Mathematical modeling of one-dimensional air movement with dispersed particles in a continuously working pneumatic mixer

V A Uvarov¹, T N Orekhova¹, E I Chekhovskoy¹, and A E Kachaev²

¹Belgorod State Technological University named after V G Shukhov, Kostyukov St., 46, Belgorod, 308012, Russia
²Moscow Polytechnic University, October Revolution St., 408, Kolomna, 140402, Russia

E-mail: nefact@mail.ru

Abstract. The improvement of methods and technologies for the production of dry building mixes, dispersed modifiers, dry paints and other finely ground, homogeneous systems is associated with the quality of their compositions, which, in turn, requires the use of high-tech energy-saving equipment. The use of the original pneumatic mixers proposed in the paper makes it possible to obtain high-quality multicomponent mixtures due to the specially organized movement of the two-phase flow meeting with the peripheral supply of the energy carrier. Forecasting and analyzing the dynamics of two- and multiphase systems distributed in the air in units of this type allows assessing the nature of the technological process of mixing components, while a mathematical description of the complex movement of particles in the air flow allows obtaining a result that helps to characterize the operating modes of the pneumatic mixer, which is important when operating this machine in production. The paper presents a method for numerical simulation of the axisymmetric motion of a two-phase flow in the homogenization chamber of a pneumatic mixer, which allows setting adequate operating modes of the unit for various dispersed systems mixed in it. The main assumptions in the construction of the mathematical model are also reflected, the conditions for setting the problem for this study are formulated, and the results are obtained in the form of analytical expressions of the main dynamic parameters of the flow with particles for the volume of the mixing chamber, depending on the design features of the pneumatic mixer.

1. Introduction

At present, the development of technologies for the production of dispersed multicomponent mixtures in our country, and throughout the world, plays a certain role in the need for the use of efficient technological machines. The peculiarity of such production facilities provides for the flexibility of technological operations and obtaining high-quality products.

Depending on the type of multicomponent powder material, it is necessary to analyze the mixers that must meet a particular production technology. For example, for the production of dry paints, it is advisable to use pneumatic mixers [2,3,4] of continuous action. The main reasons for the use of such pneumatic mixers can be considered as obtaining a homogeneous product, as well as the possibility of producing mixtures in a continuous cycle.
The constant development of pneumatic mixer designs is aimed at the possibility of producing homogeneous dispersed powders. In the designs of pneumatic mixers [2,3], the main mixing of dispersed components is carried out by an axial two-phase flow moving in the mixing chamber, which, under the action of air supplied from the periphery of the chamber, begins to swirl into a vortex (Fig. 1). Analytical studies of the dynamics of a complex flow of a two-phase environment in a pneumatic mixer allow evaluating the type of mixing process, determining the design parameters of the pneumatic mixer and its effective operating modes using examples of various compositions of multicomponent mixtures [5]. Therefore, such analytical studies are quite relevant.

![Figure 1. Vortex motion of the two-phase flow in the mixing chamber: 1 – feed of the mixture components through the booster pipe; 2 – mixing chamber; 3 – tangential energy supply; 4 – aeration and disaggregation unit of the mixture; 5 – discharge pipe.](image)

2. Materials and methods

2.1. Materials
Dry levelling plaster mix, which includes materials: cements of the PC500D0 brand, expanded perlite sand M75, lime dust, quartz sand fractions up to 0.5 mm and modifying additives

2.2. Methods
Let us consider the axisymmetric flow of a viscous air-material flow in a mixing chamber (Fig. 1) at a tangential velocity that depends only on the relative radius of the chamber \( r \), i.e. \( \omega \equiv \omega (r) \). As the tangential velocity in the end boundary layers of a viscous air-material flow depends on the axial coordinate, it is impossible to take into account the influence of the boundary layer on the end surfaces of the chamber in such a model. Therefore, we will solve the problem outside the boundary layer of the end surfaces. On the side wall of the beginning of the mixing chamber, the velocity is conditionally equal to zero (the velocity of the main flow of particles with the main energy carrier falls conditionally to zero), and in the places where the additional air flow is implemented, in the holes 3, it has a certain value. As it is impossible to reflect this in the axisymmetric flow model, we will consider the flow in the area \( 0 \leq r \leq R_2 \), where the formed two-phase flow does not depend on the design of the entrance to the chamber and has the initial value of the velocity component at:

\[
r = R_2 \quad u = u_z; \quad w = 0; \quad v = v_z.
\]  

