Optimization of the hopper design parameters with a controlled technological process of loading, storage and unloading of bulk materials

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Abstract. The subject of the study is the process of loading capacities and bodies of vehicles to increase the usable volume and static load for further storage or transportation. Based on an analysis of the mechanization of loading operations at agricultural facilities related to the production, distribution and use of animal feed, the authors identified the most promising loading scheme based on the principle of intensive dispersed flow, outlined ways to improve the loading of grain materials and animal feed, proposed a new structural and technological scheme of a loading device with a drive using the gravitational flow of bulk material to evenly distribute the flow of bulk material over a significant cross-sectional area of the tank. The article presents theoretical studies of the loading process using the proposed device and substantiates its geometric parameters. There are results of experimental studies that confirm theoretical conclusions and allow comparing the proposed device with existing analogues.

1 Introduction

Modern storages of bulk products and materials in agricultural production are highly mechanized warehouse complexes based on hoppers, silos installed separately or grouped among themselves in various configurations and combined with automated systems for warehousing, production and control of technological processes. In the presence of a significant difference in the physicomechanical properties of grain, as well as feed components, common problems occur due to the technology of warehousing, storage, production, and cleaning of the enclosing structures of storage facilities [1].

First, this refers to the formation of arches and caking of materials stored in hoppers and silos. The increase in the connectivity of bulk materials increases the problems of arching and caking, and the question arises of the appropriateness of storing some bulk materials in silos and hoppers. Known storage techniques in hoppers and silos may not always be applicable for economic, technical and technological reasons. These include the drying, granulation and periodic movement of contents from one store to another with a cycle of the last operation of 5-7 days or more [2]. Each of the above operations leads to a significant expenditure of material, energy and cash. This is especially true for bulk materials with increased connectivity.

Thus, the issue of solving and preventing the problems that arise during the long-term storage of bulk materials in hoppers and silos and affect the entire set of sequential operations of the technological process is relevant.

2 Objects and research methods

Considering the above information, for the stable and reliable functioning of storage facilities, we propose to use a new hopper-type storage facility with a controlled technological process of loading, storing and unloading bulk material [3, 4]. The advantage of this hopper is that during storage the sieves are not removed from it and serve to form arches and as pressure switches arising in bulk material during storage. Each sieve in the bunker divides it into sectors with the minimal pressure inside.

3 Results

The loading method especially affects the storage process [5]. So, the pressure arising in the tank directly depends on the method of loading: the uniform distribution of pressure over the height of the tank affects the uniformity of the outflow of material in the tank from it. The main factors determining the optimal operation of the device for controlling the technological process of loading, storage and unloading include the angle of inclination of the sieve β (x_1), the width of the slit in the sieve a (x_2), the length of the sieve l (x_3) and the installation interval between sieves h_p / B (x_4). The installation interval between sieves h_p / B is a dimensionless quantity, where h_p is the distance between the sieves, and B is the width of the hopper. We will use

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the theory of a multifactor experiment to obtain a general mathematical dependence of the generalized criterion for assessing the quality of loading on significant process factors [6]. Table 1 shows the factors affecting the process of loading bulk materials into hoppers.

Table 1. Factors affecting the boot process

Factors	Symbol.	Code	Levels of factors			Range of variation
			- 1	0	+ 1	
Angle of inclination of the sieve, deg.	β	x_1	35	45	55	10
Width of the slit in the sieve, mm	*a*	x_2	5	15	25	10
Length of the sieve, cm	*l*	x_3	25	35	45	10
Installation interval between sieves	h_p/B	x_4	1	2	3	1

To optimize the kinematic mode, we use a generalized optimization criterion that considers the above performance indicators of the loading complex. The generalized evaluation criterion is determined by the formula:

$$E = \mathrm{K}_p * \left(\frac{q_{pi} - q_{po}}{q_{po}} \right)^2 + \mathrm{K}_c \left(\frac{q_{ci} - q_{co}}{q_{co}} \right)^2 \qquad (1)$$

where q_{pi}, q_{ci} are the experimental uniformity and segregation coefficients, respectively; q_{po}, q_{co} are optimal coefficients of uniformity and segregation, respectively; K_p, K_c are significance factors (0.3 and 0.7, respectively).

