitudinal resonance is obtained for the condition:

$$k_{\theta z}\cdot l = \frac{\pi}{2}\left(1+2\frac{\nu_{31}}{n}\right)^{-\frac{1}{2}}, \tag{4.125}$$

where:

$$k_{\theta z}=\omega_0\sqrt{\rho s_{33}^{E}}\quad , \tag{4.126}$$

The radial resonance condition is expressed under the following form:

$$\frac{k_r aN_0(k_r a)-(1-\nu_{12})N_1(k_r a)}{k_r aJ_0(k_r a)-(1-\nu_{12})J_1(k_r a)}=\frac{k_r bN_0(k_r b)-(1-\nu_{12})N_1(k_r b)}{k_r bJ_0(k_r b)-(1-\nu_{12})J_1(k_r b)}\quad , \tag{4.127}$$

where: J_n are the Bessel functions; N_n – the Newmann functions (n=1, 2,..)

With the notations:

$$k_r a=R_1;\quad k_r=\frac{\omega_0}{v};\quad \omega_0=2\pi f_0\quad , \tag{4.128}$$

From equation (4.127) we get the value of velocity v, given under the expression:

$$v=\left\{\rho s_{11}^{E}\left[(1-\nu_{12}^2)+\nu_{13}(1+\nu_{12})n\right]\right\}^{-\frac{1}{2}}\quad , \tag{4.129}$$

and from relation (4.125) we get the following ratio:

$$\frac{2l}{a}=\frac{\pi}{R_1}\cdot\sqrt{\frac{s_{11}^{E}}{s_{33}^{E}}\cdot\frac{(1-\nu_{12}^2)+\nu_{13}(1+\nu_{12})n}{1+2\nu_{31}/n}}\quad , \tag{4.130}$$

In the case of cylindrical symmetry, characterized by the equalities:

$$\nu_{12}=\nu_{13}=\nu_{31}=\nu;\quad s_{11}^{E}=s_{33}^{E}=\frac{1}{Y}\quad , \tag{4.131}$$

the apparent elasticity modules become:

$$Y_z=\frac{Y}{\sqrt{1+2\nu/n}};\quad Y_r=\frac{Y}{(1-\nu^2)+\nu(1+\nu)n}\quad , \tag{4.132}$$

and the longitudinal resonance condition is expressed under the following form:

$$k_{\theta z}\cdot l=\frac{\pi}{2}\left(1+\frac{2\nu}{n}\right)^{-\frac{1}{2}}\quad , \tag{4.133}$$

where:

$$k_{\theta z}=\omega_0\sqrt{\frac{\rho}{Y}};\quad k_r=\frac{\omega_0}{v};\quad \omega_0=2\pi f_0\quad , \tag{4.134}$$

and the velocity v is expressed:

$$v=\sqrt{\frac{Y}{\rho\left[(1-\nu^2)+\nu(1+\nu)n\right]}}\quad , \tag{4.135}$$

In the case of the symmetrical complex piezoelectric transducer (fig. 4.21) comprised of two piezoelectric disks with 2 a_1 diameters, h_p height and characteristic acoustic impedance $\rho_1\cdot v_1\cdot s_1$, and two identical passive metallic elements with h height, 2 a_2 diameter and characteristic acoustic impedance $\rho_2 \cdot v_2 \cdot s_2$, the effective elasticity modules for the metal ends Y_z^m and Y_r^m are expressed as follows:

$$Y_z^m = \left[\frac{1}{Y}\left(1+\frac{2\nu}{n_1}\right)\right]^{-1} , \qquad (4.136)$$

$$Y_r^m = \left[\frac{1}{Y}\left(1-\nu^2\right)+\nu\left(1+\nu\right)n_1\right]^{-1} , \qquad (4.137)$$

where : Y is the Young module; ν - the Poisson coefficient, and n_1 is given by the relation:

$$n_1 = -\frac{T_z}{T_r} = -\frac{T_z}{T_\theta} , \qquad (4.138)$$

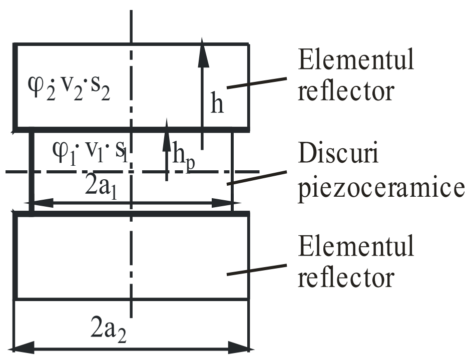


Fig.4.21. Symmetrical complex piezoceramic transmitter.

