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JUSTIFICATION, SELECTION AND CALCULATION OF YEAR-ROUND SYSTEMS OF NATURAL VENTILATION IN LIVESTOCK PREMISES

Problem statement. A dependence of heat, humidity and air conditions of the livestock buildings for the different seasons of the year is considered.
Results and conclusions. The dependence is obtained by grapho-analytical method. Zones of external air parameters are justified for application of the systems of natural (horizontal, shaft, active aeration) and mechanical supply-and-exhaust ventilation. The calculated dependences and recommendations on design and operation of natural ventilation system in non-heated livestock premises in different seasons of the year are presented.

Keywords: livestock premise, grapho-analytical method, natural ventilation, gravity pressure, wind pressure, energy saving.

Introduction

Constantly functioning biological heat and moisture animal emissions are known to be present in livestock premises. If heat $Q_б$ is emitted in the cold season, heat technological characteristics of an external fencing of non-heated livestock premises are to provide a specific heat flow through them so that cattle could not be supercooled ($\Sigma Q = 0$ at a calculated air temperature $t_н$). In cases when heat values $t_н$ are higher than the calculated ones, removing heat excess from a livestock premise is carried out by ventilation systems.

The presented interpretation of livestock premises energy balance methodically justifies the introduction of specific heat flow $q_б^н$ considering biological heat release and a building spaceand-planning solutions as resistance to heat transmission $R_о^{тр}$ by external fencing constructions is normalized

$$R_о^{тр} = \left(t_в - t_н\right) / q_б^н, \tag{1}$$

where $t_в$ is a calculated internal air temperature, °C;

$$q_б^н = \left(1 - m\right) Q_б / F \text{, watt/m}^2,$$

where F is the area of underground walls and coverage, m^2, m is a coefficient considering a heat loss proportion through the floors and banked parts of the internal walls (m = 0.03…0.05 for above-ground buildings; m = 0.08…0.10 for buildings with a 0.50…0.65 banked part of the external walls through the height [1]).

Evident heat transmissions $Q_б$, watt and moisture releases $G_{вл}$, gr/h, made by animals are calculated by the conventional methods [1, 2, 16—18].

The minimal external air amount $G_{н.\min}$, gr/h, for the assimilation of the moisture emitted by cattle at the moisture content of dry air incoming $d_{пр}$ and removed $d_{у}$, gr/kg from a livestock premise is $G_{н.\min} = G_{вл}/(d_{уд} - d_{пр})$. The maximum heat input for warming this amount of the external air is [3]

$$Q_в = c_в G_{н.\min} \left(t_н^р - t_н\right), \tag{2}$$

where $c_в$ is specific air heat capacity, watt hour/(kg °C).

The warming necessary for controlling external air moisture excesses in the cold season does not allow to regard livestock premises as completely non-heated. The external temperature $t_н^р$, at which a building warming starts to be necessary, is calculated from a heat balance of each construction:

$$t_н^р = t_в - \frac{Q_б}{F / R_о^{тр} + c_в G_{н.\min}}. \tag{3}$$

In order to provide a calculated heat-moisture regime in non-heated livestock premises, the dominating application of natural energy sources should be taken into consideration. Thus it is now essential to design natural ventilation systems used in all-year livestock premises operation with their operational and energy efficiency validated [19—23].

1. Analysis of the heat, moisture and air modes

The equation for heat and air balances for non-heated livestock premises with the natural ventilation systems has the following form:

$$\frac{Q_б - Q_п}{I_в - I_н} = \frac{Q_в}{I_в - I_н} \; 3 \; \frac{G_{вл}}{d_{уд} - d_{пр}}. \tag{4}$$

where $Q_п$ is overall heat input for a building, watt; $I_в$ and $I_н$ are heat contents of internal and external air watt h/kg respectively.

The graphic dependence between heat, moisture and air balances of livestock premises given in [2] characterize the interconnection of physical processes merely in qualitative terms. With the grapho-analytical method for building the processes used and the method of external fencing heat technological characteristics normalization presented above considered, the application spheres of natural and mechanic ventilation systems in livestock premises have been expanded and qualititavely refined (Fig. 1).

