Application of nanopowders in industrial production of mixed feed

M Chkalova1*, V Shahov1, V Pavlidis1, S Solovyov2

1Orenburg State Agrarian University, Chelyuskintsev str., 18, 460014, Orenburg, Russian Federation.
2Russian Academy of Sciences, Leninsky prosp., 14, 119991, Moscow, Russian Federation.

*e-mail: chkalovamv@mail.ru

Abstract. One of the main directions of the feed manufacturing industry development is the improvement of the output product quality that ensures its efficacy in modern agricultural production. Some international experience in using the essential microelements in the form of nanopowders in the diets of farm animals has been gained. The article is devoted to the development and justification of a technical solution to the problem of dispensing ultrafine (nano) powders in the industrial production of combined feeds. The authors carried out theoretical and experimental studies of the influence of the conditions of functioning of industrial-technological equipment on the properties of several nanopowders of micro metals. The parametric model of the proposed pneumatic dispenser of bulk nanomaterials allows taking into account various structural and technological changes in the dosing process during the preparation of feed mixtures. The author presents a methodology for calculating the oscillatory system of a pneumatic dispenser, including an annular membrane with fixed edges, based on the equivalent replacement of a system with distributed parameters (membrane) with a system with lumped parameters, which allows replacing the oscillatory model with a translational motion model. An engineering-mathematical model that describes forced membrane oscillations, the dispenser oscillation system and the behaviour of the ultrafine material in the working chamber was constructed on its basis. Practical implementation of the results made it possible to obtain a prototype of bulk ultrafine materials dispenser.

1. Introduction

The industrial production of mixed feed is an established industrial sector in the Russian Federation. In modern conditions, the production of mixed feeds is becoming an increasingly important link in the agro-industrial complex [1]. Qualitative and quantitative parameters of livestock production are largely determined by the efficiency of the technological processes of feed production organisation and innovative methods to improve their basic characteristics.

The development of the mixed feed industry and improving combined feeds quality is a prerequisite for the rapid and economically viable livestock production growth, as well as one of the main factors in agricultural production development [1]. The solution to the problem of increasing the efficiency of industrial production of combined feeds is becoming more relevant than ever.

The purpose of the study is to establish the possibilities and conditions for the use of ultrafine materials in a feed production line; development of a technical solution to the problem of dispensing ultrafine powders during feed preparation. To achieve this goal, it is necessary to develop a methodology for experimental studies of the influence of the operating conditions of technological
equipment on the properties of ultrafine powders of micro metals; to obtain an engineering solution to
the problem of dispensing ultrafine powders during feed preparation.

The total mixed ration accumulates the best qualities of the basic raw material and fully meets the
animal's need for nutrient, mineral and biologically active substances. The feed nutrients will be best
digested only if an equivalent amount of macro- and micronutrients, vitamins, and other essential
nutrients are involved in the metabolic processes of the organism [2-5] (Table 1).

Table 1. Role of trace elements in metabolic processes of farm animals’ organism

| Trace elements | Importance for Metabolism |
|----------------|---------------------------|
| Fe             | It is associated with blood haemoglobin level, included in catalase cytochromes and other enzymes and is deposited in the form of ferritin and hemosiderin. **The adult animals get it with fodder** |
| Cu             | It belongs to strong cytoplasmatic tic poisons, but in small amounts, it is needed to convert iron into the hemo-form available for synthesis, to be transferred into the bone marrow. Copper is needed for the formation of enzymes, catalysing the transformations of tyrosine, ascorbic acid, etc. **The animals get copper with fodder** |
| Co             | Cobalt is part of vitamin B12. It activates hydrolytic enzymes, increases the synthesis of nucleic acids and muscle proteins, and contributes to higher live weight gain in young animals and increase of farm animals’ performance. **The animals get cobalt with fodder** |
| Mn             | Manganese has a beneficial effect on the growth and development of young animals, plays a significant role in the reproduction processes. **The animals get manganese with fodder** |
| Zn             | Zinc is contained in the insulin hormone and influences the animals’ growth, gain and reproduction. The zinc metabolism is connected with that of calcium, sulphur and copper. **The animals get zinc with fodder** |
| Cr             | Chrome participates in the synthesis of proteins, cholesterol and fatty acids, activates the enzymes necessary for carbohydrate metabolism, regulates carbohydrate metabolism and the level of glucose in the blood, which normalizes the permeability of cell membranes. **The animals get chrome with fodder** |

2. Materials and methods

In recent years, research aimed at exploring the possibilities of obtaining high-quality feed using the
combined use of bio-additives and trace elements in nano form has been conducted [6,7].
Nanomaterials (in the form of ultrafine powders) contain structural elements whose geometric
dimensions do not exceed 100 nm, and radically different in their properties and effects from
substances in the form of macroscopic dispersions and continuous phases.

