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Study of Potential Application Air Curtains in Livestock Premises at Cattle Management Farms

Aleksey Kuzmichev [1], Aleksei Khimenko [1,*], Dmitry Tikhomirov [1], Dmitry Budnikov [1], Marek Jasiński [2], Vadim Bolshev [1] and Ivan Ignatkin [3]

1 Federal Scientific Agroengineering Center VIM, 109428 Moscow, Russia
2 WWSIS "Horyzont", 54-239 Wrocław, Poland
3 Moscow Timiryazev Agricultural Academy, Russian State Agrarian University, 127550 Moscow, Russia
* Correspondence: avmkh87@gmail.com; Tel.: +7-499-174-85-95

Abstract: Recommendations on the selection of air curtains and the calculation of their parameters for livestock premises in cattle management farms are made. The air curtain functioning principle is analyzed from the air jet theory point of view. The block diagram and modular design of air curtains with a variable air jet direction vector and with controlled slit width are designed. Laboratory tests of the newly designed air curtain structure are performed in accordance with the microclimate requirements for the cattle management farm premises. Based on the experimental results, the major air curtain parameters are calculated for the range from 10° to 60° of angle α between the direction of the air jet outward from the air curtain slit and aperture plane, and for the air curtain slit width b_0 in the range from 0.05 m to 0.15 m with the account of the wind speed V_{w} variations. Calculated values for amounts of energy that have to be consumed to ensure the required air jet velocity, in the output from the air curtain, and those for the quantity of thermal energy required to heat the air supplied to the air curtain, depending on the angle α and on the slit width b_0, can be helpful for selecting the power capacity of both the air curtain fan and electric heater. A block diagram of the air curtain control for cattle management farm premises is designed, enabling automatic control of the airflow rate, the angle of the air jet output from the air curtain slit, and the temperature of the heated air supplied to the air curtain, considering particular climate conditions. According to the preliminary estimate, applications of the newly designed air curtain will make it possible to reduce the energy consumed to maintain the required microclimate conditions in cattle management premises by 10% to 15% in the cold period.

Keywords: air curtain; air jet theory; air jet velocity; air mixture; airflow rate; microclimate in cattle management premises; wind load

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1. Introduction

For the central nonblack earth areas of Russia where the major part of cattle management enterprises is located, the duration of the time period with average daily air temperature below 0 °C is 40% to 45%, at least. Maintaining the necessary microclimate parameters in cattle management premises of farms normally requires up to 60% of the total thermal energy consumed for heat supply purposes. The efficiency enhancement of the heat supply and ventilation systems aimed at the reduction of energy consumed for providing and maintaining normative microclimate parameters, in cattle management premises of livestock farms, is an essential objective [1,2]. For regions with a winter design temperature below −20 °C, either the availability of an entrance hall at the gate of cattle management premises or the application of air curtains with air heating is a mandatory requirement [3]. For these regions of Russia, the winter design temperature value is from −33 °C to −29 °C. Winter outdoor air design temperature is defined as the average temperature of the coldest five-day period with a probability of 0.92, in accordance with SP

131.13330.2020 building climatology. For standard projects of modern, rapidly erected cow house buildings composed of metal structures and sandwich panels, entrance halls at the gate are not normally provided. This is, first of all, determined by the specificity of feed distribution technology with the application of mobile feed distributors. The matter is that the entire length of the feed distributor with a tractor will exceed the dimensions of extensions to the gate (entrance halls) of the cow house. That is why it is expedient to use air curtains in order to avoid cold outdoor air income through the open cow house gate and to heat the air jet at the same time.

In accordance with the technological requirements, the following works have to be carried out in the cow house premises, during the day, requiring opening the gate: concentrated feedstuff distribution, three-time feed distribution, driving cows out to the paddock yard and then back home to the cow house, cleaning the feeding pans and the feed-ways, cleaning drinking pans, cleaning cows, cleaning manure channels, bedding replacement, as well as treatment and prophylactics and veterinary activities. Performing these daily works is associated with opening the gate at least six to seven times per day, resulting in cold outdoor air income into the cow house premises in the winter period and, consequently, an indoor air temperature reduction below its standard value (12 °C) [3], particularly in the area near the gate. Furthermore, air curtains have to be installed at the gates and apertures in exposed walls that are opened more than five times per shift, for at least 30 min, in regions with an outdoor air design temperature of −8 °C and lower (SP 60.13330.2020 heating, ventilation, and air conditioning), which corresponds to the working conditions of cattle management farms and climate parameters of the regions of Russia under consideration.