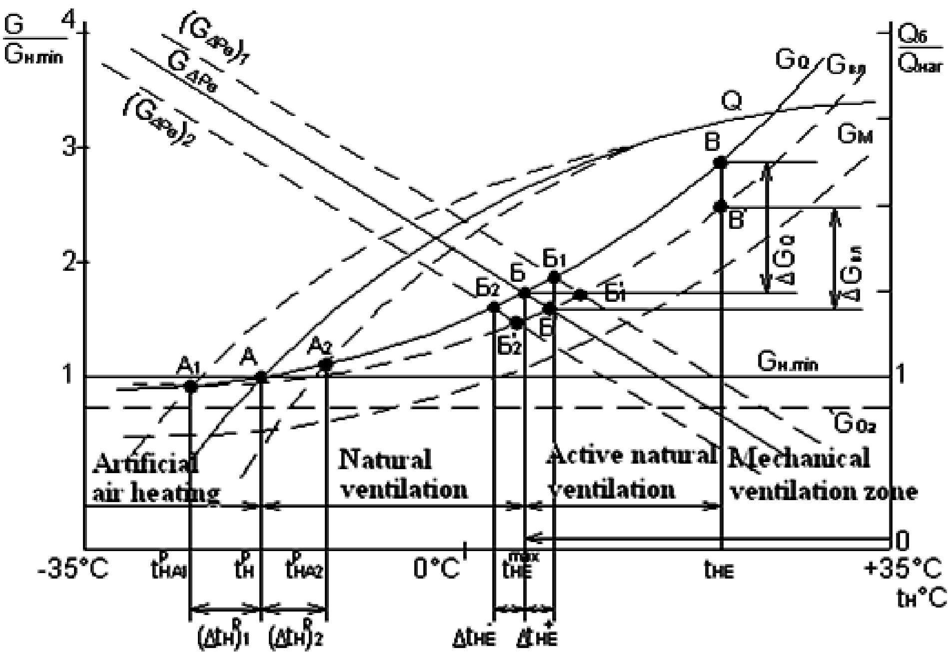

Fig. 1. The interrelation between heat, moisture and air regimes for livestock premises:

The grapho-analytical dependencies were plotted in the system of interdependent coordinates. The interrelation between the actual air input G and minimal air input required for moisture removing $G_{н.\min}$ which exceeds the air amount needed for breathing (by oxygen) $G/G_{н.\min}$ is laid off as ordinate. The interrelation between evident biological heat releases by animals and heat input for warming the incoming air ($Q_б/Q_в$) is also laid off as ordinate. The ratio $Q_б/Q_в = 1.0$ at the arbitrary external air temperature $t_н^p$ (Point *A* in Fig. 1).

Lack or excess of heat in a building is presented in curve *Q* figure which is a function of a resistance value to the fencing building heat transmission, the value of the external air temperature and the number of the cattle in a livestock-premise. The lines $G_{н.\min}$ and G_{O_2} display the essential air exchange in removing water vapour and oxygen supply. Curves G_Q, $G_{вл}$ and $G_М$ determining the essential air exchange in the cycle of all-year livestock-premise operation are drawn based on the balance equations in accordance to the evident heat, moisture, harmful or flammable gases. The line $G_{\Delta Pe}$ characterizes the value of a possible air exchange at the expense of gravitational ΔP_t and wind ΔP_v pressures.

Point *A* describes the external temperature limit up to which it is possible to maintain the calculated external air parameters at the expense of natural factors. It corresponds to the conditional temperature $t_н^p$. At the lower temperatures natural warming of incoming air is required. This limit may be extended up to $t_{нA_1}^p$ as resistance to fencing building heat transmission increases or is narrowed up to a $t_{нA_2}^p$ as the resistance decreases.

Point *Б* lying at the interplane of the curve G_Q and the line $G_{\Delta Pe}$ (if Point *Б* at the inplane of $G_{вл}$ with $G_{\Delta Pe}$ when $G_{вл} > G_Q$) defines the highest external temperature $t_{н.е}^{\max}$ at which the natural pressure ($\Delta P_e = \Delta P_t + \Delta P_v$) provides the supply of the external air amount calculated.