World science has gained some experience in the development and application of ultrafine
materials in agriculture. Recent studies have shown their effectiveness in crop production, fodder
production [8-10] and livestock farming.

The main methods for producing ultrafine powders of trace metals with particle diameters up to
100 nm, which can be used for feeding farm animals, are presented in Table 2.

The common disadvantages of the methods considered (excluding the Exploding Wire Method
(EWM) are: low performance, significant energy consumption, a wide range of particle size
distribution, poor purity of the output product and high safety requirements. The presence of these
drawbacks is a serious obstacle to the production of ultrafine powders on an industrial scale. Including
metal powders and trace metals for feeding farm animals including, on an industrial scale.

Table 2. Methods for producing ultrafine metal powders for feeding farm animals

| Method                      | Methodology          | Materials   |
|-----------------------------|----------------------|-------------|
| Evaporation and condensation| In vacuum or inert gas| Zn, Cu, Cr  |
The electrical explosion of conductors

High-energy destruction

Chemical methods

Synthesis

Thermal

Detonation treatment

Thermal decomposition

Table 3. Operating conditions of technological equipment affecting ultrafine material

| Technological operation | Conditions influencing the ultrafine material |
|-------------------------|-----------------------------------------------|
| Micronization of mixed feed components | -heating to 90 °C for 45 s |
| Expanding of mixed feeds | -the product passes through the expander for some seconds at the temperature from 105 to 110 °C |
| | -the feed moisture before it enters the press-granulator mixer is 8-15%; |
| | -the feed moisture content after it leaves the mixer does not exceed 17.2%; |
| Pressing of mixed feeds | -steam pressure is up to 0.7 MPa; |
| | -steam temperature is 140 – 180 °C; |
| | -conditions of pellets cooling: |
| | -pellet cooling conditions: increasing the temperature of feed by 10 -11 °C as a result of conditioning in a steam mixer is equivalent to increasing its humidity by 0.7-1.0%; |
| Extrusion Separation | -the product temperature at the outlet is 120 – 130 °C |
| Magnetic separators | magnet shape sizes, mm residual magnetic induction, mT |
| | bar 62*25*62 1350 |
| | ring 52*27*35 380 |
| | tablet Ø134*54*12 390 |

Based on the analysis of the technological conditions for the operation of the industrial feed production line, we developed a laboratory experiment technique aimed at studying the properties of nanomaterials in modelling temperature conditions, humidity, and residual magnetic and electromagnetic induction. A series of laboratory experiments showed the stability of ultrafine powders of iron, zinc and copper oxides synthesised by the electric explosion method to oxidation and sintering at room temperature. However, a high chemical and diffusion activity was revealed when heated to temperatures of the working feed mixture.
The obtained results formed the basis of the idea of many technical solutions, the implementation of which will increase the efficiency of the preparation of combined feed based on the use of ultrafine materials. The device (pneumatic dispenser of ultrafine materials) operates as follows (Figure 1).

![Figure 1. Principal scheme of the pneumatic dispenser of loose ultrafine materials.](image)

The dispensing is performed by opening the solenoid-magnet valve 2 for a strictly fixed time. The loose ultrafine material from the storage tank one is moved through the calibrated opening to the dispensing chamber 3. When air is supplied into the pneumatic actuator, the membrane four is being deformed and moves the rod 5 to the right. The dispensing chamber three is overlapped by the inner spherical surface of the pneumatic actuator body. With further movement of the rod to the right, the valve 6 opens a passage for compressed air through the hollow channel 7 into the dispensing chamber 3. The compressed air presses the loose ultrafine material located in the dispensing chamber and moves it along the channel 7 to the right. Under the action of the compressed air mixture and the loose ultrafine material, the shut-off valve eight is being opened. The dispensing chamber three and the hollow channel seven are cleaned of the loose ultrafine material, which enters the receiving chamber 9 for its future use as intended when the air supply into the pneumatic drive discontinues, the shut-off valve 8 closes [13].

