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Theoretical basis for the calculation of energy parameters of a paddle mixer with high-speed operation

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Abstract. The article touches upon the issues related to the obtaining dry modified building mixes in a paddle mixer of forced action with a high level of power impact on the mixed components and with a minimum consumption of power resources. The analysis of modern structures of paddle mixers of forced action is given. The promising directions for their improvement are provided. An improved structure of a high-speed mixer with a vertical shaft and a fixed drum is presented. The description of the principle of a mixer is given. The dependence for calculating the total power of a high-speed blade mixer taking into account its structural and technological parameters is obtained. The analysis of the results of experimental studies is given, which allows evaluating the influence of the structural parameters of a mixer on the specific power consumption. The obtained results confirm the effectiveness of the proposed structure of a paddle mixer with a high-speed mixing mode for obtaining high-quality dry modified building mixes with minimal power consumption.

1. Introduction
Nowadays dry building mixes (DBM) are one of the most promising building materials. Such mixes are able to provide high quality of performed work, their effectiveness and high speed, reduce the labor intensity of production, improve the stability of physico-mechanical characteristics of the finished product and reduce the cost of transportation and storage [1]. For the preparation of DBM it is necessary to use components that provide the desired technological and operational properties, both at the stage of application and at the stage of the finished product [2, 3]. Taking into account the variety of existing formulations and complex modified compositions of dry mixes, the mixing stage can be considered the most crucial stage in production, since it is here that the uniform distribution of all the initial components in the total volume of the prepared mixes should occur. Consequently, in order to solve all the tasks in the way of obtaining high-quality modified building dry mixes, it is necessary to use mixing equipment, which allows providing the mixture with all the declared characteristics [4, 5, 6].

2. Methods and materials
The analysis of structural and technological parameters of paddle mixers of forced action showed that the optimization of mixing of dry building mixes mainly concerns the structure of mixing devices and various schemes for their use [2, 5, 7, 8]. At modern enterprises, where the technological line provides the use of mixing equipment according to the dry mixing method. The various types of mixers are used: ribbon, drum horizontal, rotary, etc.

   As experience has shown, fast and high-quality mixing is achieved in mixing equipment using the

principle of converting bulk material into a fluidized state using a fast-rotating vertical rotor [1, 2, 4, 6]. In order to increase the efficiency of the mixing process of dry components and, first of all, improve the quality of the homogeneity of obtained mixture, a paddle mixer of forced action with a vertical blade shaft is proposed, protected by the Russian Federation patent for a useful model [9].

The mixer (figure 1) for bulk materials mixing consists of a cylindrical drum 1 installed in the support element 10, which is fixed to the base 12. There is a hatch in the lower part of the drum, which is used to unload mixes and is closed by the cover 8 with the help of the lever 14.
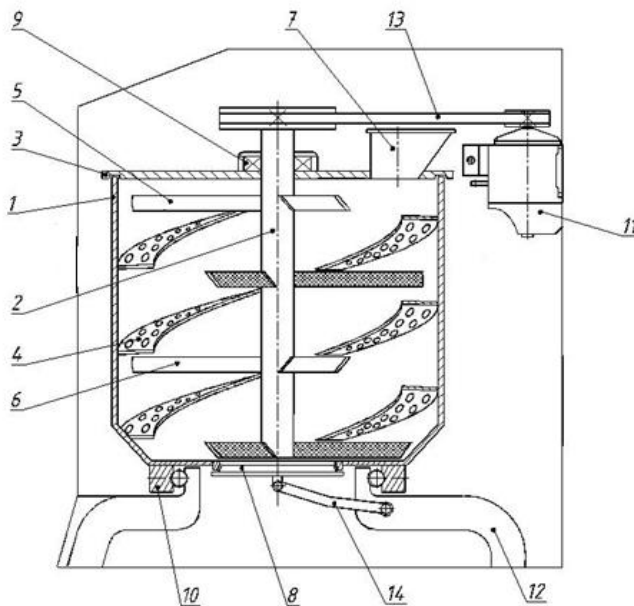
Figure 1. Paddle mixer of forced action for dry mixes: 1 – drum; 2 – vertical shaft; 3 – fixed cover; 4 –spiral surfaces of drum blades; 5 – top row of the blades of vertical shaft; 6 – vertical shaft blades; 7 – bulk loading spout; 8 – unloading cover; 9 – bearing unit of vertical shaft; 10 – drum support; 11 – electric motoe; 12 – the base of /a mixer; 13 – vee belt transmisssion; 14 – lever.

