Justification of the parameters of the system for removing ammonia from the pig-breeding module

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Abstract. The issues of selecting parameters and operating modes of a system designed to remove ammonia from a pig-breeding module are considered. The aim of the work was to justify the scheme of the suction device layout of exhaust ventilation, which ensures the removal of ammonia from the animal keeping area at the lowest energy costs and maximum economic effect. The analysis of the effect of gases on the animal organism is carried out. The parameters of the exhaust ventilation system at the maximum air exchange in the pigsty are determined, taking into account the constantly changing parameters of the outdoor air and animal groups. Mathematical models are proposed that describe the dependences of changes in the radius of the spectrum and the active absorption front on the geometric and kinematic parameters of the harmful gas removal system. The method of comparing the layout of the suction pipes was used to identify the most effective scheme for removing ammonia from manure channels. The energy costs of using exhaust systems are determined. A technical and economic assessment of the proposed layout options for suction devices is given. Various layout options for suction devices are considered. Dependencies between the geometric and kinematic parameters of the system are established. Based on the feasibility study, the scheme of the ammonia removal system that provides the greatest economic effect is determined. The results can be used in the development of ammonia removal systems from pig-breeding facilities. The proposed mathematical models make it possible to determine the most rational arrangement of the suction devices for the most efficient removal of ammonia.

1. Introduction

Today, pig-breeding is one of the few sectors of Russian agribusiness, where the level of profitability is constant, and production is steadily expanding. From 2012 to 2015, the number of pig production in Russia increased from 2559 thousand tons to 2981 thousand tons per year. One of the most pressing problems in pig-breeding is the creation of an optimal microclimate on the farm. At a high concentration of livestock in a confined space, the air is contaminated by ammonia, carbon dioxide, hydrogen sulfide, organic compounds and dust [1, 2]. As a result, the death rate increases, the weight gain and the safety of animals decrease, and cannibalism phenomena occur [3]. The effect of harmful gases on the animal’s body is shown in Figure 1. As can be seen from this figure, the highest
concentration of ammonia has the most adverse effect on the animal’s body.

Figure 1. The effect of the gas composition of the air on the body of the animal.

The main directions of research on the removal of ammonia can be divided into 3 groups: the development of biotechnological measures [4], the development of air purification systems [5, 6] and the development of systems for removing contaminated air from animal keeping areas [7, 8].

Based on the results of the study [9], it was found that the exhaust air removal system using clandestine channels provides a reduction in ammonia content compared to the exhaust shaft system. The following prerequisites were also established for the further development and improvement of systems for removing ammonia from animal keeping areas:

- the volume of air removed from the zone of manure channels should be at least 50% of the amount of air exchange;
- the spacing of the suction pipes should be less than 6 m to ensure a more uniform extraction of harmful gases.

2. Materials and methods

The studies were carried out in relation to a pig-breeding module for 500 animals, adapted for the conditions of the southern zone of Russia. The farm provides a gravity-based manure removal system, which includes 5 manure collection channels connected by a common collector located at the end of the building. Above this manure removal system are concrete crevice floors. The gravity channels of the batch hydraulic system are made with a slope of 0.005 towards the manure collector. The width of the manure channel is 0.9 m, the depth is 0.8 m. The width of the collector channel is 1.2 m, the depth is 1 m.

With modular technology, various groups of animals are kept at different times in the premise. The calculation of the required air exchange was carried out to reduce the concentration of carbon dioxide, water vapor, ammonia and the rate of air exchange taking into account the cyclogram of livestock movement and constantly changing parameters of outdoor air. For the calculated air exchange, the average value of peak air exchanges was taken, which for the considered pig-breeding module was 75,000 m³/h.

For effective removal of ammonia from manure channels, an exhaust ventilation system was proposed, shown in Figure 2.
Fig. 2. The scheme of the pig-breeding module with the application of a network of ducts to remove ammonia from the manure channels: 1 - exhaust ducts; 2 - air inlet pipes; 3 - common exhaust duct; 4 - ventilation unit.

Exhaust ducts are installed under the crevice floors 1. Air inlet pipes are distributed on these ducts made of tubes in the shape of "goose-necks" 2. The air is removed through exhaust ducts, which are connected by one common exhaust duct 3, at the end of which a ventilation unit is installed 4. For transporting contaminated air, ducts from unplasticized polyvinyl chloride PVC-U (NPVH) were selected.