The pneumatic dispenser for loose ultrafine materials includes a control system located in a separate cabinet. The control system makes it possible to specify any volume (amount) of the loose ultrafine material, entering the dispensing chamber, and controls the supply of compressed air to the pneumatic drive.

3. Results and discussion
To solve the question of how to introduce ultrafine bulk materials, technical capabilities were studied, among which, in our opinion, the most promising are the design changes of the pneumatic dose of powdered materials. Due to the need to use ultrafine powders, we had to significantly change its design, based on which an engineering mathematical model was constructed that describes the forced oscillations of the membrane, the oscillatory system of the dispenser and the behaviour of the ultrafine material in the working chamber. The constructed model involves verification and therefore does not contain specific parameter values and impedance characteristics. We describe the forced oscillations of the annular membrane with fixed edges in the housing of the pneumatic actuator and calculate the oscillatory system of the pneumatic dispenser, including this membrane.

An annular membrane fixed along the contour located in the housing of the pneumatic actuator performs forced oscillatory movements under the influence of air pressure; on the other side of the membrane, the air medium remains unperturbed. Air pressure is created using the airflow pumped by the compressor, and varies according to a certain law, evenly distributed over the entire membrane area. We will assume as standard that the resistance to movement of the membrane is proportional to the speed of this movement.
The studies conducted by the authors allowed us to determine the function that describes the change in air pressure in the working chamber of the pneumatic drive as harmonic. Then using the wave differential equation of partial derivatives of the second-order of the hyperbolic type, which describes the free vibrations of the membrane, and taking into account the technical characteristics of the compressor that determine the pressure function, we obtain:

$$\rho_m \frac{\partial^2 u}{\partial t^2} + r_m \frac{\partial u}{\partial t} - T \left( \frac{\partial^2 u}{\partial r^2} + \frac{1}{r} \frac{\partial u}{\partial r} \right) = \rho_0 e^{i\omega t},$$  \hspace{1cm} (1)

where \(u = u(r, t)\) is the deviation of the annular section of the radius \(r\) membrane at the time moment \(t\); \(\rho_m\) – the surface density of the membrane material (constant); \(r_m\) – the resistance coefficient of the surface unit (constant); \(T\) – stress in the given annular membrane section (constant); \(\rho_0\) – the amplitude of air pressure; \(\omega\) – the circular frequency of the acting driving force.

The above equation describes the established steady forced oscillations of the annular membrane with fixed edges in pneumatic drive body.

In the framework of steady oscillations, the setting of initial conditions is not required, the boundary condition has the form:

$$u(r, t)\big|_{r=R_0} = 0,$$

where \(R_0\) is the outer radius of the annular membrane, the boundedness of the required function will be taken into account below. The nontrivial solutions of equation (1), with the given boundary conditions, are to be sought in the following form:

$$u(r, t) = u_1(r) \cdot e^{i\omega t},$$ \hspace{1cm} (2)

with the coinciding boundary conditions for the amplitude and the sought functions.

When we substitute the expression (2) into equation (1) and after some transformations made, we obtain a new equation in polar coordinates

$$\frac{\partial^2 U_1}{\partial r^2} + \frac{1}{r} \frac{\partial U_1}{\partial r} + k^2 u_1 = -\frac{\rho_0}{T},$$

where

$$k^2 = \frac{\rho_m \omega^2 - i r_m \omega}{T}.$$  \hspace{1cm} (3)

From the physical point of view, the parameter \(k^2\) is a generalised numerical characteristic of the transverse wave distribution on the membrane surface after air supply into the pneumatic drive housing of the loose ultrafine materials dispenser.

If the membrane made free oscillations, then the right side of equation (3) would be equal to zero, and the equation itself would be referred to as the Bessel’s equation with the standard record of the general solution. In our case, the solution of equation (3) with allowance for the right-hand side is written as follows:

$$u_1(r) = -\frac{\rho_0}{k^2 T} + C_1 M_0(kr) + C_2 N_0(kr),$$

where \(C_1 M_0(kr) + C_2 N_0(kr)\) is the general solution of the Bessel equation, \(M_0(kr)\) and \(N_0(kr)\) are the Bessel functions of the I and II type of the zero-order of the complex variable.