In the course of field research, the effect of side curtains installed on the walls on the microclimate in premises and on the behavior of cows has been evaluated for a 400-animal cow house, built of easily installed structures, for the low-temperature period (from −19 °C to −12 °C). It was found that the use of side curtains made of polycarbonate produces a positive effect on the microclimate of the premises in the winter period (an increase in temperature by 3.2 °C and 8.8 °C along with a decrease in the wind speed on premises by 11.68% to 21.74% compared to those in the same premises without side curtains or with thick straw bedding). It was noted that the number of cows resting on the floor, during the lowest temperature period, increased compared to their accommodation in cow houses without the side-mounted heat-isolating panels [4–6]. Li Q. et al. [7] performed numeric simulations of cattle management premises in order to study the influence of the eight possible operation modes of opening the side curtains installed on the walls on the microclimate and on the airflow velocity for a typical cow house premises with natural ventilation during wintertime. The change in air temperature and relative humidity, as well as that of the floor temperature in cow house premises of various designs dedicated to various animal management types, was studied in the winter period depending on the cow house orientation and on the wind effect on the building [8–10]. Havelka et al. [11] developed an algorithm for optimal microclimate control aimed at providing the necessary comfort conditions for animals, adherence to the requirements for minimizing production costs, and for the transition to sustainable energy sources with regard to energy-efficient technologies.

Tryhuba et al. [12] developed an imitation model of the energy supply system for agricultural enterprises with the use of wind power plants based on the stochastic simulation method, ensuring this system's parameters substantiation with respect to the cost criterion. A wind-receiving device with an axial aerodynamic airflow accelerator was designed for rural areas with low wind speeds insufficient for stable power generation with the use of conventional wind power installations (WPI). Based on the results of those experimental studies and simulations, it was shown that the application of WPI with vortex-type wind flow accelerators makes it possible to increase the electric energy production by up to 400%, on an annual basis, and to increase the installed capacity operation factor by up to 52%, depending on the annual average wind speed rate compared to conventional WPI [13,14].

In order to provide standard microclimate parameters for cattle management premises, an integrated energy-saving heat supply system was designed comprising electric thermal storage (ETS) units and a ceiling fan [15]. The results of the simulations and experimental studies of the heat storage cells and the thermal state of the newly-developed ETS unit in operation modes of charging and heat emission of ETS unit were reported [16,17]. An energy-saving air heating system was developed, featuring thermal energy recuperation of the exhaust air as well as ozonizing and deep recirculation [18]. An installation for heat supply and cooling in cattle management premises with the use of geothermal energy [19] and an energy-saving air dehumidifier with the application of thermal-electric cells [20] were designed. A mathematical model describing the process of air cooling in the integrated climate control unit of the adiabatic (evaporation) operation mode, for cattle management premises, was developed. The effectiveness of this unit was confirmed in the course of experimental studies [21].

Kiktev et al. [22] designed an automated microclimate management system for cattle management premises with the use of an air curtain that controls its performance depending on the change in outdoor temperature and that of internal air, making it possible to raise the energy efficiency of the cattle management premises by at least 10%. Kim et al. [23] studied the thermal conditions of double-layer plastic greenhouses equipped with heat air curtains during the wintertime. It was found that, for the constant temperature difference between the outdoor air and that inside the greenhouse, the mean daily thermal energy consumption was proportional to the value of the heat transfer coefficient. Applications of heated air curtains enable an increase in the average temperature of the greenhouse's internal surface. By switching in the heated air curtain only during the night period, it was possible to reduce energy consumption by 28.7%, which can be explained by the decrease in the greenhouse's heat transfer coefficient.