Thus, the external temperature interval between Points *A* and *Б* is the building natural ventilation zone. The natural ventilation zone extends to the value $\Delta t_{н.е}^{+}$ when there is a loss of the pressure circulating in the air building (points $Б_1$ or $Б_1'$) or is narrowed down to $\Delta t_{н.е}^{-}$ when there are additional resistances in the system (points $Б_2$ $Б_2'$). The natural ventilation zone may be extended at the expense of the active natural aeration application.

In Fig. 1 this zone is located between the points *Б* and *В*, so the natural ventilation zone extends up to the maximum possible external air temperature $t_{н.е}$. At the warm-season external air temperature exceeding $t_{н.е}$ application of mechanical influx-and-extract ventilation is important.

The qualitative grapho-analytical laws given allow to find out and predict the energetic efficiency of volume-planning, constructional and thermal physic solutions for livestock premises, their engineering equipment and cattle-keeping technologies.

2. Methods of all-year natural ventilation calculation

The natural pressure ΔP_e occurring is used for creating the kinetic energy of influx $v_{пр}$ and extract $v_{уд}$ streams, for overcoming the aerodynamic resistance of the apertures, pits $\zeta_{пр}$, $\zeta_{уд}$, as well as for pressure losses during the air flow through a building ΣRl, i. e.

$$\Delta P_e = \Delta P_t + \Delta P_v = v_{пр}^2 \rho_н \zeta_{пр} / 2 + \Sigma Rl + v_{уд}^2 \rho_в \zeta_{уд} / 2. \qquad (5)$$

2.1. Cold season. In order to calculate natural ventilation systems for livestock premises, let us consider a period with the external air temperature lower than the conditional one $t_н^p$ to be the cold season (in Fig. 1 it is artificial air warming zone, $t_н < t_н^p$).

In common cow houses for 200 cows in the climate zone with the external air temperature $t_н \approx -30$ °C the temperature value is $t_н^p \approx -13...-15$ °C, the average January monthly temperature $t_я \approx -12$ °C, i. e. a period of time during a year when $t_н < t_н^p$ is not longer than 8…12 days. During this period the internal air temperature during the calculated air exchange $G_{н.\min}$ may fall up to $t_в = 4...6$ °C.

Such a temperature fall, however, as shown in [1, 4—10, 16, 17, 19, 21, 22], does not actually lead to a decline in the yield of milk and does not affect the cattle activity. On the other hand, it should be noted that the cold season allows for a decrease in the limited air exchange to 2.5…3.0 m^3/(part·centner) [11, 12] and even lower up to total loss of air supply [9]. Thus as a result, we cam maintain that during the cold season ($t_н^p > t_н$) in non-heated livestock premises the systems of organized natural ventilation may be turned off. As for a possible occasional air entry, it is the least likely to occur due to the inevitable wind pressure.

2.2. Transitional season. During this period the external air temperature lies within the range of $t_н^p$ to $t_{н.е}^{\max}$ (in Fig. 1 it is the natural ventilation zone). The temperature $t_{н.е}^{\max}$ corresponds to the acceptable internal air temperature $t_в$ starting form which the active building aeration becomes possible (open windows, gates, etc.) when the cattle are kept on a tether. When they are freely pastured, the temperature $t_{н.е}^{\max}$ corresponds to the start of the pasture period.

The largest natural ventilation systems workload is observed in a period close to the temperature $t_{н.е}^{\max}$ (Point *Б* in Fig. 1). The natural air exchange is carried out by the combination of gravitational forces (shaft ventilation) and wind pressure (horizontal ventilation).

2.3. Warm season. This is the period with the external air temperature higher than $t_{н.е}^{\max}$ (Fig. 1). There are only cattle kept on a tether in a livestock premise. All the accessible methods of natural ventilation (horizontal, shaft, active aeration) are used for removing biological heat and moisture emissions. The windows, external doors, gates and technological apertures are open.

3. Horizontal ventilation systems

The horizontal ventilation is performed in two ways: either through slit-like apertures with a regulated air entry in the external doors or by the atmospheric air infiltration through the cladding.

The horizontal ventilation scheme through under window slit-like apertures is shown in Fig. 2. The apertures are usually filled with a local porous material (hay, straw, etc.).