In addition to the boundary condition, the equation (1) is connected with the natural requirement of the boundedness of the function in question at the centre of the membrane ring, i.e. with \(r = 0\):

$$\forall t |u(r, t)| < +\infty.$$  \hspace{1cm} (4)

From this condition, which is also valid for the function \(u_1(r)\), it follows that \(C_2 = 0\), (the Neumann function \(N_0(kr)\) \(\longrightarrow \infty \) \(r \longrightarrow +0\) takes into account the damping of oscillations, linearly independent of \(M_0(kr)\)), and

$$C_1 = \frac{\rho_0}{k^2 T M_0(R_0)}.$$  \hspace{1cm} (5)

The solution of equation (3) for the given boundary condition and the condition for the boundedness of the function in question has the form:

$$u_1(r) = \frac{\rho_0}{k^2 T} \left( \frac{M_0(kr)}{M_0(R_0)} - 1 \right),$$

and the required solution of equation (1) determines the function:

$$u(r, t) = \frac{\rho_0}{k^2 T} \left( \frac{M_0(kr)}{M_0(R_0)} - 1 \right) \cdot e^{i\omega t},$$  \hspace{1cm} (6)

The parametric solution obtained sets completely and describes the forced oscillations of the annular membrane with the predetermined parameters \((R_0, \rho_m, r_m, T)\), which is fixed along the contour in the pneumatic drive housing of the dispenser of loose ultrafine materials.
For further studies, it may be useful to calculate the deviation of the membrane points from the equilibrium position. Reasoning inductively, we consider a special case of the membrane points’ deviation from the neutral position under the influence of the static pressure uniformly distributed over the area. To do this, we write the differential equation:

$$\frac{d^2u}{dr^2} + \frac{1}{r} \frac{du}{dr} = -\frac{P}{T},$$  \hspace{1cm} (5)

where \( u = u(r) \) – the transverse deviation of the annular membrane section of radius \( r \); \( T \) is the tension in the given annular membrane section (constant); \( P \) is the value of static pressure (constant).

The special solution of equation (5), satisfying the boundary condition \( u(r)|_{r=R_0} = 0 \), is a function of the form:

$$u(r) = \frac{PR_0^2}{4T} \left( 1 - \frac{r^2}{R_0^2} \right),$$

where \( R_0 \) is the outer radius of the annular membrane; \( \frac{PR_0^2}{4T} \) is the deviation value of the inner contour, which is rigidly fixed on the rod.

If we use the resulting parametric solution (4), then we can find the average deviation of the annular membrane points from the equilibrium position at any (every) time point, with the pressure being changed according to the harmonic law:

$$u_{cp}(t) = \frac{1}{\pi (R_0^2 - r_0^2)} \int_{r_0}^{R_0} u(r, t) 2\pi r dr = \left[ \int krM_0(kr) d(kr) = krM_1(kr) \right] =$$

$$= \frac{2\rho_0}{k^2T(R_0^2 - r_0^2)} \cdot e^{i\omega t} \left[ \frac{R_0M_1(kR_0) - r_0M_1(kr_0)}{kM_0(kR_0)} - \frac{(R_0^2 - r_0^2)}{2} \right] =$$

$$= \frac{\rho_0}{k^2T} \left[ \frac{2(R_0M_1(kR_0) - r_0M_1(kr_0))}{kM_0(kR_0)(R_0^2 - r_0^2)} - 1 \right] \cdot e^{i\omega t},$$  \hspace{1cm} (6)

where \( M_1(kr) \)– the Bessel function of the first type of the first order; \( R_0 \) – the outer radius of the annular membrane; \( r_0 \) – its inner radius.

The function \( u_{cp}(t) \) sets harmonic oscillations, the amplitude and phase of which are determined by the excitation frequency \( \omega \). Moreover, \( \frac{\rho_0}{k^2T} \left[ \frac{2(R_0M_1(kR_0) - r_0M_1(kr_0))}{kM_0(kR_0)(R_0^2 - r_0^2)} - 1 \right] \) are a complex numerical characteristic, the modulus of which coincides with the amplitude of the described harmonic oscillations, and the argument coincides with the phase of these oscillations.