Strongin and Zhivov [24] published recommendations on selecting and the application of air curtains. They calculated the parameters of air curtains of various types designed for production premises. A conclusion was made concerning the efficiency of the tween-type (two parallel air jets) integrated air-thermal curtains. Tikhomirov et al. [25] designed recommendations and a method for calculating the parameters of air curtains for cattle management farm premises. Shelekhov et al. [26] carried out experimental studies on air temperature distribution in the gate aperture for air curtain operation modes with and without air heating. An amount of 25 thermal-electric units were installed in the air curtain that produced about 500 W of electric power for an outdoor temperature of –12 °C, ensuring the functioning of a 180 W air curtain without the need to consume electricity from the utility network. A method was developed for improving the operation of the heat air curtain and for a reduction in its energy consumption by increasing the velocity of the air jet in the output from the air curtain slit. At the same time, the slit width of the air curtain was reduced in order to form a planar air jet with the help of a circular nozzle system [27]. Johnson et al. [28] described the advantages of air curtains compared to the application of entrance halls by the premise's gate. The influence of various factors on the conditions of the air jet exhaust from the air curtain, in the gate aperture and for various air curtain operation modes, was investigated [29,30]. The air curtain efficiency was evaluated for various values of air jet velocity in the outlet through experimental studies. The obtained results were compared with those of the air curtain operation simulation with the use of the 3D computational fluid dynamics (CFD) model [31,32].

Nevertheless, based on the results of the performed review and the analysis of publications, the conclusion has to be made that the problem of air curtains application in cattle management accommodations has been studied to an insufficient extent.

2. Materials and Methods

When opening the gate, outdoor airflow enters the cow house premises. Air motion through the gate occurs due to the following factors: wind, reduced pressure in the bottom part of buildings, the difference between the indoor and outdoor air densities, reduced pressure in the cow house premises due to the excessive airflow rate created by the exhaust ventilation system over that of the intake air. Too high an air exhaust in cow house premises can affect the efficiency of the air curtain because of outdoor air penetration through the open gate in quantities exceeding calculated values. That is why operation modes of air curtains have to be considered while calculating the air exchange in the cow house premises.

Engineering air curtains should be determined with an account of the climate parameters of particular locations, in which case one of the basic parameters is the wind speed and its direction in relation to the building orientation. A deviation of these parameters from their calculated values affects the conditions of air jet formation in air curtains. The aerodynamic characteristics of buildings exposed to environmental factors have an effect on the air jet formation in the air curtain, as well. Air curtains have to be, in all cases, engineered and selected taking into account the wind pressure changeability effect. Figure 1 shows diagrams of the pressure drop and air exhaust formation produced by wind, for the closed and open gates, in a site belonging to the category: 'isolated building in open terrain'. Cattle management accommodations, as a rule, belong to this development category [33].