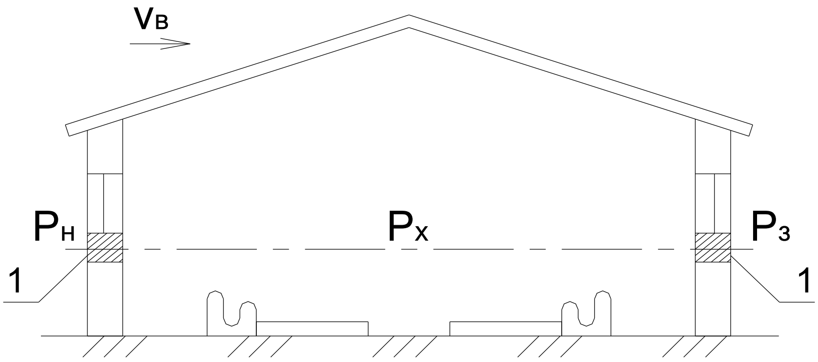

Fig. 2. The horizontal ventilation system scheme:
1 — under window slit-like apertures

The full calculation of the horizontal systems is presented in [2, 13]. The wind pressure on the windy side of the building is

$$\Delta P_н = c_н v_в^2 \rho_н / 2,$$

on the leeward side is

$$\Delta P_з = c_з v_в^2 \rho_н / 2,$$

the internal excess pressure at the apertures centre level is p_x. The aerodynamic coefficients for common livestock premises are $c_н = 0.6…0.8$, $c_з = −0.4…−0.2$ [2, 14].

The area of slit-like apertures from the windward $F_н$ and the leeward $F_з$ sides of a building is

$$F_н = F_з = G / 3600 \mu \rho_н v (c_н - c_з) \sqrt{\rho_в / (\rho_в + \rho_н)}. \quad (6)$$

The air rate in (6) is $G_{н.\min}$ at a thoroughly uncalculated external air temperature at $G_{н.\min} \to 0$. The graphic functions for the air rate coefficient μ and degree of aperture filling in a ventilation shaft at various air flow speeds are given in Fig. 3.

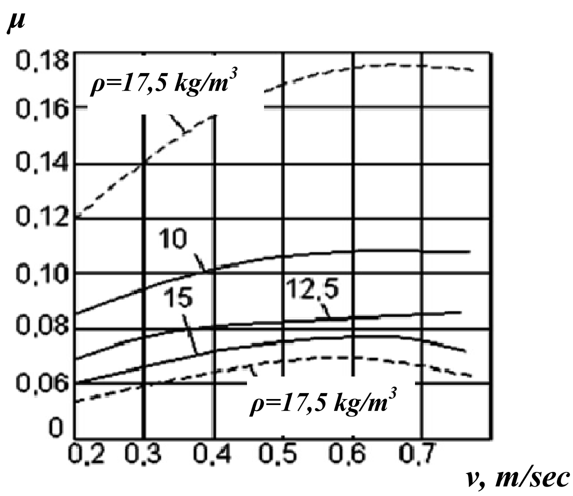

Fig. 3. The air rate coefficient μ in an aperture filled with straw [1]

According to the air rate coefficient μ and air flow speed in a non-filled aperture $v = G_{пр} / F_{пр} \rho_н 3600$, the degree of aperture filling is found.

The quantitative wind pressure determination is to be conducted from the average speed of January wind direction and its recurrence. Let us agree that the largest algebraic difference of the aerodynamic coefficients is taken as the design-basis ($c_н - c_з$).

Another horizontal ventilation type achieved by the external air infiltration is based on the physical effect of steam ventilation through air-penetrating cladding. Let us define the conditions of the inclusion of external walls into the stable infiltration mode under an easily calculated gravitational pressure ΔP_t and unstable wind pressure of an occasional value ΔP_v at the design-basis wind speed $v_в$ (Fig. 4).