A vertical shaft 2 is installed inside the cylindrical drum 1, which is fixed in the bearing assembly 9 of the fixed cover 3. On the shaft, in each of the rows, three blades are installed 6, rotated relative to each other by 120 º. At the same time, the adjacent blades of each row are rotated relative to each other by 60 °. The shape of the ends of the blades of the lower row of vertical shaft is similar to the shape of the bottom of mixer drum, and the blades 5 of the last (upper) row have a reverse angle of installation relative to the blades of lower rows. Mounted in a spiral crew, the surfaces of the blades of the drum 4 are rigidly fixed on the inner wall of the mixing drum 1.

They are made in the form of a three-way helical spiral with discontinuities in the surfaces of rotation of the blades of vertical shaft (figure 1). These screw surfaces of the drum blades have a perforated working surface with aperture size 5–7 times bigger than the particles of mixed components. A mixer for bulk materials mixing works as follows: the mixed components are loaded through the spout 7, installed on a fixed cover 3 in the upper part of the mixing drum and geting inside it, where under its own weight they fall down and accumulate in the bottom of the drum 1.

As a result of the rotation of vertical shaft 2, its blades 6 of each row except the top one, throw mixed components on the top row of screw perforated surfaces of the blades 4 of a drum 1, spiral-mounted on its inner surface. This allows the mixes to move not only horizontally, but also, in vertical directions which is very important.

Once the part of mixes is on the screw surfaces of the blades of the drum 4, it moves up and is dropped from the blades, and the rest spills out of the formed stagnant zones through the holes on the working surface of the drum blades, which are 5-7 times larger than the particle size of the mixed components. Thus, the mixes reach the upper part of the drum 1 of the mixer, where the blades 5, having a reverse installation angle relative to the blades of the lower rows of the vertical shaft, "cut off" the upward-moving mixes from the perforated drum blades of the last (upper) row and direct it down towards the main flow. After unloading the mixer through the cover 8, the process is repeated.

The intense nature of the movement of material on the perforated surface of the blades of the mixer drum provides the creation of additional circulation flows of the movement of the components of mixes from the stagnant zones of the mixer.

Thus, the proposed structure of the mixer with a high-speed mode of bulk materials mixing will improve the quality of the mixes and increase the degree of unloading of the finished product due to the flow and multiple trajectories of particles of material, contributing to the movement of the components of the mixes in horizontal and vertical directions inside the mixer drum.

3. The theoretical basis for the determination of the power parameter of the mixer

According to the literature sources [1, 7], when the values of the circumferential rate of rotation of the blade are about 4-5 m / s, the material converts into a fluidized state, which is characterized by the formation of a funnel around a vertical shaft located in the center of the cylindrical body of the mixer. The particle of the material mix, at the same time, begins to circulate inside the cylindrical body of the mixer as a result of the impact of blades on it. The lower layers of the material begin to move upward near the inner surface of the cylindrical body, and the upper layers of material particles along spiral trajectories begin to move around the vertical shaft and then drop down along the surface of the funnel to the central shaft. Based on the above mentioned facts, it is possible to make the conclusion that the vortex motion of the particles of mixes is formed in the upper layers of the material.

The total power of the paddle mixer necessary for mixing the particles of the material will consist of the power expended to maintain the high-speed mode of the mixes in the zone of vortex motion N_v power, which is consumed in order to overcome the forces of resistance to the motion of the blade N_b [1, 4, 9, 10].