The authors have developed the methodology for calculating the oscillatory system of the pneumatic dispenser, which includes the annular membrane with fixed edges, based on the equivalent replacement of the system with distributed parameters (membrane) by a system with lumped parameters. Such an approach makes it possible to replace the model of vibrational motion by the model of translational motion. The substitution of the annular membrane for an equivalent system with one degree of freedom, for example, for a linear oscillator, the mass element of which is a flat round rod, greatly simplifies the calculations and avoids complex equations of mathematical physics. Therefore, under the same excitation conditions, it is possible to substitute the membrane for a piston of the same cross-sectional area [14].

The piston motion is described by a linear inhomogeneous differential equation of the second order with a special right-hand side:

$$m_p \frac{d^2x}{dt^2} + r_p \frac{dx}{dt} + k_p x = p_0S_p e^{i\omega t},$$  \hspace{1cm} (7)

the solution of which has the form

$$x(t) = \frac{p_0S_p e^{i\omega t}}{k_p - m_p \omega^2 + ir_p \omega},$$

where \( x(t) \) – the piston’ deviation from the equilibrium position at any time moment; \( m_p \) – the piston mass; \( r_p \) – the resistance coefficient to the piston’s movement; \( k_p \) – the spring stiffness of the linear oscillator; \( S_p \) – the piston area which is equal to the area of the membrane.
Then we equate the right-hand parts of equations (6) and (8), based on the identity of the laws of
the membrane and the equivalent piston motion, and obtain the sought parameters of the oscillator
expressed by the parameters of the annular membrane:

\[ m_p = p_m S_p, \]

\[ k_p = m_p \omega^2 + S_p T R e \left[ k^2 \left( \frac{2M_1(k R_0)}{k R_0 M_0(k R_0)} - 1 \right)^{-1} \right], \]

\[ r_p = \frac{S_p T}{\omega} \Im \left[ k^2 \left( \frac{2M_1(k R_0)}{k R_0 M_0(k R_0)} - 1 \right)^{-1} \right], \]

As a result, we have determined the parameters of the linear oscillator, the piston of which, on
the one hand, is equivalent to the initial membrane by the response to outward action, and on the other
hand, it is identical to it by the impact on the surroundings. Therefore, we can substitute the membrane
with an equivalent piston, wherever it is located in the oscillatory system and carry out all further
calculations with the piston of the linear oscillator [14,15].

In the course of laboratory experiments at the premises of the Engineering Department of the
Orenburg State Agrarian University, the parameters of a linear oscillator (rod) were obtained, which
made it possible to simulate the introduction of ultrafine powders into the finished feed mixture. It was
decided to manufacture the stem from structural steel, the stem length is 230 mm, the diameter is 20
mm, the mass is 354 g, the stem stroke is 44 mm. Based on equations (9) - (11) of the mathematical
model, the membrane parameters were analytically determined: effective area - 229 cm², thickness -
not more than 8 mm, the surface density of the material - not more than 1.5 g/cm².

The limits of the working pressure of the sprayed mixture from 202.6 KPa to 810.4 KPa, the
consumption of the sprayed mixture from 0.35 cm³ / s to 0.95 cm³ / s, the spray form is a symmetrical
torch with an angle of 120° have been experimentally established. To manufacture an atomiser
of ultrafine materials, the brass with good wear resistance, anticorrosion and antifriction properties was
selected at the Department of Materials and Construction Materials.

4. Conclusion
A prototype dispenser of bulk ultrafine materials with overall dimensions of 322x200x260 mm and a
mass of 5.48 kg is being tested during production experiments at the premises of the Orenburg State
Agrarian University instructional farm. The design of bulk ultrafine materials dispenser is presented
for research to the Federal Institute of Industrial Property (application № 2018114335 of 18.04.2018),
where the stage of examination of the essence of the invention is completed and the patent is being
prepared. The engineering solution to the problem of dosing powders of micro metals in the process of
preparing the feed mixture obtained by the authors is based on:
- experimentally established the influence of the conditions of formation of the working feed mixture
  on the properties of ultrafine powders;
- the analysis of the set of technological conditions for the combined feed industrial production;
- the ultrafine materials dynamic properties analysis.

The mathematical model of the pneumatic dispenser of ultrafine (nano) materials constructed by
the authors makes it possible to unify engineering calculations taking into account the introduced
structural and technological changes and to obtain analytically some of the parameters.

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