Here \( r \) - conditional radius of the mixing chamber, m; \( R_2 \) - initial conditional radius of the mixing chamber, m; \( u, u_z \) – radial velocities at radii \( r \) and \( R_2 \), m/s, respectively; \( w \) - vertical speed, m; \( v, v_z \) - tangential velocities at radii \( r \) and \( R_2 \), m/s, respectively.
As it will be shown below, the difference \( R_2 - R_3 \) for non-cylindrical mixing chambers with a uniform arrangement of tangential inlet slots, or holes, on the side surface can be 1±2 mm. The physical analog of the model shown in Fig. 1 is a mixing chamber with an initial radius \( R_2 \), in which the curved surface of the pipe is connected to the booster pipe, through which the energy carrier – air (with particles) is supplied with a flow rate \( Q = 2\pi R_2 L \cdot u_2 \) (where \( L \) is the length of the mixing chamber, m).

It follows for \( v \equiv v(r) \) that the radial velocity of the flow depends only on the radius, i.e. \( v = v(r) \), and from the traditional continuity equation in [6] – the axial velocity is linear in \( z \), so \( \partial^2 w / \partial z^2 = 0 \). Then the continuity equations for the formulation of our problem will take the form:

\[
\frac{u}{r} \frac{du}{dr} - \frac{v^2}{r} = - \frac{1}{\rho} \frac{\partial p}{\partial r} + v \frac{d}{dr} \left( \frac{1}{r} \frac{dr u}{dr} \right); \tag{2}
\]

\[
\frac{u}{r} \frac{dv}{dr} = v \frac{d}{dr} \left( \frac{1}{r} \frac{dr v}{dr} \right); \tag{3}
\]

\[
\frac{u}{r} \frac{dw}{dr} + \frac{w}{r} \frac{dw}{dz} = - \frac{1}{\rho} \frac{\partial p}{\partial z} + v \left( \frac{\partial^2 w}{\partial r^2} + \frac{1}{r} \frac{dw}{dr} \right); \tag{4}
\]

\[
\frac{1}{r} \frac{dr u}{dr} + \frac{1}{r} \frac{dw}{dz} = 0. \tag{5}
\]

Here \( z \) – vertical coordinate of the particle position in the vortex, m; \( p \) - the pressure of the environment taken at the point coinciding with the center of the particle volume, Pa; \( \rho \) - density of the carrier phase (air), kg/m³.

3. Results

To describe the circumstances of the problem, in addition to (1), the missing boundary conditions must be specified. As follows from Fig. 1, there is no axial movement of the two-phase environment on the left end surface, so:

\[
\text{at } z = 0 \quad w \equiv 0. \tag{6}
\]

Through the central hole with radius \( R_1 \) of the lower end surface, the two-phase environment exits the mixing chamber, so:

\[
\text{at } z = L \quad R_1 \leq r \leq R_2; \quad w \equiv 0. \tag{7}
\]

From the condition of the axial symmetry of the problem, it follows that on the axis of the mixing chamber:

\[
\text{at } r = 0 \quad u = v = 0. \tag{8}
\]

The system of equations (2)–(5) is represented by the second order differential equations for the velocity components \( u, v, w \) and the first – for the pressure \( p \). To find the higher derivatives from the equations at any point, they need to know the value of the functions and the lower derivatives at that point. It follows that to determine these values; eight boundary conditions must be set. But as the unknown functions \( w \) and \( p \) depend on two variables, the boundary conditions for them in general cannot be expressed as constants, but must depend on a single coordinate, for example, \( r = R_b, \quad w = w_b(z) \) and \( p = p_b(z) \) where \( R_b \) is the radius of the bounding curved surface of the mixing chamber.

In the special case, when an unknown function, for example \( w \), is linear in \( z \), this dependence can be expressed by two constant boundary conditions:

\[
\text{at } r = R_{b1} \quad z = z_1; \quad w = w_{b1}; \tag{9}
\]

\[
\text{at } r = R_{b2} \quad z = z_2; \quad w = w_{b2}. \tag{10}
\]

If the desired function has a more complex form, for example, it is quadratic, then the boundary condition for it can be expressed by setting three constants.