Element reflector-reflecting element

Discuri piezoceramice – piezoceramic disks

For the piezoceramic disks one obtains:

$$Y_z = \left[s_{33}^E\left(1+\frac{2\nu_{31}}{n}\right)\right]^{-1} , \qquad (4.139)$$

$$Y_r = \left\{s_{11}^E\left(1-\nu_{12}^2\right)+\nu_{13}\left(1+\nu_{12}\right)n_2\right\}^{-1} , \qquad (4.140)$$

where ν_{12} is the Poisson coefficient and is expressed:

$$\nu_{12} = -\frac{s_{12}^E}{s_{11}^E} , \qquad (4.141)$$

and

$$\nu_{13} = -\frac{s_{13}^E}{s_{11}^E}; \quad \nu_{31} = -\frac{s_{13}^E}{s_{33}^E}; \quad n_2 = -\frac{T_z}{T_r} = -\frac{T_z}{T_\theta} , \qquad (4.142)$$

The resonance condition for the passive elements is:

$$k_r^m a_2 J_0\left(k_r^m a_2\right) = \left(1-\nu\right) J_1\left(k_r^m a_2\right) , \qquad (4.143)$$

where:

$$k_r^m = \omega_0 \sqrt{\rho_2 / Y_r^m}; \quad \omega_0 = 2\pi f_0 \ , \tag{4.144}$$

From the (4.143) relations, the following expression is obtained:

$$\omega_0 a_2 \sqrt{\frac{\rho_2}{Y} = R_1^m (1 - \nu^2) + n_1 \nu (1 + \nu)^{-\frac{1}{2}}} \ , \tag{4.145}$$

where R_1^m is the first root of equation (4.143).

The resonance condition for piezoceramic elements has the following form:

$$k_r a_1 J_0 (k_r a_1) = (1 - \nu_{12}) J_1 (k_r a_1) \ , \tag{4.146}$$

where:

$$k_r = \omega_0 \sqrt{\frac{\rho_1}{Y}} \ , \tag{4.147}$$

From the (4.146) relations, the following equality is obtained:

$$\omega_0 a_1 \sqrt{\rho_1 s_{11}^E = R_1 \{(1 - \nu_{12}^2) + n_2 \nu_{13} (1 + \nu_{12})\}^{-\frac{1}{2}}} \ , \tag{4.148}$$

The resonance condition for the complex transmitter becomes:

$$tg(k_1 l_1) tg(k_2 l_2) = \frac{\rho_1 v_1 S_1}{\rho_2 v_2 S_2} \ , \tag{4.149}$$

where it was noted:

$$k_1 = \frac{\omega_0}{v_1}; \quad v_1 = \sqrt{\frac{Y_z}{\rho_1}}; \quad k_2 = \frac{\omega_0}{v_2}; \quad v_2 = \sqrt{\frac{Y^m}{\rho}} \ , \tag{4.150}$$

and l_1, l_2 S_1 and S_2 are the dimensions of the ceramic and of the passive elements respectively.

The resonance condition (4.149) can be also expressed under the following form:

$$tg(k_1 y_0 h) tg[k(1 - y_0) h] = \frac{\rho_1 v_1 a_1^2}{\rho_2 v_2 a_2^2} \ , \tag{4.151}$$

Experimentally it is observed that although the ceramic-reflector subset only transmits longitudinal oscillations to the radiant element, longitudinal oscillations as well as transverse ones appear in it due to the existent coupling in a solid medium These oscillations, according to Hooke's generalized law, are propagated independently and the characteristic impedance of the radiant element is a sum of the characteristic impedances corresponding to each type of generated radiations.