We processed the results of experimental studies using the Statistica program [7]. The data obtained after the experiments in accordance with the planning matrix allow us to obtain the regression equation (in decoded form), which is the dependence of the generalized load quality criterion *E* on the four required factors for a particular material:

- for zeolite:

$$E = -0{,}42 + 0{,}02 \cdot \beta + 0{,}3 \cdot a + 0{,}02 \cdot l - 0{,}17 \cdot h - 0{,}0006 \cdot \beta \cdot a -$$
$$- 0{,}0008 \cdot \beta \cdot l - 0{,}003 \cdot \beta \cdot h - 0{,}01 \cdot a \cdot l + 0{,}27 \cdot a \cdot h - 0{,}016 \cdot l \cdot h -$$
$$- 0{,}005 \cdot \beta \cdot a \cdot h - 0{,}003 \cdot a \cdot l \cdot h + 0{,}0002 \cdot \beta \cdot l \times h + 0{,}0005 \cdot \beta^2 -$$
$$- 0{,}055 \cdot a^2 + 0{,}0003 \cdot l^2 + 0{,}143 \cdot h^2 \qquad (2)$$

- for bran:

$$E = 0{,}3549 - 0{,}0386 \cdot \beta - 0{,}0473 \cdot a + 0{,}1176 \cdot l - 0{,}3735 \cdot h -$$
$$- 0{,}0022 \cdot \beta \cdot a - 0{,}0074 \cdot a \cdot l - 0{,}0073 \cdot a \cdot h - 0{,}0071 \cdot l \cdot h -$$
$$- 0{,}0662 \cdot a^2 + 0{,}1196 \cdot h^2 \qquad (3)$$

- for meal:

$$E = 0{,}68 - 0{,}0003 \cdot \beta + 0{,}1 \cdot a + 0{,}01 \cdot l - 0{,}2 \cdot h + 0{,}0004 \cdot \beta \cdot a -$$
$$- 0{,}0001 \cdot \beta \cdot l + 0{,}0022 \cdot \beta \cdot h - 0{,}003 \cdot a \cdot l + 0{,}08 \cdot a \cdot h - 0{,}005 \times$$
$$\times l \cdot h - 0{,}002 \cdot \beta \cdot a \cdot h + 0{,}0002 \cdot a \cdot l \cdot h + 0{,}00041 \cdot \beta^2 - 0{,}022 \times$$
$$\times a^2 + 0{,}07 \cdot h^2 \qquad (4)$$

Solving equations 2, 3, 4, we find the desired parameters: $\beta = 36^0$, a = 0.8 cm, l = 27.4 cm, h_p / B = 2.8 for zeolite; β = 38^0, a = 1.2 cm, l = 25 cm, h_p / B = 2.5 for bran; $\beta = 36.4^0$, a = 1.1 cm, l = 19 cm, h_p / B = 2.3 for meal.

Based on the obtained equations (2, 3, 4), we plot the dependence of the generalized criterion for assessing the quality of the load on the angle of inclination of the sieve □, on the width of the slit in the sieve *a*, on the length of the sieve *l* and the installation interval between sieves - h_p / *B*, (Fig. 1, Fig. 2, Fig. 3, Fig. 4).

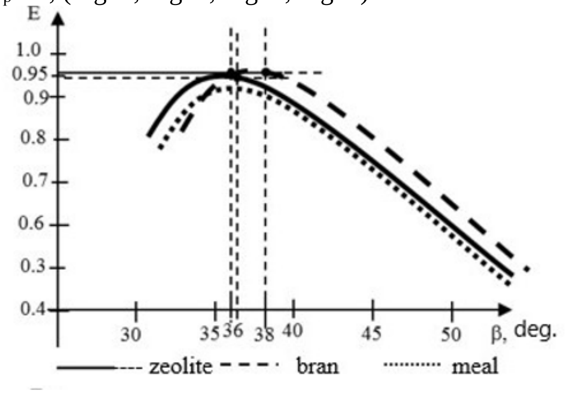

Fig. 1. Dependence of the generalized loading quality assessment criterion on the angle of inclination of the sieve.