A priori, we have no known dependencies of the function \( p \) and \( w \) on the axial coordinate \( z \) or radius \( r \). Therefore, there must be at least ten boundary conditions in the form of constants. Expressions (1), (6)–(8) present only seven boundary conditions. Therefore, problem (2)–(5) is underdetermined. To set additional boundary conditions, it is necessary to have a clear physical basis, and they should describe the situation of the two-phase flow under consideration to the maximum extent. For example, in our problem, the pressure in the mixing chamber remains undefined.
To ensure the movement of the two-phase flow in the mixing chamber with the speeds set according to (1), it must be affected by a certain pressure drop, the lower level of which must be set at the outlet of the chamber. This pressure of the external environment, for example $p_{\text{ext}} = 0$, cannot be set over the entire output section of the mixing chamber, as it varies along the radius. Apparently, such a condition could be set at the exit of the camera at infinity, where the speed of movement tends to zero. But in this case, there must be changes in the tangential velocity with respect to $z$, which contradicts the $v \equiv v(r)$ model.

The difficulty in setting the boundary conditions is typical for many works, including [1, 7]. In order to overcome it, they accept any hypotheses or solve the problem under arbitrary boundary conditions or arbitrary values of the integration constants. To obtain solutions that correspond to reality, the boundary conditions must meet the conditions of the problem as much as possible. In the future, when analyzing the obtained solutions, we will return to the problem of boundary conditions.

As the first term in equation (1) does not depend on $z$, after integrating (5) with respect to $z$, we can write the result as:

$$ w = \psi_1(r) + z\psi_2(r). \quad (9) $$

But according to the boundary condition (6) $\psi_1(r) = 0$. As $u$ and $v$ depend only on $r$, when differentiating (2) with respect to $z$, we get:

$$ \frac{1}{\rho} \frac{\partial^2 p}{\partial r \partial z} = 0. \quad (10) $$

When substituting (9) into equation (4), the pressure derivative can be written as:

$$ -\frac{1}{\rho} \frac{\partial p}{\partial z} = A \cdot z, \quad (11) $$

where $A$ can depend only on $r$. Then, after differentiating (11) by $r$, taking into account (10), we get $\partial A / \partial r = 0$, i.e., $A = \text{const}$. After substituting (11) in (4), we find:

$$ u \frac{d\psi_2}{dr} + \psi_2^2 - v \left( \frac{d^2\psi_2}{dr^2} + \frac{1}{r} \frac{d\psi_2}{dr} \right) = A, \quad (12) $$

where according to (11)

$$ A = -\frac{1}{\rho z} \frac{\partial p}{\partial z} = \text{const}. \quad (13) $$

Let us move on to dimensionless variables:

$$ \varphi = \frac{vr}{\nu R_1}; \quad f = \frac{ur}{u_R}; \quad \bar{p} = \frac{p}{0.5 \rho u_1^2}; \quad y = \left( \frac{r}{R_1} \right)^2. \quad (14) $$

Here $\nu_1$ - tangential air velocity, m/s; $u_1$ - radial air velocity, m/s; $R_1$ - conditional radius of the discharge pipe, m.

Then from the continuity equation (5) we obtain taking into account (6):

$$ w = (2vF_1 / R_1^2)zf' = w_{cyp}f'z/L, \quad (15) $$

where $F_1 = -u_1 R_1 / v = Q / 2\pi L$ - радиальное число Рейнольдса; $f' = df / dy$; $w_{cyp} = Q / \pi R_1^2$.

From the comparison of (15) with (9), it follows $\psi_2 = (2vF_1 / R_1)f'$. After substituting $\psi_2$ in (12) and moving to the new variables (14), we have:

$$ f''^2 = \frac{F_1}{2y} \left( f' \right)^2 - f''(f + 2/F_1) - C, \quad (16) $$

where

$$ C = \frac{A(R_1^2/2v)^2}{F_1^2}. \quad (17) $$

Equation (3) after substituting the new variables (14) takes the form:

$$ \varphi'' = -F_1 f \varphi'/2y. \quad (18) $$

Equation (2) in the new variables can be written as follows:

$$ \frac{\partial \bar{p}}{\partial y} = \left( \frac{f}{y} \right)^2 - \frac{2ff'}{y} - \frac{4f''}{F_1} + K_1^2 \left( \frac{\varphi}{y} \right)^2, \quad (19) $$