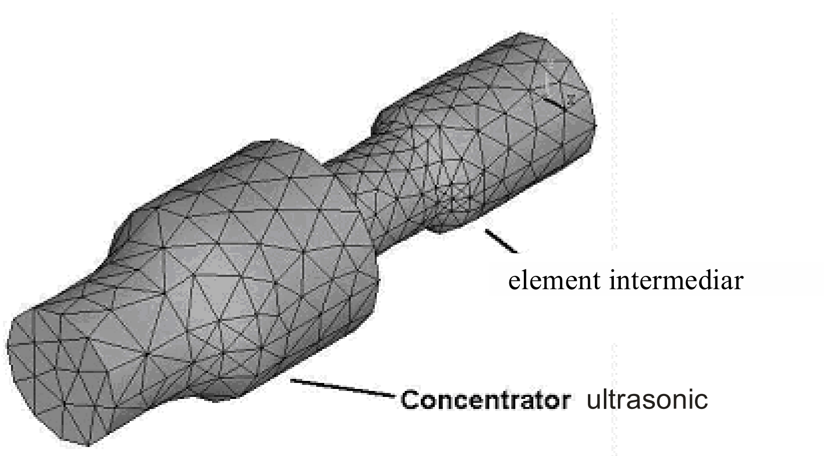
CHAPTER V

THEORETICAL AND EXPERIMENTAL CONTRIBUTIONS TO THE CALCULATION, CONSTRUCTION AND EXECUTION OF ULTRASONIC ENERGY CONCENTRATORS USED IN THE ULTRASOUND FILTERING OF NATURAL GASES

Theoretical and experimental contributions to the finite elements analysis of certain ultrasonic concentrators used in the ultrasound filtering of natural gases

The modeling, using finite elements, of the intermediary element - concentrator ensemble

The intermediary element – concentrator ensemble used in ultrasound filtering is represented in figure 5.18.



Element intermediar - Intermediary element

Concentrator ultrasonic - ultrasonic concentrator

Fig. 5.18. Intermediary element – ultrasonic concentrator ensemble

The concentrator as well as the intermediary element is built out of Titanium alloy steel with the following material properties:

PROPERTY TABLE EX 0.10200E+12 (ELASTICITY MODULE)

PROPERTY TABLE NUXY 0.30000

PROPERTY TABLE ALPX 0.93600E-05

PROPERTY TABLE DENS 4850.0 (density)

PROPERTY TABLE KXX 7.4400

PROPERTY TABLE C 544.00

From the main menu, the type of structural analysis is chosen which also conditions calling upon the libraries that contain the mesh elements.

The mesh element chosen from the ANSYS library is SOLID92, a 3-D element with 10 nodes, tetrahedral solid presented in figure 5.19.

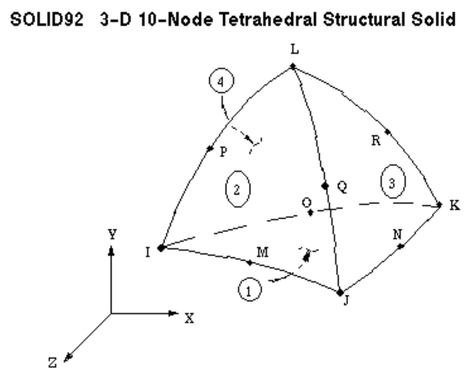


FIG. 5.19. SOLID 92 element.

The PREPROCESSOR is activated from the main menu, in which the volume geometry is generated.

Meshing this volume with the SOLID92 element generates 2968 elements with 4746 nodes as in figure 5.20.

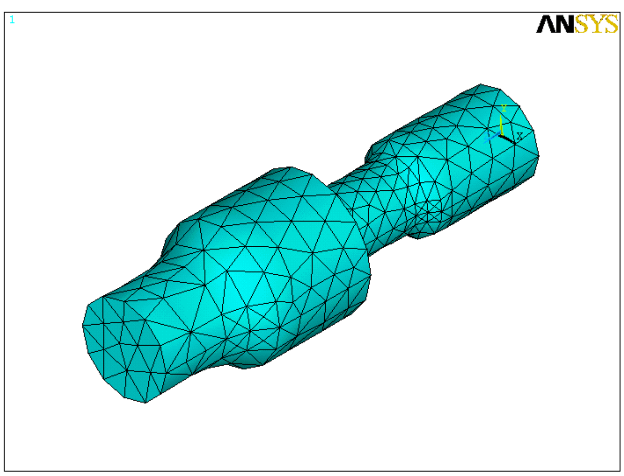


Fig. 5.20. Finite element meshing of the volume of the intermediary element – concentrator ensemble.

After activating the "SOLUTION" processor the modal analysis type is selected. The frequencies corresponding to certain vibration modes close to the resonance frequency are obtained.

At the end of the analysis, by calling upon the GENERAL POST-PROCESSOR, the deformed and non-deformed states corresponding to certain vibration modes are obtained for frequencies close to the resonance frequency.