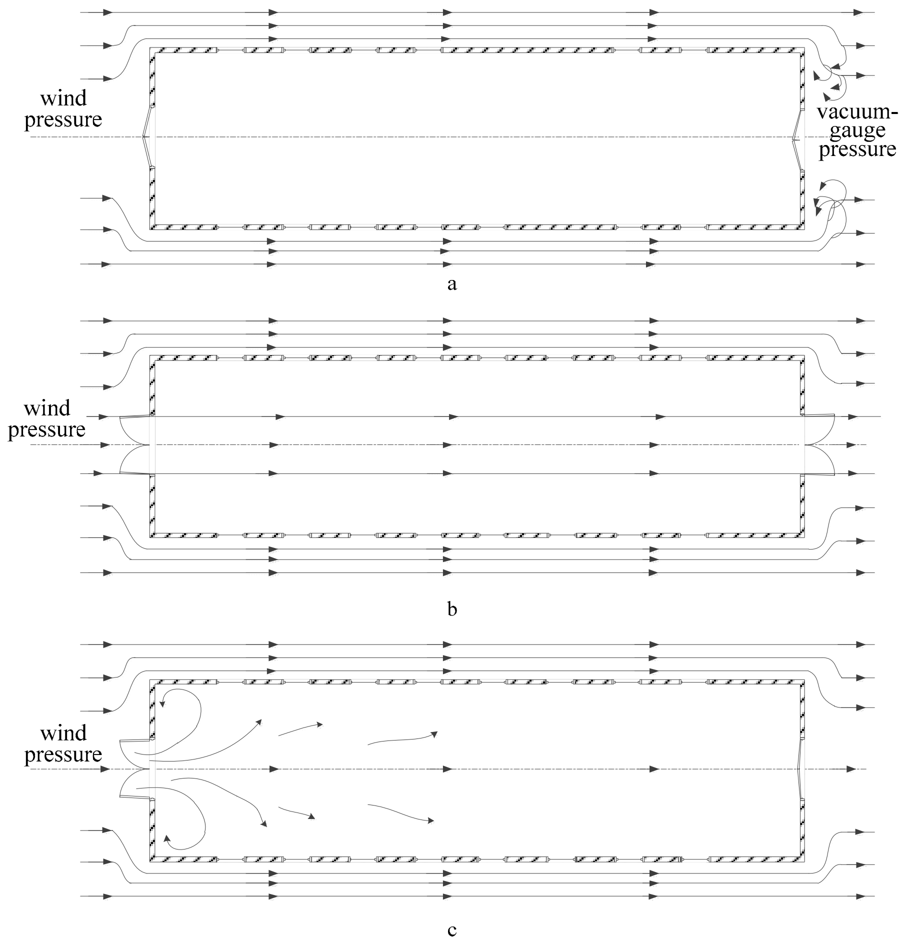

Figure 1. Diagram of airflow formations under wind load on cattle management buildings: (**a**)—for the closed status of the both apertures; (**b**)—for the two open apertures; (**c**)—for only one open aperture.

2.1. Theoretical Substantiation of the Air Curtain Operation

The air curtain calculation method is widely used, in which the flow rate of the air in the air curtain is determined with an account of the wind load and air-tightness of premises subject to protection. This calculation method is based on the vectorial addition of the flow velocity vectors of the air entering the aperture and those of the average air velocity along the air jet axis of the air curtain.

The conceptual part of this calculation method is represented by the air flap model preventing cold air penetration into the premises. An estimation of the blocking properties has to be performed by condition of the minimum mass transfer over the axis line of the air jet, with an account of the aperture flow-passage factor μ, defined on the basis of experimental data. The value of coefficient μ is selected depending on previously determined values of parameter q equal to the relation of the flow rate G_0 of air coming from the air curtain to that of air passing through the gate aperture ($G_{\mathrm{d\_air}}$) [33,34].

An air curtain's thermal capacity is defined with a consideration of the air temperature at the air output from its slit. It is calculated with an account of the outdoor air temperature and the rated temperature at the end of the air jet. Furthermore, the value of the relation of the protected aperture area to that of the air curtain slit cross-section F_0 has to be preliminarily selected. In a first approximation, it is advisable to select q = 0.6–0.7 and F_0 = 20–30, regardless of any variation in air curtain operation conditions. Regarding the issue of air curtain parameters selection (airflow rate and air temperature in the output from the slit and the cross-section of the slit), one can conclude that the maximum cost reduction values correspond to the greatest values of q. Evidently, extending the involved value range of q leads to an increase in cost reduction. Selecting the values of the slit flow passage for an air curtain with no linkage to a required air throw makes it difficult to estimate the air curtain's blocking properties. The available experimental data on $\mu = f(q, F_0)$ dependence are only applicable to air curtains with an angle of 30° between the direction of the air jet thrown from the slit and the aperture plane [35].

The values of parameters μ and q depend on a number of variables including: pressure drop, wind flow speed, air jet velocity and efflux angle, air humidity and temperature gradient, and gate aperture geometry. This dependence on the above variables has the following generalized form:

$$f(V_\mathrm{w}, V_0, \Delta p, \Delta t, \alpha, F_\mathrm{d}) \rightarrow f(\mu, q), \tag{1}$$

where V_w is the normal component of the wind speed in relation to the aperture plane (m/s); V_0 is the velocity of the air jet ejected from the air curtain slit (m/s); α is the angle between the direction of the air jet thrown from the slit and the aperture plane; Δp is the pressure difference on either side of the air curtain (Pa); Δt is the temperature difference for outdoor and indoor air (°C); F_d is the aperture cross-section area (m^2).