According to the results of the hydraulic calculation and taking into account the assortment of reinforcing products (State standard 32413-2013), the diameters of ducts, the characteristics of which are given in Table 1, were adopted for further studies.

Table 1. Dimensions of NPVH ducts for the manufacture of suction pipes (State standard 32413-2013).

| Outer diameter $d_{out}$, mm | Wall thickness, $\delta$, mm | Outer diameter $d_{out}$, mm | Wall thickness, $\delta$, mm |
|-----------------------------|------------------------------|-----------------------------|------------------------------|
| 160                         | 4.5                          | 355                         | 9.5                          |
| 200                         | 5                            | 400                         | 11                           |
| 250                         | 7                            | 450                         | 12                           |
| 315                         | 8.5                          | 500                         | 13.5                         |

To determine the air velocities in the immediate vicinity of the suction inlet, the absorption velocity spectra obtained as a result of experimental studies were used [10].

The velocities in the absorption spectrum at various distances from the center of the suction inlet can be determined from the expression [10]:

$$\frac{\nu_1}{\nu_2} = k\left(\frac{d_{out}}{x}\right)$$

where $k$ is a dimensionless electric coefficient that takes into account the nature of the stream gravity to the inlet, for round holes without bounding surfaces $k=0.06$.

Using the recommendations for the design of suction, we placed the suction pipe as close to the source of hazard as possible, in this case above the crevice floors. In turn, the axis of the suction inlet of the pipe can be located perpendicular to the suction plane (Fig. 3a) and parallel to the suction plane (Fig. 3b).
In each of these two cases, a suction sphere forms around the suction axis. However, with the perpendicular arrangement of the suction axis, the center of the suction sphere is closer to the source of ammonia in comparison with the parallel arrangement of the suction axis. In addition, when using the design shown in Figure 3a, mechanical impurities cannot enter the duct. However, when arranging the pipe with the suction axis perpendicular to the suction plane, even with the smallest diameter of the “goose-neck”, the axis in the inlet is located outside the manure channel in the animal keeping area. Therefore, despite many shortcomings (distance from the suction axis, the possibility of foreign impurities getting into the removed air), the suction pipe of the design shown in Figure 3b was accepted.

For mounting the suction pipe, tees and branches are provided (Figure 3b). The bending radii of the branches along the axis make up the outer diameter $d_{\text{out}}$. For reliable fastening of the branches, a free duct section with a length of at least $0.4d_{\text{out}}$ mm (Technical specification 6-49-18-90) is adopted.

Thus, taking into account the socket section at the branch, the wall of the manure channel is at a distance exceeding 1.5 times the caliber of the suction inlet. Therefore, it cannot be considered a limiting plane, and formula (1) is applicable for determining the velocities in the absorption spectrum.

For effective absorption of harmful vapors by inlets, it is necessary that the suction velocity be higher than the normalized air velocity in the premises of the pig-breeding module [11]. In accordance with regulatory data, this value is 0.3 m/s (Departmental standards of technological design 2-96). It was determined at what distance from the suction axis the velocity drops to the minimum necessary value, i.e. what is the radius of the absorption spectrum.

For this, the following numerical values were substituted into expression (1):

$$v_x = 0.3 \frac{m}{s}; k_x = 0.06$$

The suction velocity $v_0$ at the entry to the inlet varies in the range from 0.5 to 2.5 m/s according to the recommendations for the calculation of suction devices [12]. The diameters of the suction inlet were changed according to the standard sizes shown in Table 1.

3. Research results
The calculation results for determining the effective absorption zone are shown in Figure 4.
Figure 4. Change in the radius of the absorption spectrum ($x$) from the air velocity ($v_0$) at the entry to the inlet and the diameter of the suction pipe ($d_0$).

As can be seen from the graphical dependencies shown in Figure 4, the radius of the absorption spectrum increases with increasing axial velocity at the entry and with increasing diameter of the suction inlet. At the same time, with the same diameter, the intensity of the change in the radius of the spectrum decreases with increasing velocity. Thus, we can conclude that with an increase in the axial velocity at the inlet to the suction for the same passage section, a noticeable increase in the suction intensity is not observed. Therefore, the increase in the radius of the spectrum is most affected by the diameter of the inlet.

From consideration of the layout options for the suction pipes at these values, the number of "goose-necks" can be determined from the expression

$$n_e = \frac{L_d}{d_0 \cdot v_0}$$

(2)

where $L_d$ is the length of the duct, m.

The calculation results are presented in Table 2.