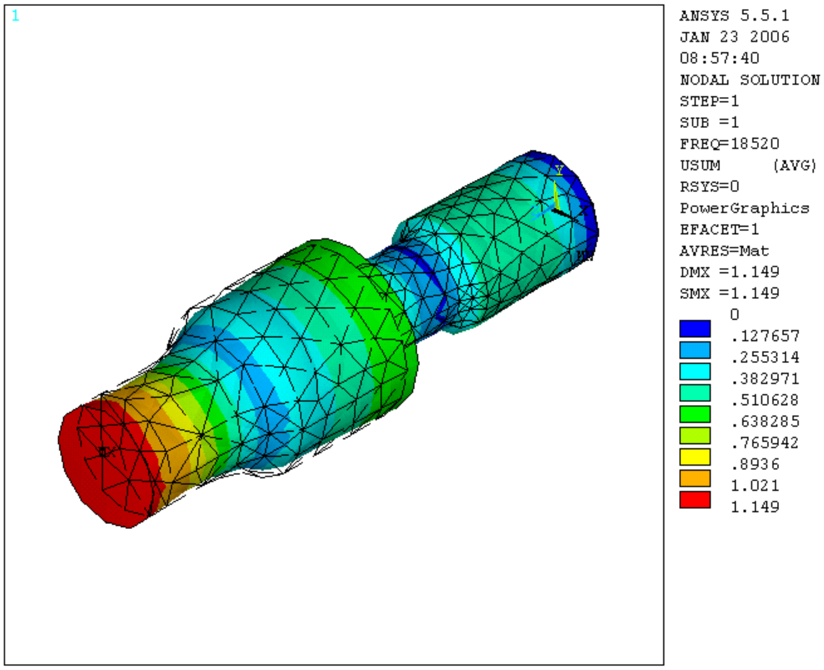


Fig. 5.21. The isometric representation of the deformed/non-deformed state of the intermediary element – concentrator ensemble at 18520 Hz.

The representations, by setting the graphic interface of the deformed/non-deformed states in isometric and vertical view for the chosen frequencies, are given by figures 5.21 and 5.22. In figures 5.21 and 5.22 the vibration mode at a 18520 Hz frequency is presented.

At this frequency, the concentrator preferentially performs a translation along the OZ axis. The values of the movements are presented on a color scale corresponding to the translation on the OZ axis.

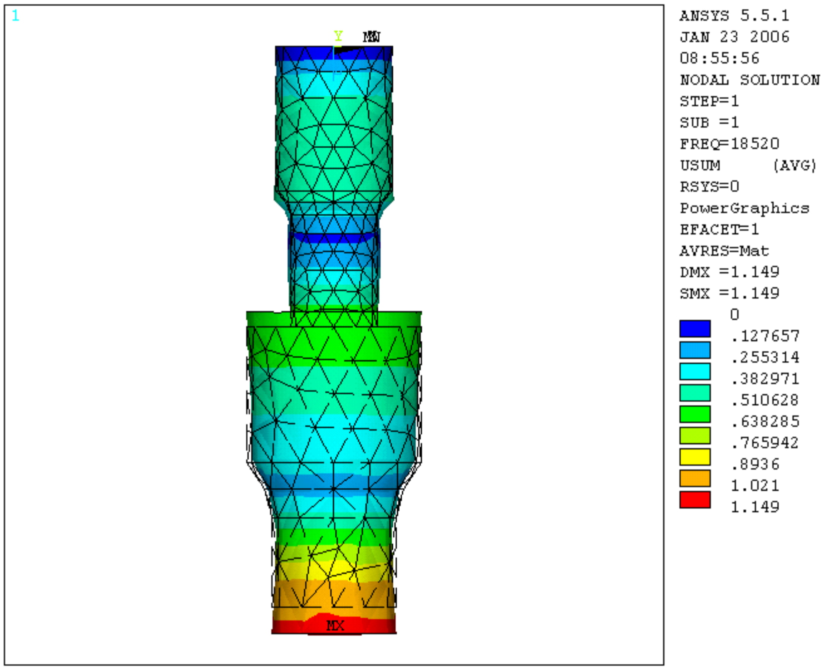


Fig. 5.22. The vertical representation of the deformed/non-deformed state of the intermediary element – concentrator ensemble at 18520 Hz.

Figures 5.23 and 5.24 present the vibration mode at a 20283 Hz frequency. At this frequency, the intermediary element is deformed radially.