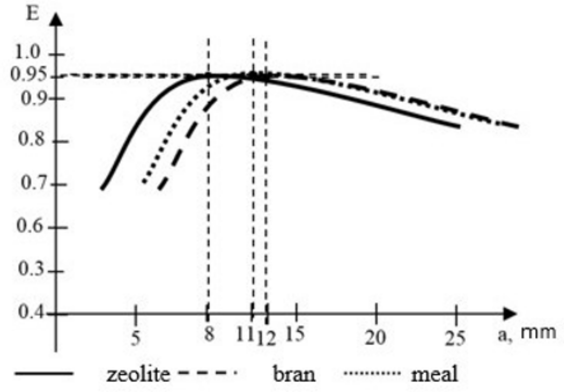

Fig. 2. Dependence of the generalized loading quality assessment criterion on the width of the sieve slit:

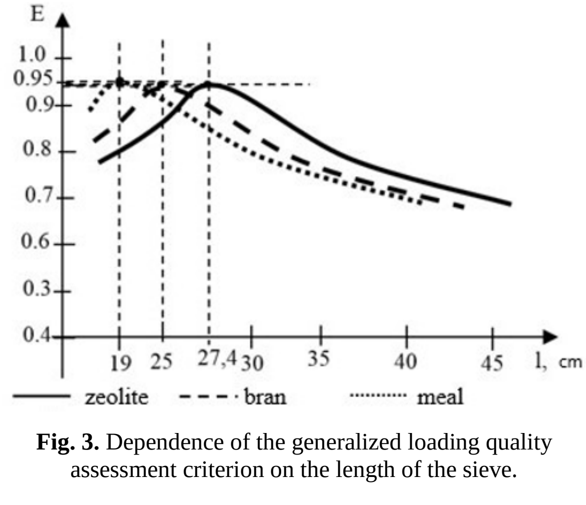

Fig. 3. Dependence of the generalized loading quality assessment criterion on the length of the sieve.

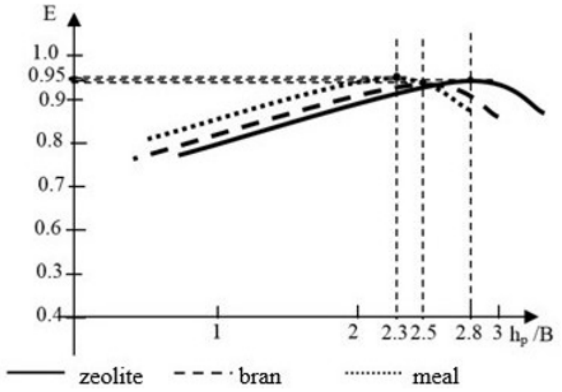

Fig. 4. Dependence of the generalized loading quality assessment criterion on the interval of installation of sieves.

These graphs show that for optimal loading parameters and stable tank operation it is necessary to provide the following optimal design parameters: for zeolite, the angle of inclination of the sieve is 36^0, the slit width in the sieve - 0.8 cm, the length of the sieve - 27.4 cm and the installation interval between sieves - 2.8; for bran, the angle of inclination of the sieve is 38^0, the width of the slit in the sieve - 1.2 cm, the length of the sieve - 25 cm, the installation interval between sieves - 2.5; for meal, the angle of inclination of the sieve is $36.4\ ^0$, the width of the slit in the sieve - 1.1 cm, the length of the sieve - 19 cm, the installation interval between sieves - 2.3.

We will consider the main factors affecting the functioning of the hopper with sieves during storage. 1. The number of sieves, it depends on the height of the tank and affects the pressure distribution over the height of the tank: uniform distribution of pressure affects the uniformity of production unloading. 2. The ratio of the horizontal section of the tank and the sieve, it must comply with the condition $S_b / 2 \le S_s < S_b$, where S_b is the horizontal sectional area of the hopper, S_s is the horizontal sectional area of the sieve. If this condition is met, the sieve will serve as a support for the formation of arches, thanks to which it will be possible to control the release process. 3. The angle of inclination of the sieve, which affects the shear coefficient.