where $K_1 = \nu_1 / u_1$ - parameter of twisting of the two-phase flow at the boundary of the discharge pipe, $\bar{p} = p(y)/(0.5 \rho u_1^2)$ – the radial component of the pressure, depending only on the radial coordinate.
Taking into account that
\[ \frac{d}{dy} \left( \frac{f_2}{y} \right) = -\left( \frac{f_2}{y} \right) - \frac{2ff'}{y}, \]
this equation can be partially integrated. Setting the boundary conditions at some point \( y = a \), \( p(a) = p_a, f(a) = f_a, f'(a) = f'_a \), we find:
\[ \bar{p} = \bar{p}_a - \left( \frac{f_2}{y} \right) \left( \frac{f_2}{a} \right) - \frac{4}{F_1} (f' - f'_a) + K_2^2 \int_a^y \left( \frac{q}{y} \right)^2 \, dy. \]  
(19)

The full pressure profile, which depends on both the radial and axial coordinates, can be determined by integrating the expression (11). After bringing it to a velocity head of \( 0.5\rho u_1^2 \), we get:
\[ \bar{p}(r, z) = -\frac{4L}{u_1^2} \zeta^2 + \bar{p}, \]  
(20)
where \( \zeta = z/L; \bar{p}(y, 0) \) – pressure at \( \zeta = 0 \), which is determined with the equation (20).

As we can see, the problem was reduced to a system of ordinary differential equations of the third order. Equations (16), (18), (19) taking into account (14), (15) and (20), the velocity and pressure fields in the mixing chamber are determined. The pressure is clearly not included in the equations for the velocities (16)–(18). However, it has an indirect effect on the velocity profiles via the constant \( A \).

Indeed, the equation for the meridional motion (16) does not depend on the tangential velocity. But as the pressure according to (19) depends on the tangential velocity, the latter affects the profiles \( u \) and \( w \) through the constant \( A \). So, the constant \( A \) for the axial pressure gradient (11) is a parameter by which the velocity and pressure profiles are related in the resulting system of equations.

In comparison with the system of continuity equations in [6], equations (16) and (18) for the velocity components have a lower order of derivatives by one. Despite the different ways of their output, these systems correspond to each other. We show that for \( v = v(r) \), the continuity equations (2) – (5) coincide with equations (16)–(18). Taking into account (14) for the current functions, we can write:
\[ -\frac{1}{r} \frac{\partial u}{\partial z} = \frac{u_1 R_1}{r} f, \]
from where, after integrating by \( z \), we have:
\[ \psi = -u_1 R_1 f z + C_2. \]  
(21)

If, in accordance with (14), we proceed to dimensionless variables, then:
\[ \psi = \frac{2\pi}{L} \zeta + C_1. \]  
(22)

As at \( \zeta = 0 \) there is pet currents, then \( \psi = 0 \) and, consequently, \( C_1 = 0 \). Taking into account that \( \varphi \) is independent of \( \zeta \) and \( \psi \) is linear in \( \zeta \), the right-hand sides of equations (2) - (5) and (14) vanish. And as \( N = 2\pi F_1 \), equation (14) turns into (18), and the left part of equation (16) takes the form:
\[ 2yf'' + 4f''' + F_1 f'' + F_3 f + F_3 = 0. \]  
(23)

It is easy to see that after differentiating by \( y \), equation (16) turns into expression (23).

In this case, they can determine the solution for the peripheral area of the mixing chamber. Substituting the boundary condition on the upper tangential surface of the energy supply (7) into the expression for the axial velocity (15), we write:
\[ f' = 0 \text{ at } R_1 \leq r \leq R_2. \]  
(24)

Integrating (24) taking into account \( u(R_1) = u_1 \), we get:
\[ f = 1 \text{ at } 1 \leq y \leq y_2, \]  
(25)
where \( y_2 = (R_2/R_1)^2 \).