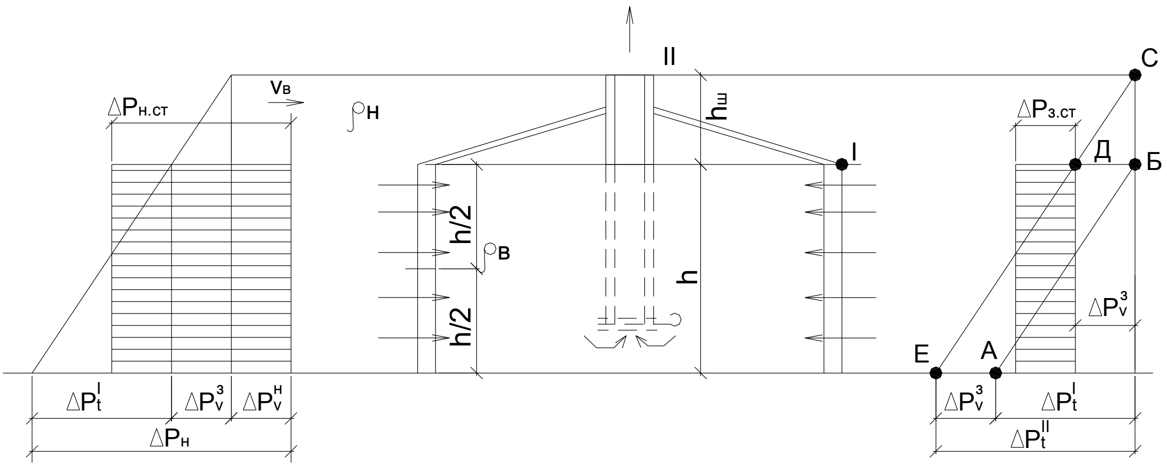

Fig. 4. Design-basis pressure curves during the stable air infiltration

The lowest pressure drop for the air infiltration takes place in the upper plane of the leeward wall (plane I): gravitational pressure inside a building is $\Delta P_t^I = h(\rho_н - \rho_в)g$; the external wind pressure is $\Delta P_v^з = c_з v_в^2 \rho_н / 2$.

$(\Delta P_t^I + \Delta P_v^з) \geq 0$ is necessary for the stable infiltration.

Point *Б* is to coincide with the point *Д* on the plot. An increase in the gravitational pressure during the installation of a discharge shaft of the height $h_ш$:

$$\Delta P_t^{II} = (h + h_ш)(\rho_н - \rho_в)g$$

makes this shift possible. The pressure developed by the shaft is equal to the vacuum on the leeward side

$$\Delta P_v^з = h_ш(\rho_н - \rho_в)g .$$

In this case the total excess pressure from the windward side is $\Delta P = \Delta P_t^I + \Delta P_v^з + \Delta P_v^н$.

The amount of the air [15] infiltrated through the external wall of the area $F_{ст}$ is

$$G = \Delta P F_{ст} / R_н \tag{7}$$

where $R_н$ is a resistance to the air permeability of a construction, m^2 h Pa / kg.

The average pressure drops of the windward and leeward sides respectively are

$$\Delta P_{н.ст} = \Delta P_v^н + \Delta P_v^з + 0,5\Delta P_t^I;$$
$$\Delta P_{з.ст} = 0,5\Delta P_t^I. \tag{8}$$

The amount of the external air coming into a livestock premise through the windward $G_{пр}^н$ and the leeward $G_{пр}^з$ walls in the expanded form takes the following form:

$$G_{пр}^н = \left[0.5\left(c_н - c_з\right)v^2\rho_н + 0.5h\left(\rho_н - \rho_в\right)g\right]F_{ст} / R_и; \tag{9}$$

$$G_{пр}^з = 0.5h\left(\rho_н - \rho_в\right)gF_{ст} / R_и. \tag{10}$$

Professor V. M. Valov [9] suggests using macroporous ceramsite concrete panels for the external walls, the resistance of air permeability of which is within the range of $R_и$ = 0.5…4.5 m^2 h Pa/kg. The value $R_и$ for the windows is determined according to the acting standards for walls and gates of livestock premises $R_{и.дв}$ = 0.3 m^2 h Pa/kg [9].

The overall plane area of ventilation shafts of the natural ventilation systems examined during the cold season is by the average air speed in a shaft, m/sec, [2]:

$$v_{ср.ш} = 4\sqrt{0.85\Delta P_t / \left(\Sigma\zeta + 0.02h_ш / D\right)} \tag{11}$$

where $\Delta P_t = \left(0.5h + h_ш\right)\left(\rho_н - \rho_в\right)$, kg/$m^2$, the air supply is in the middle of the external wall height centre (0.5 h); $\Sigma\zeta$ is the sum of local resistances during the air flow through a shaft; $D = 2ab / \left(a + b\right)$ is an equivalent shaft diameter, m; a and b are shaft section sizes, m.