The calculation expression for q has the following form [34]:

$$q = \frac{1}{\mu}\sqrt{\frac{\mu_0 - \mu}{\frac{F_\mathrm{d}}{F_\mathrm{s}}\frac{\gamma_\mathrm{mix}}{\gamma_0}\sin\alpha}}, \tag{2}$$

where μ_0 is the mass-flow coefficient of airflow through the gate for the air curtain idle status, depending on the gate design (μ_0 = 0.5 to 0.8); μ is the mass-flow coefficient of airflow through the gate protected by the air curtain; γ_mix is the volumetric density of the air mixture composed of air supplied from the air curtain and outdoor air (kg/m^3); γ_0 is the volumetric density of air supplied from the air curtain (kg/m^3); F_d is the area of the gate (m^2); F_s is the total area of slits ejecting air jet from the air curtain (m^2); α is the angle between the direction of the air jet thrown from the slit and the gate aperture plane.

A generalized diagram for calculating air curtains with an account of wind load is shown in Figure 2. It has to be noted that, in this case, neither the character of the air jet development nor its trajectory are considered.

Hereafter, it is expedient to consider air curtain operation with regard to the air jet theory provisions.

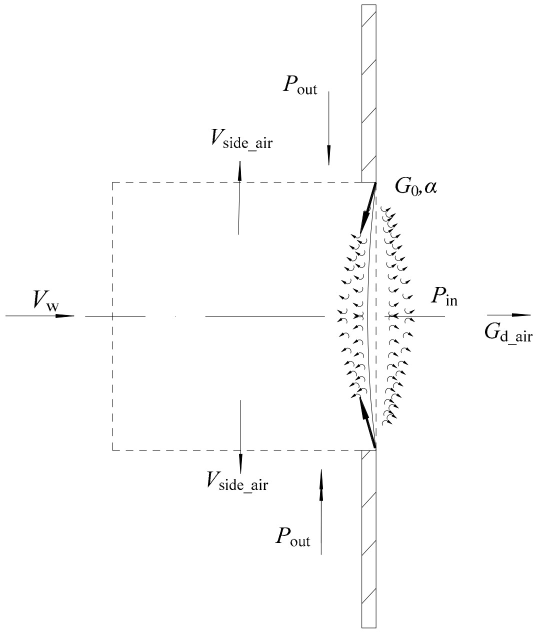

Figure 2. Diagram for air curtain parameters calculation with an account of wind load: V_w—wind speed (m/s); V_{side_air}—velocity of airflow through the side surface of the calculated volume (m/s); G_{d_air}—flow rate of air (mixture of air supplied by the air curtain G_0 and outdoor air) entering through the gate aperture into the premises (kg/s); α—direction angle of air jet output from the air curtain slit; P_{in}—air pressure inside the premises (Pa); P_{out}—air pressure outside the premises (Pa).

The air curtain, at the gate aperture, is a planar nonisothermal air jet that develops on the interface of two media with different temperatures. The pressure drop outside and inside the premises results in a deviation in the air jet axis. Under certain assumptions that will be discussed below, the air jet theory can be applied to define air curtain parameters. A diagram of the physical model for air curtain calculation with regard to the air jet theory is shown in Figure 3.

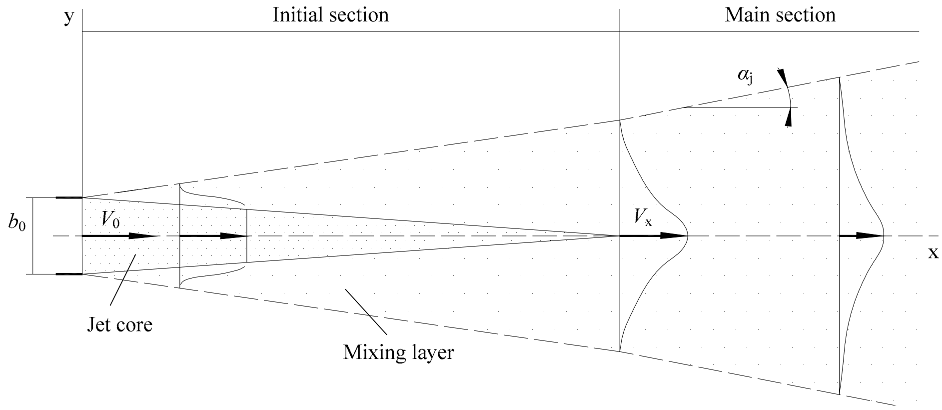

Figure 3. Air jet flow character after its ejection from the slit.