Taking into account (25), it follows from equation (16) that \( C = 0 \), and therefore \( A = 0 \). Therefore, in the peripheral area of the mixing chamber, as follows from (11), the pressure is constant in height and changes only in the relative radius. Then, according to (19), the pressure profile at any point in the periphery of the mixing chamber takes the form:
\[ \bar{p} = \bar{p}_1 + 1 - \frac{1}{y} + K_2^2 \int_1^y \left( \frac{q}{y} \right)^2 \, dy, \]  
(26)
where \( \bar{p}_1 = \bar{p}(1) \) – point pressure \( y = 1 \).
At a constant \( f = 1 \) at the periphery of the chamber, equation (18) for the tangential velocity can be integrated. To this end, we write (18) as follows:

\[
\int \frac{d\varphi'}{\varphi'} = -0.5F_1 \int \frac{dy}{y}. \tag{27}
\]

After integration, we get:

\[
\varphi' = \varphi'_1 \cdot y^{-0.5F_1}, \tag{27}
\]

where \( \varphi'_1 = \varphi'_1(1) \) – the value of the derivative of \( \varphi \) at the boundary of the peripheral region at \( y = 1 \). The value \( \varphi'_1 \) is determined from the solution of the problem for the central area of the mixing chamber. As a result of repeated integration (27), we find the dependence for the tangential velocity of the two-phase flow at the periphery of the mixing chamber \( 1 \leq y \leq y_2 \):

\[
\text{at } F_1 \neq 2 \varphi = \varphi_2 - \frac{\varphi'_1}{1 - 0.5F_1} \left( y_2^{1 - 0.5F_1} - y^{1 - 0.5F_1} \right), \tag{28}
\]

where \( \varphi_2 = \varphi(R_2) = \frac{v_2 R_2}{v_1 R_1} \) – the value of the relative circulation at the periphery of the mixing chamber.

Expression (28) at \( F_1 \neq 2 \) can be written also by this way:

\[
\varphi = \varphi_2 - \frac{\varphi'_1}{1 - 0.5F_1} \left[ y_2 - y \left( \frac{R_2}{r} \right)^{F_1} \right] \text{at } 1 \leq y \leq y_2, \tag{29}
\]

where according to (27)

\[
\varphi'_2 = \varphi'_1 y_2^{-0.5F_1}. \tag{30}
\]

The obtained expressions for the tangential velocity of the two-phase flow allow integrating the expression (26) for the pressure at the periphery of the chamber. After substituting formula (28) for \( \varphi \) at \( F_1 \neq 2 \), the relation (26) is expressed as

\[
\tilde{p} = \tilde{p}_1 + 1 - \frac{1}{y} + K_1^2 \int_1^{y_2} \left( a + b y^{-0.5F_1} \right)^2 dy, \tag{31}
\]

where

\[
\begin{align*}
a &= \varphi_2 - \frac{\varphi'_1 y_2^{1 - 0.5F_1}}{1 - 0.5F_1}, & b &= \varphi'_1 y_2^{-0.5F_1}.
\end{align*}
\]

After integration, we get:

\[
\tilde{p} = \tilde{p}_1 + 1 - \frac{1}{y} + K_1^2 a^2 \left( 1 - \frac{1}{y} \right) + \frac{2abK_1^2}{0.5F_1} \left( 1 - y^{-0.5F_1} \right) \]

\[
+ \frac{K_1^2 b^2}{F_1 - 1} (1 - y^{-1-F_1}). \tag{32}
\]

Here, the integration is performed at \( F_1 \neq 1 \). As in practical cases solutions for \( F_1 \gg 1 \) are of interest, solutions for \( F_1 = 1 \) and for \( F_1 = 2 \) are not given.

As \( \varphi(1) = 1 \), it follows from (28) :

\[
1 = \varphi_2 - \frac{\varphi'_1}{1 - 0.5F_1} y_2^{1 - 0.5F_1} - \frac{\varphi'_1}{1 - 0.5F_1} = a - b.
\]

It will be shown later that \( \varphi'_1 \) is in most cases less than one, so for \( F_1 \gg 1 \), the parameter \( |b| \ll 1 \), and the value \( a \sim 1 \). Then the last two terms in formula (32) can be ignored and the pressure at the periphery of the mixing chamber is written as:

\[
\tilde{p} = \tilde{p}_1 + (1 + K_1^2) \left( 1 - \frac{1}{y} \right) \text{at } F_1 \gg 1 \text{ and } 1 \leq y \leq y_2. \tag{33}
\]

4. Discussion

Expressions (24), (25), (29) and (32), (33) determine the components \( w, u, v \) of the velocity and pressure \( p \) of the two-phase flow during the homogenization of the dispersed components at the periphery of the mixing chamber. The parameters of the tangential velocity and pressure depend on the value of the derivative \( \varphi'_1 \) at the boundary of the outlet opening of the discharge pipe.