To calculate the power of the vortex motion in the funnel zone, we use the equatation:

$$E = 2 \cdot \pi \cdot \alpha \cdot U_0^2 \cdot (H_{max} - Z_0) \int_0^{R_{vor}} \left(\frac{d\theta}{dr}\right)^2 r dr. \tag{1}$$

In the integral expression (1), we change the integration over the variable r to integration over the angle θ according to the equatation:

$$dr = \frac{dr}{d\theta} \cdot d\theta = \frac{r}{sin\theta} \cdot d\theta . \tag{2}$$

Substituting (2) with (1) leads to the following result:

$$E = 2 \cdot \pi \cdot \alpha \cdot U_0^2 \cdot (H_{max} - Z_0) \cdot \int_{\frac{\pi}{\pi}}^{\frac{\pi}{2}} \frac{sin^2\theta}{r^2} \cdot \frac{r}{sin\theta} \cdot r d\theta =$$

$$= 2 \cdot \pi \cdot \alpha \cdot U_0^2 \cdot (H_{max} - Z_0) \cdot \int_{\pi}^{\frac{\pi}{2}} sin\theta d\theta = 2 \cdot \pi \cdot \alpha \cdot U_0^2 \cdot (H_{max} - Z_0). \tag{3}$$

Ratio (3) can have the following form:

$$E = 2\pi \cdot \frac{\gamma_0 \cdot V_{vor}}{k} \cdot \frac{(H_{max} - Z_0)}{R_0} \cdot U_0^2 \tag{4}$$

where the volume of material involved in the vortex motion of the material is determined by the following equatation:

$$V_{vor} = \pi \cdot R_k^2 \cdot (H_{max} - Z_0) - V_в . \tag{5}$$

The transformations (5) lead to the relation:

$$E = 2 \cdot \pi \cdot \frac{\gamma_0 \cdot V_{vor}}{k} \cdot \frac{(H_{max} - Z_0)}{R_0} \cdot \left[\omega^2 \cdot (a + L)^2 \cdot \left(1 + \frac{1}{4 \cdot f_0^2}\right) - 2 \cdot g \cdot Z_0\right]. \tag{6}$$

Using the equatation (6), we find the expression for the amount of power required to maintain the vortex motion of the particles of the mixes during high-speed mixing:

$$N_v = 2 \cdot \pi \cdot \frac{\gamma_0 \cdot V_v}{k} \cdot \frac{(H_{max} - Z_0)}{R_0} \cdot \omega \cdot \left[\omega^2 \cdot (a + L)^2 \cdot \left(1 + \frac{1}{4 \cdot f_0^2}\right) - 2 g Z_0\right]. \tag{7}$$

The power N_b required to overcome the forces of resistance to the motion of the mixer blade will be composed of the power N_1 used to overcome the resistance force exerted by the mixes material pressure on the blade surface, power N_2 used to overcome the friction resistance along the inner side surface of the cylindrical body due to the pressure by centrifugal force F_c, the power N_3, used to overcome the shear resistance of the mixes of material relative to the mixes located above the blade, and of N_4 – the power used to overcome the friction resistance on the bottom of the cylindrical body when moving the blade of the material [9, 10]:

$$N_b = N_1 + N_2 + N_3 + N_4. \tag{8}$$

The target value of the power N_1 will be determined by the following expression:

$$N_1 = f_0 \cdot Q \cdot v_r = \frac{f_0 \cdot m_l \cdot g}{\sin \alpha} \cdot v_r, \tag{9}$$

Let us calculate the mass of the material mixture m_l, moving the blade in a cylindrical coordinate system:
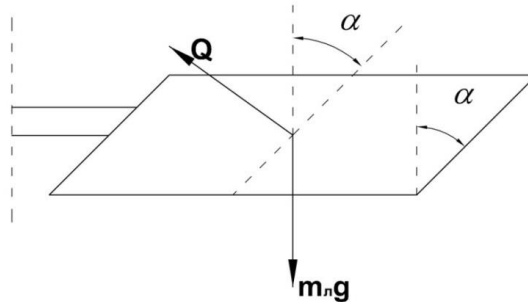
$$m_l = \frac{\gamma_0}{k} \cdot \int_0^{2\pi} d\chi \int_0^{h \cdot \cos \alpha} dZ \int_0^L r dr = \frac{\pi \cdot \gamma_0}{k} \cdot h \cdot \cos \alpha \cdot (L^2 - a^2), \tag{10}$$

where h - the height of the blade; α - the angle of deviation of the blade from the vertical line.

In order t calculate the power N_1, we turn to the structural model presented in figure 2. According to the presented scheme we find:

$$Q \cdot \sin \alpha = m_l \cdot g, \tag{11}$$

where Q - the value of the pressure exerted on the blade by the material being mixed.