It is advantageous to perform the air exchange from the operating zone. Such a system layout provides for eliminating harmfulness from their formation zone, preserving a thermal cushion under the covering and the stable infiltration through the external walls (see Fig. 4, dotted line).

4. Gravitational ventilation systems

In Fig. 1 the area of gravitational (shaft) natural ventilation systems application is called the natural ventilation zone which lies within the range of $t_н^р$ to $t_{н.е}^{\max}$. In the systems of this type the air is removed from the upper zone through the heated shafts and then is supplied through the under- or above-window apertures with the hay and straw taken out (Fig. 5).

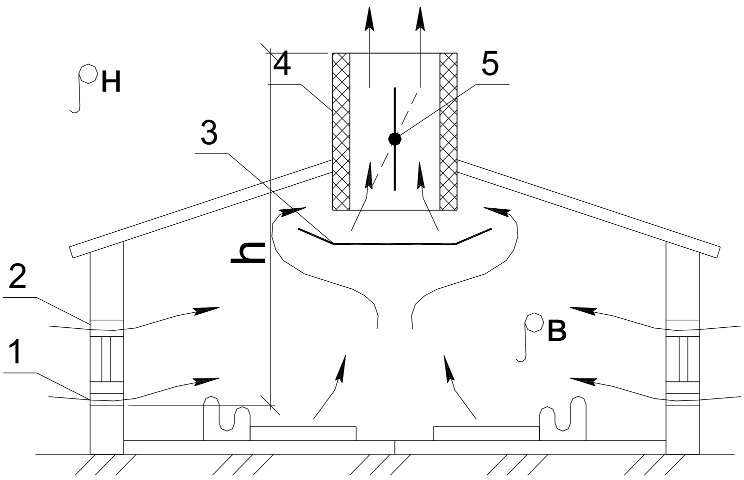

Fig. 5. Shaft ventilation scheme:
1, 2 — under- and above-window influx apertures; 3 — saucer; 4 — shaft; 5 — throttle

The design-basis gravitational pressure (Fig. 5) $\Delta P_t^{ш} = \left(\rho_н - \rho_в\right) hg$. The external air density is calculated from the average temperature: ($t_н^p$ + $t_{н.е}^{\max}$)/2. The value $t_{н.е}^{\max}$ may be presented by the minimum admissible temperature in a building $t_в^{\min}$ = 6…7 °C; the internal air density $\rho_в$ is found at $t_в$ = 12…16 °C.

During the transitional season windows, gates, and external doors are shut. The average air speed in a shaft is determined by (11).

5. Active natural ventilation (aeration) systems

Active natural ventilation (aeration) systems are used in a warm season when cattle are kept on a tether. The application zone of these systems in Fig. 1 is located between Points *Б* and *В*. Active aeration is efficient at the external air temperatures from $t_{н.е}^{\max}$ when gravitational pressure is not enough to create the design-basis air exchange, when the complex of natural air exchange sources for the heat and moisture excess assimilation in a building is completely exhausted.

All the shafts, apertures, doors, and gates are open in the active natural ventilation regime.

Conclusions

The method of determining the value of a resistance required to heat transmission $R_o^{тр}$, of a cladding for non-heated livestock premises systematically binds the function of constructions with individual biological indices of cattle $Q_б$, volume-planning building solutions F, a regional climate characteristics $t_н^p$. The latter is the basis for the choice of engineering equipment and its operation modes in livestock premises during their all-year operation.

The experimental results presented reveal the physical sense of the common equation for heat and air balances of non-heated livestock premises. They also quantitatively refine the grapho-analytical method of defining natural ventilation types (horizontal, shaft gravitational, aeration) which can be advantageously and efficiently used in each of the seasons.

The methods of designing each of the natural ventilation types due to the wind ΔP_v and gravitational ΔP_t pressures in the cold, transitional and warm seasons are presented.

The design functions were for the first time obtained for horizontal natural ventilation systems under the wind pressure through regulated slit-like apertures in the external walls and due to infiltration through claddings as well.

The conditions of stable infiltration during changes of climate factors are grounded.

The boundary conditions under which the design-basis parameters in livestock premises in the warm season can be maintained by natural ventilation gravitational systems have also been discussed.

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