Thus, as a result of using the boundary condition on the upper end cap, the solution of the problem was divided into solutions in two areas: peripheral and central. To determine \( \varphi'_1 \), it is necessary to
solve the system of equations (16), (18) for the central area \( 0 \leq y \leq 1 \). The boundary conditions in this area will be:

\[
\begin{align*}
&\text{at } y = 1 & f &= 1; f' = 0; \varphi = 1, \\
&\text{at } y = 0 & f &= 0; \varphi = 0.
\end{align*}
\] (34)

Equations (16), (18) together with the boundary conditions (34) represent a boundary value problem for a system of two ordinary differential equations. As the radial Reynolds number is \( R_1 \gg 1 \), the equations have a small parameter at the highest derivative. In the numerical solution, these derivatives are determined by dividing the right-hand side by a small parameter, so they can far exceed the values of the functions and the lower derivatives. This leads to a strong swing of the results and their boundless increase. Such equations are known to be called rigid differential equations. As equation (16) depends only on one unknown function \( f \). The function \( f \) determines the radial and axial velocity profiles whose vectors lie in the meridional plane. Due to the presence of a tangential velocity, the two-phase flow does not move in this plane, and it is spatial. After determining the function \( f \), it is possible to solve equations (18) for \( \varphi \), for known \( f \) and \( \varphi \), to integrate equation (19) for pressure and find the velocity and pressure fields for any radius of the mixing chamber.

5. Summary
Scientific results in the field of dispersed powdery materials determine the main directions for improving the method and technology of mixing them together in the production of specific types of products. At the same time, the homogeneity of such systems is the main characteristic of the required quality in the production of modern dispersed materials. A method of numerical simulation of the axisymmetric motion of a two-phase flow in the homogenization chamber of a pneumatic mixer was developed, which allows establishing adequate operating modes of the unit for various dispersed systems mixed in it. The main assumptions in the construction of the mathematical model are also reflected, the conditions for setting the problem for this study are formulated, and the results are obtained in the form of analytical expressions of the main dynamic parameters of the flow with particles for the volume of the mixing chamber, depending on the design features of the pneumatic mixer.

6. References
[1] Klyuev S V, Khezhev T A, Pukharenko Y V, Klyuev A V 2018 Fiber concrete for industrial and civil construction Materials Science Forum 945 120-124
[2] Uvarov V A, Orekhova T N, Gordienko S I, Kachaev A E Continuous pneumatic mixer for the production of dry building mixes Patent of the Russian Federation 102533
[3] Uvarov V A, Orekhova T N, Klyuev S V, Kachaev A E Countercurrent pneumatic mixer for the production of dispersed-reinforced mixtures Patent of the Russian Federation 141488
[4] Orekhova T N, Uvarov V A, Gordeev S I, Kachaev A E Pneumatic mixer for multicomponent dry building mixes Patent of the Russian Federation 115682
[5] Sevostyanov V S, Kachaev A V, Mikhailichenko S A, Sivachenko T L, Farafonov A A 2016 Study of the process of movement of a fibrous suspension in the dispersal node of a wet grinding disintegrator Bulletin of the Belarusian-Russian University 1 60–68
[6] Romanovich A A, Amini E, Romanovich M A 2020 Improving the efficiency of the material grinding process IOP Conference Series Materials Science and Engineering 012060
[7] Romanovich L G, Chekhovskoy E I 2018 Determination of rational parameters for process of grinding materials pre-crushed by pressure in ball mill IOP Conference Series Materials Science and Engineering 042091
[8] Timoshenko V I, Knyshenko Yu V, Lyashenko Yu G, Deshko A E 2008 Method of experimental substantiation of technological parameters of devices with the use of a gushing layer Science and innovations 4(2) 21–32
[9] Smulsky I I 1983 Weighed layer of particles in a cylindrical vortex chamber Journal of applied chemistry 8 1782–1789
[10] Bogdanov V S, Ilyin A S, Nesmeyanov N P 2004 Processes of grinding and classification in cement production ASV 199

Acknowledgements
This work was realized in the framework of the Program of flagship university development on the base of the Belgorod State Technological University named after V G Shukhov, using equipment of High Technology Center at BSTU named after V G Shukhov.