Figure 2. The structural model for the determination
of the forces influencing the blade

Substituting (11) with (9) leads to the following result:

$$N_1 = \frac{\pi \cdot \gamma_0}{2 \cdot k} \cdot h \cdot (L^2 - a^2) \cdot (L + a) \cdot \omega_0 \cdot g \cdot ctg\alpha. \tag{12}$$

According to the definition the value of the power N_2 will be calculated through the following expression:

$$N_2 = f_0 \cdot F_c \cdot \omega_0 \cdot (L + a), \tag{13}$$

thus

$$F_c = \frac{m_{\text{л}} \cdot \omega_0^2 \cdot (L+a)^2}{L+a} = \frac{\pi \cdot \gamma_0}{k} \cdot h \cdot (L^2 - a^2) \cdot (L + a) \cdot \omega_0^2 \cdot \cos \alpha. \tag{14}$$

Taking into account (14), (13) the expression has the following form:

$$N_2 = \frac{\pi \cdot f_0 \cdot \gamma_0}{k} \cdot h \cdot \omega_0^3 \cdot (L^2 - a^2) \cdot (L + a)^2 \cdot \cos \alpha. \tag{15}$$

Let us find the expression that determines the value of power N_3:

$$N_3 = A_3 \cdot \omega_0 = \frac{L \cdot h \cdot \gamma_0 \cdot g \cdot \omega_0}{4 \cdot k} \cdot (L^2 - a^2) \cdot \cos \alpha. \tag{16}$$

The volume of work necessary to overcome the resistance of force will be determined by the following equatation:

$$A_3 = \int_a^L F_r dr = \frac{L \cdot h \cdot \gamma_0 \cdot g}{2 \cdot k} \cdot \cos\alpha \int_a^L r dr = \frac{L \cdot h \cdot \gamma_0 \cdot g}{4k} \cdot (L^2 - a^2) \cdot \cos\alpha. \qquad (17)$$

If we denote the value of the shear (tangential) stresses that occur in the bulk material at a distance r from the axis of rotation through $\tau(r)$, the values of these stresses can be determined on the basis of the Jansen ratio [1, 10]

$$\tau(r) = \frac{1}{2} \cdot \frac{\gamma_0 \cdot g}{k} \cdot r, \qquad (18)$$

then the value of resistance force F_r of the material shift by the blade will be equal to:

$$F_\tau = h \cdot L \cdot \cos\alpha \cdot \tau(r) = \frac{L \cdot h \cdot \gamma_0 \cdot g}{2k} \cos\alpha \cdot r. \qquad (19)$$

The value of the power N_4 we find according to the ratio:

$$N_4 = f_0 \cdot m_l \cdot g \cdot \bar{v}_{ok}, \qquad (20)$$

where $\bar{v}_{cr}$ is the average value of the circumferencial rate of the blade, which is determined according to the expression:

$$\bar{v}_{cr} = \frac{\omega_0}{L+a} \int_a^L r dr = \frac{\omega_0}{2} \cdot \frac{(L^2 - a^2)}{L+a}, \qquad (21)$$

Substituting (21) with (20) with regard to (9) leads to the following result:

$$N_4 = \frac{1}{2} \cdot f_0 \cdot \frac{\pi \cdot h \cdot \gamma_0 \cdot g \cdot \omega_0}{k} \cdot \frac{(L^2 - a^2)^2}{L+a}. \qquad (22)$$

The total power of the high-speed paddle mixer is determined by:

$$N_0 = N_v + N_b, \qquad (23)$$

where N_v –the power used to maintain the high-speed mode of the mixes in the zone of vortex motion; N_b –the power used to overcome the forces of resistance to the motion of the blade.

If there are *n* blades on the shaft, then the total power N_0 used to drive a material in high-speed blade mixer will be defined by the following expression:

$$N_0 = N_v + \psi_b \cdot n \cdot (N_1 + N_2 + N_3) + N_4, \qquad (24)$$

where ψ_b –coefficient taking into account the mutual influence of the blades on each other during their movement.

Thus, the obtained relation (24) determines the total power of the high-speed paddle mixer, depending on its structural and technological parameters.

4. Experimental research
In order to carry out experimental studies of the influence of constructive and technological parameters of the mixer on the power indices of the mixing process, the following factors were chosen as variable ones [10]:

- Rotary velocity of the vertical shaft, min^{-1}
- The angle of the blade on the vertical shaft relative to the vertical plane (blade angle of attack), degrees;
- Cross section value of the screw surface of the drum blades, %.