The geometric shape of the horizontal section of the tank also affects the storage process. If this cross section is rectangular, then the concentration in the tank corners will be stressed, which leads to the material freezing [8 - 12]. Vibration during storage also has a negative effect, compacting the material and impairing its outflow. Temperature conditions additionally affect the storage process.

When the ambient temperature changes, the physicomechanical properties of the stored material also change. For example, with increasing temperature, the meat and bone meal is sintered and forms a monolithic mass. When storing bulk material, vaulting occurs with increasing horizontal pressure. Static vaults arising during storage adversely affect the release of bulk material. In turn, the element of the loading device serves as a support for the formation of arches, but simultaneously its mobility allows adjusting the release of material from the tank. It is enough to lower the element of the loading complex by only 1 degree to start the outflow of material [13, 14]. We used the measuring complex developed at the Voronezh Research Institute of the Feed Industry (VRIFI) to determine the pressures arising in the internal cavity of the storage. It includes pressure sensors, signal converters, an alternating voltage source and a voltmeter (Fig. 5).

Fig. 5. Experimental installation with sensors and measuring complex

The measuring elements of the sensor are two strain gauges glued on both sides of an elastic beam rigidly fixed at one end to the sensor housing. The free end of the beam with the help of a plate with a rod takes up the acting forces from the side of bulk material. Two resistors are mounted in the sensor housing for a balanced bridge. The use of a signal transducer of strain gauge sensors (type PA-1) allows converting pressure into an electrical DC signal, recorded by a voltmeter. As the last, we used the M890G digital multimeter. The compaction of bulk material in the hopper depends on the stress distribution in the absence of lateral expansion. Fig. 6 shows the change in the density of bulk materials from the height of filling it into the tank.

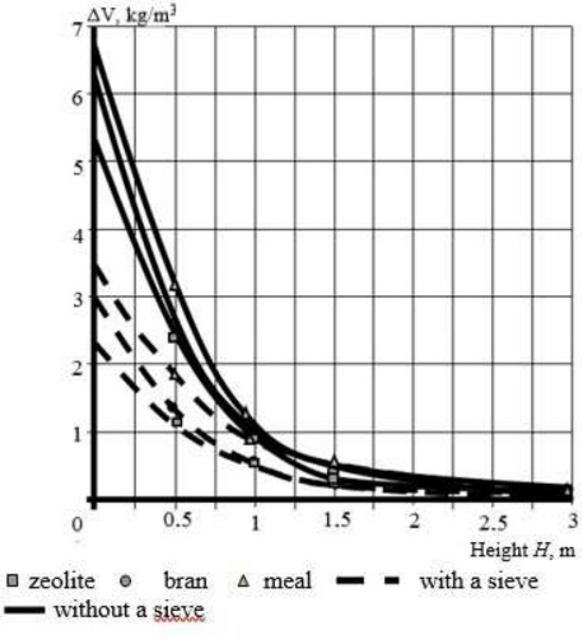

Fig. 6. Change in the density of bulk materials from the height of their filling.

4 Discussion

From the above dependence (Fig. 6) it follows that the compaction of bulk materials in the hopper directly depends on the height of their backfill: with an increase in the backfill height *H*, the density in the lower layers of the material increases. We also need to note that the density of materials during storage with a sieve changes significantly less and is 3.5 kg / m^3, 3 kg / m^3 and 2.35 kg / m^3 for meal, bran and zeolite, respectively. When stored without a distribution sieve, the density of these materials changes by 6.85 kg / m^3, 6.4 kg / m^3 and 5.35 kg / m^3, respectively. Since zeolite is a well bulk material and has a smooth particle surface, it is practically not compacted during storage. This material fills the required volume, which does not change significantly with time.

Therefore, the compaction of the material is markedly reduced when using a sieve, which is also a pressure switch. Therefore, the use of distribution sieves ensures uniform and stable release of materials after long-term storage. Fig. 7,8 show the horizontal stresses measured in various sections of the hopper. We took the angle of inclination of the sieves, the length of the sieve, the width of the slit in the sieve, and the distance between the sieves as optimal in accordance with the results of our studies [15 - 19].