CHAPTER VI

FINAL CONCLUSIONS. ORIGINAL CONTRIBUTIONS. TRENDS AND PERSPECTIVES OF FIELD RESEARCH

Original contributions

The theoretical and experimental researches included in this paper have been carried out over many years, in different areas of the national system of natural gas transport, starting from the extraction end to the end user, on routes, in certain control – measuring stations, compression stations and even at end users.

The results obtained are the fruit of an activity of over 20 years in the field of natural gases, a field that has a pretty high technical risk level and one that implies numberless tests and checks until their practice is authorized.

The design and commissioning to good effect of some ultrasonic filters that possess certain advantages compared to classical filters have been also made possible thanks to the original contributions of the author of the doctoral thesis in the field of theoretical research, as well as in that of experimental research.

For reasons of technological secrecy and confidentiality, the paper contains only extracts of a small portion of experimental results and principle schemes, since they include patentable elements.

Original contributions to the field of theoretical research

The main original contributions to the field of theoretical research could be the following:

- The original summary of the research concerning the purification and filtering of natural gases;
- The analysis of the phenomena and effects that emerge upon the propagation of ultrasonic waves in the natural gas medium that involve solid and liquid impurities of different shapes and sizes;
- The analysis of the ultra-acoustic field specific to the filtering process in which the medium is a natural gas permeated by solid and liquid impurities of different shapes and sizes;
- Determining the reflection and ultra-acoustical transmission coefficient, ultra-acoustical absorption and refraction coefficient created by the presence of the "slime" formed by solid impurities entailed by natural gases;
- The calculation elements regarding the depth of retention, the minimum diameter of the retained particle and the pressure drop at the top of the most important categories of filtering: cyclonic, with an active filtering element;
- The calculation and design of certain ultra-acoustic systems used in the construction of four categories of filtering;
- The MEF design of ultra-acoustic systems after determining the modes of vibration at which the ultra-acoustic field for standing waves or the resonance mode activity is obtained;
- Explaining the "ultrasonic agglomeration" phenomenon used in heightening the retention level of fine particles and the level of "ultrasonic agitation" employed in cleaning the active filtering element;
- The calculation and design of ultrasonic energy concentrators used as final parts in the ultra-acoustic system and which have variable action and shapes that correspond to the nature of the phenomena and effects that must occur in the ultrasonic field;

- ➢ The MEF design of ultrasonic energy concentrators and determining the variation of the particle velocity amplitude along the concentrator, on which the “ultrasonic agitation” phenomenon mainly depends;
- ➢ Establishing the conditions that need to be fulfilled by an ultrasonic filter for it to perform the filtering process at high capacity and with increased efficiency.

Original contributions in the field of experimental research

The main original contributions in the field of experimental research are the following:

- ➢ The results obtained in the case of natural gas filtering using ultrasonic filtering;
- ➢ The design and creation of the model FCU-01 ultrasonic cyclone filter, with the possibility of working in resonance mode by “ultrasonic agitation” or standing waves mode with ultrasonic agglomeration;
- ➢ The design and creation of a vertical ultrasound gas filter, model FGVU-01 that can work in a resonance mode and through ultrasonic agitation of the active filtering element;
- ➢ The design and creation of a horizontal ultrasonic cone filter, model FCOU-01, that can retain liquid particles and solid impurities;
- ➢ The design and creation of a final ultrasound gas filter, model FFGU-01, that realizes the total retention of the finest dust and water particles and that works in resonance mode;
- ➢ The design and creation of four ultra-acoustic systems used in the construction of ultrasonic filters.

The trends and perspectives of research in the field

The preoccupations of any researcher in the field of natural gases involve the increase of safety in use and the decrease of the technical risk linked to the transportation from the extraction area to the end user.

As the main source of energy for many areas of an economy, the efficient use of natural gases implies the concentration of major research forces towards increasing it. Filtering and purification are two essential operations that natural gases must undergo and their improvement is a constant process.

The main trends in this field of research are:

- discovering new natural gas deposits;

- the implementation of the filtering operation as close to the extraction area as possible to limit the erosion of the other constituent elements of the National Gas Transmission Company (SNTGN);
- the establishment of ultrasonic field parameters that would allow optimal filtering in as few steps as possible;
- the implementation of certain simple and secure operation contributions;
- the reduction of exploitation and maintenance costs.

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