As the response functions, which reflect the technical and economic performance of the mixer and the quality of the products in the most prominent way, we choose:

- Specific power consumption, kWh / t (q);
- Coefficient of heterogeneity of the resulting dry mix, % (V_C);
- Resistance to direct pull, Mpa (σ_o).

In order to analyze the changes in the specific power consumption of the mixer, on the basis of statistical processing of the results of experimental studies, a regression equation in natural form was obtained [10]:

$$q = -18.14325 + 0.0009 \cdot \alpha^2 - 0.0019 \cdot \alpha \cdot C -$$
$$-0.0003 \cdot \alpha \cdot n_p + 0.1867 \cdot \alpha + 0.00125 \cdot C^2 -$$
$$-0.00015625 \cdot C \cdot n_p + 0.0824375 \cdot C -$$
$$-0.00003125 \cdot n_p^2 + 0.0545625 \cdot n_p \tag{25}$$

The analysis of the graphs (figure 3 a, b) at different angles of installation of the blade on the vertical shaft (19, 25, 35, 45 and 51º) of the mixer showed that:

1. When the angles of installation of the blades, varying in the range of 19 ... 25º, the graphs (figure 3 a) have an increasing character. With the increase in the shaft rotary velocity by about 1.5 times (470 ... 630 min-1), the specific power consumption increases 4 times with the cross section of the spiral drum blade of 30 ... 46 % and 2 times with the cross section values 14 ... 20 %, reaching a maximum value of 4.9 kWh / t. It can be explained by the high resistance of the movement of the mixing material and the weak movement of the material from the layer to the layer through the holes in the screw surface. The minimum values q = 1-2.4 kW · h / t with n_p = 470 min^{-1} are explained by the fact that at low speeds of the shaft there will be less resistance of the medium and friction force.

2. With the increase in the installation angle of the blade to 35 ... 45° (figure 3, b), they are of an increasing and decreasing nature and a slight decrease in the specific energy consumption is noticeable.

The maximum values of the response function q at n_p = 550 min^{-1} are 4.3–2.8 kW h / t in the range of cross section values of the spiral surface of 14–46 %. Moreover, the minimum values of specific energy consumption are observed at n_p = 630 min^{-1}, which is about 2 times less than at the angle of attack of the blades of 19º-25º. It can be explained by the decrease in resistance and a large displacement of material from layer to layer due to the formation of a trace that occurs at a sufficiently high frequency of rotation of the blade shaft, and when centrifugal forces influencing the particles of the material prevail over their gravity forces, which ensures fluidization of the mixes. When increasing the angle of the blade shaft to 51º, the graphs are decreasing in nature, which can be explained by the increase in friction forces.
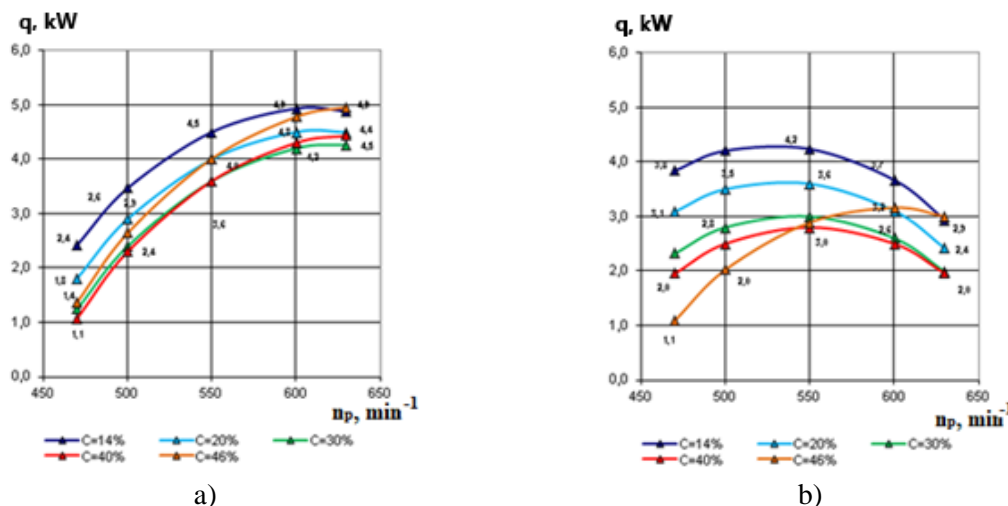
Figure 3. The graphs of changes in the specific energy consumption q depending on the frequency of rotation of the blade shaft n_p at fixed values of the angle of attack of the shaft α: a) where α=19-25°; b) where α=35-45°.