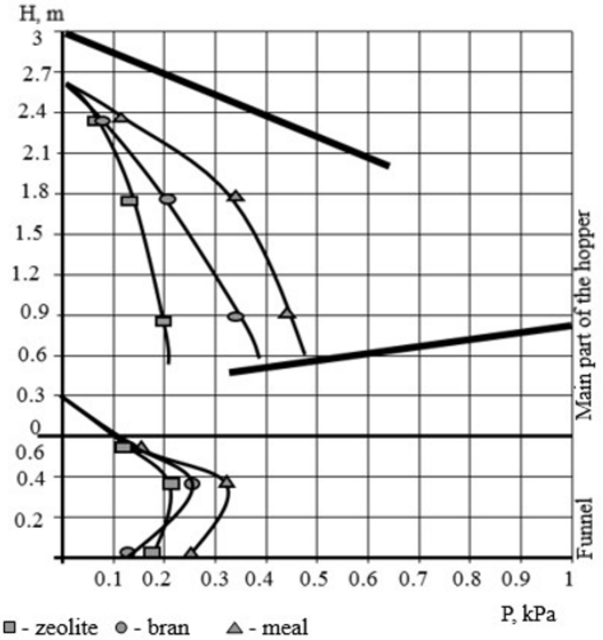

Fig. 7. Dependence of horizontal pressure on the height of the tank with a sieve.

Increasing the filling height of the tank leads to exponentially increasing the vertical pressure within the bulk material column. Horizontal stresses arising in the hopper are directly dependent on vertical ones. At the same time, the coefficient of internal friction of the material has a special effect on their ratio. During storage of bulk material, horizontal pressure can reach a critical value. This results in the formation of static arches in the hopper, which lead to compaction of the material. This, in turn, causes freezing of the bulk material and increasing energy costs for unloading and deterioration in the quality of the stored material. We have previously indicated that static arches are mainly formed at the junction of the main tank with the discharge funnel, where the horizontal pressure is maximum, as shown in Fig. 8.

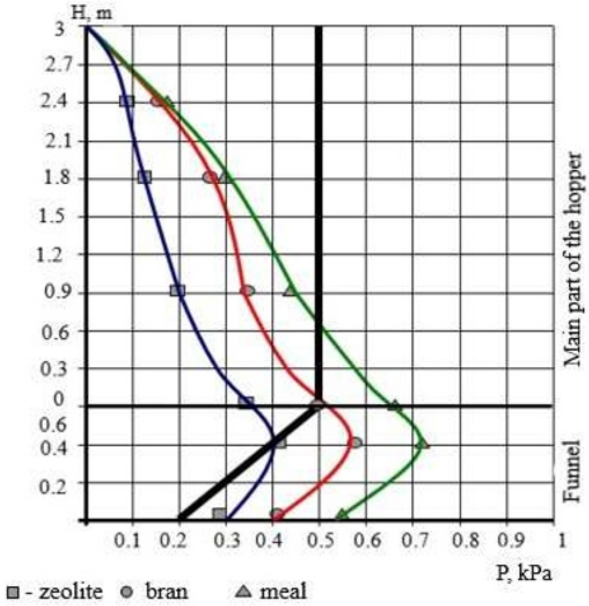

Fig. 8. Dependence of the horizontal pressure on the height of the tank without a sieve.

This fact is due to the different density of bulk material along with the height of the hopper. It is necessary to reduce both horizontal and vertical pressure to exclude static arches. The use of sieves in the device for controlling the technological process of loading, storage and unloading allows achieving this effect, as shown in Fig. 7. The sieves remove part of the load from bulk material and ensure its stable unloading from the hopper.

The sieves in the proposed hopper for controlling the technological process of loading, storage and unloading are pressure stabilizers. This will allow storing grain, feed or other bulk materials for the required period without losing their quality, which reduces the cost of material, energy and money during storage and unloading of such materials.

5 Conclusion

Experimental studies of the hopper with a controlled technological process of loading, storage and unloading made it possible to determine the optimal design parameters of the proposed storage for various materials, considering their physical and mechanical properties. Using a repository with optimized parameters allows for long-term storage of bulk materials without loss of quality, and subsequently their stable unloading.

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