Table 2. Calculation results for determining the number of suction pipes in a 40 m long duct.

| $d_0$, m | 2.5 | 2  | 1.5 | 1  | 0.5 |
|---------|-----|----|-----|----|-----|
| 0.151   | 5   | 7  | 9   | 13 | 26  |
| 0.19    | 4   | 5  | 7   | 11 | 21  |
| 0.236   | 3   | 4  | 6   | 8  | 17  |
| 0.298   | 3   | 3  | 4   | 7  | 13  |
| 0.336   | 2   | 3  | 4   | 6  | 12  |
| 0.378   | 2   | 3  | 4   | 5  | 11  |
| 0.426   | 2   | 2  | 3   | 5  | 9   |
| 0.473   | 2   | 2  | 3   | 4  | 8   |

We determine the length of the front of the "active" suction, where the suction velocity exceeds the air velocity in the livestock premise. For this, we multiply the values of the suction spectrum radius (Figure 4) by the number of pipes corresponding to the same suction velocities and inlet diameters.

The calculation results are presented in Figure 5. An analysis of the presented graphic images of second degree polynomials shows that the "active" absorption zone, on the contrary, is greatly influenced by axial velocity. With the same diameter of the suction inlet, the length of the "active section" practically does not change.
The largest “active” zone was obtained using axial velocity $v_0 = 0.5$ m/s. Thus, all calculations were subsequently performed at a given axial velocity.

After arranging the suction pipes for the remaining diameters, we established, as can be seen from Figure 6, the suction plane of the pipe with a diameter of 315 mm is located directly above the right wall of the channel. This ensures good removal of harmful impurities from the zone of the right lateral surface of the channel, that is, from the region from which the removal of ammonia is the least effective [9]. At the same time, with this arrangement of the “goose-neck”, it is difficult to remove harmful gas from the zone of the opposite wall of the manure channel. The most intensive removal of ammonia will be when using pipes with a diameter of 160 to 250 mm. The absorption spectrum area is completely above the manure channel. Therefore, all further calculations were performed for pipes with diameters of 160, 200 and 250 mm.

**Figure 5.** Change in the length of the “active” suction front from the axial suction velocity ($v_0$) and the diameter of the suction inlet ($d_0$).
Figure 6. Layout schemes of suction pipes of various diameters.

The spacing of the pipes for the remaining duct diameters is determined by the formula

\[ l_{sp} = \frac{l_d}{n_g - 1} \]  

(3)

where \( l_d \) - duct length, m.

The step value when using all diameters of the suction devices ranged from 1.6 to 2.5 m, which is more than 3 times less than the recommended value 6 [9]. Therefore, the probability of uniform absorption of harmful gases is much higher.

According to the traditional method, an aerodynamic calculation of the duct network shown in Figure 1 was performed. Using the mathematical apparatus (Construction Norms and Regulations 2.04.01-85), we determined the roughness coefficient for polypropylene ducts. The results of aerodynamic calculation are presented in Figure 7. The layout option of the ammonia removal system with pipes with a diameter of 160 mm was designated as option A, with a diameter of 200 mm - option B, with a diameter of 250 mm - option C.
As can be seen from Figure 7, the greatest energy consumption was obtained using pipes with a diameter of 160 mm (option A), the smallest - when using pipes with a diameter of 250 mm (option C).

When conducting an economic assessment, we also used the cyclogram of animal movement and research data [4]. The increase in live weight of pigs per day was adopted at 6% more due to changes in the concentration of ammonia in the premise with pigs. Statistical indicators of economic efficiency (capital investments, operating and reduced costs) indicated the advisability of using a system with pipes with a diameter of 315 mm. However, dynamic indicators (net present value, profitability index and payback period of capital investments) showed that the most efficient system is the use of suction pipes with a diameter of 160 mm (Figure 8).

Figure 7. Change in power consumed by the ventilation unit.

Figure 8. Indicators of the dynamic efficiency of exhaust ventilation systems in clandestine channels.
4. Conclusion
To ensure uniform absorption of harmful gases, in particular ammonia, the systems with the smallest pipe diameters and the lowest possible suction speed, which amounted to 0.5 m/s, turned out to be the most effective. Air suction devices with diameters of 160, 200 and 250 mm successfully fit into the design solutions of the pig-breeding module. Suction inlets are located directly above the manure channels and provide efficient exhaust of air with a high concentration of ammonia. Moreover, a system with 160 mm diameter air suction pipes brings the greatest economic effect.

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