The analysis of the graphs (figure 4) at a fixed value of the cross section of the spiral surface of 14, 20, 30, 40 and 46 % showed that:

1. For the all fixed values of the cross section at the angles equal to 19°, 25°, 35° values have increasing nature, and at angles equal to 45°, 51° they decrease.
2. The minimum values of the specific power consumption obtained at np = 470 min^{-1}.
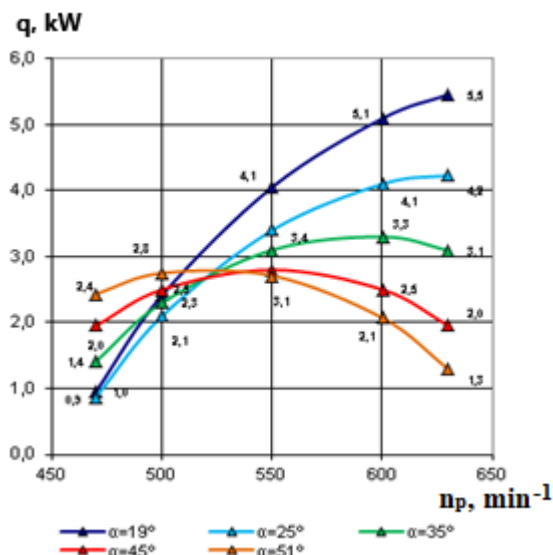
Figure 4. The graph of specific energy consumption **_q_** from the frequency of rotation of the blade shaft **_n_**$_\mathbf{p}$ at a fixed value of the cross section of the spiral surface of the blades of the drum **_C_**.

5. Conclusion

Thus, the minimum specific power consumption (figure 3, figure 4) with the value of cross section, varying within 30-46 %, is equal to:

- 0.9-1.2 kW · h / t at n_p = 470 min^{-1} and the angle of installation of the blades 19°-25° (at low rates of rotation of the shaft will be less than resistance to the movement of the medium);
- 1.2-1.5 kW · h / t at n_p = 630 min^{-1} and blade attack angle equal to 51° (at high rates of the shaft, the blades start cutting the material into layers, and the fluidized state of loading additionally reduces friction forces).

The proposed method for the calculation of total power of a paddle mixer with a high-speed mode of operation for obtaining dry modified building mixtures allows determining its rational structural and technological parameters at minimal power consumption.

6. Acknowledgments

References

[1] Gorshkov P S 2013 *Rotary Spiral-Blade Mixer of Periodic Action,* PhD thesis, Belgorod, pp 10-112, 169
[2] Bullard J W 2003 Annual Report 1-39
[3] Park K B 2006 *Cement and Concrete Research* **36 (8)** 728-734
[4] Bogdanov V S, Bogdanov D V, Antsiferov S I, Gorshkov P S and Matusov M G 2014 *Int. J. of Applied Eng. Res.* **22(9)** 15777-89
[5] Hu J and Stroeven P 2006 *Image Anal. Stereol.* **25** 43-53
[6] Stroeven P, Sluys L J, Guo Z and Stroeven M 2006 *Forma* **21** 227-242
[7] Makarov Yu Y 1973 *Equipement for Mixing Bulk Materials* (Moscow: Engineering) pp 180-199
[8] Bazhenov Yu M, Korovyakov V F and Denisov G A 2003 *ABC* 1-95
[9] Bogdanov V S, Gorshkov P S, Nesmeyanov N P and Brazhnik Yu V 2013 *Bulletin of BSTU*

named after V. G. Shukhov [in Russian – Vestnik BGTU im. Shukhova] **4** 62-64

[10]   Brazhnik Yu V 2017 *Improving the Design and Process of Mixing in the Lobed Mixer with High Speed Mode,* PhD thesis, Belgorod, pp 5-146, 194