During its propagation from the air curtain slit, the air jet becomes displaced under the effect of the pressure drop Δp, on both sides, due to the wind load on the building and becomes mixed with the outdoor air from one side, and with the indoor air from the other, resulting in the establishment of an average temperature value (see Figure 4). A properly designed air curtain should only allow the air curtain to jet through the gate aperture.

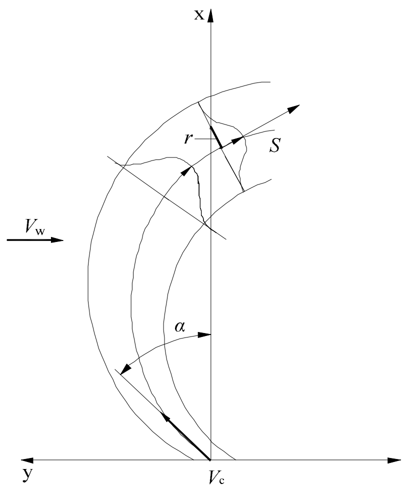

Figure 4. Air jet trajectory in the cross-flow: r—half-width of the air jet core, S—air jet axis length.

Batch-operated cut-off air curtains with bidirectional air delivery are commonly believed to be most effective for cattle management accommodations. The application of air curtains of this type enables their direct installation at the gate aperture, mainly without entrance halls, making it possible to leave vehicles and loaders standing in the aperture without affecting the air curtain operation in case of bulky materials during vehicle passage [34,36,37].

While calculating the parameters of batch-operated air curtains, an important requirement is that their operation should not affect the air distribution and thermal conditions inside the premises. A part of the air jet supplied by the air curtain into the premises should have a temperature value t_{mix} close to that of the indoor air t_{in}. Compliance with this requirement ensures maintaining the necessary thermal conditions in the premises independently of the air curtain operation mode. The required flow rate of the air input to the air curtain is determined with regard to the pressure distribution calculated from the specified air exchange conditions for closed aperture and idle air curtain statuses. In order to comply with the requirement of a stable air balance within premises during air curtain operation, the flow rate of air incoming from the air curtain has to be equal to that of air intake from the premises to the air curtain [37].

Four variants of pressure difference between p_{in} and p_{out} are possible, resulting in the formation of various air jet axis trajectories (see Figure 5):

- for indoor air intake:
  (1) $p_{in} < p_{out}$—outdoor pressure exceeds that inside the premises, over the entire aperture height;
  (2) $p_{in} > p_{out}$—indoor pressure exceeds that outside the premises, over the entire aperture height.
- for outdoor air intake:
  (3) $p_{in} < p_{out}$—in the bottom part of the aperture;
  (4) $p_{in} > p_{out}$—in the upper part of the aperture.

In order to maintain the material balance between the flow rate of air delivered into the premises with the air jet from the air curtain and that of the air intake by the air curtain, the air jet axis has to pass through the point with coordinates $x = x_j$ and $y = -r$, for indoor air intake, or $x = x_j$ and $y = r$, for outdoor air intake [34].

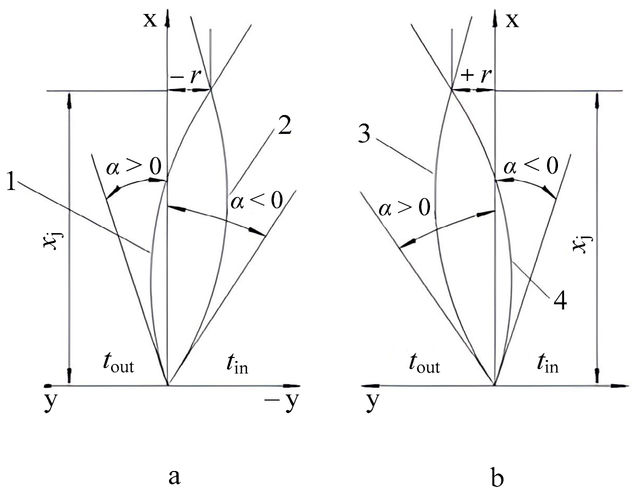

Figure 5. Options for the air jet axis position along the operating interval length, for batch-operated air curtain: (**a**)—for indoor air intake; (**b**)—for outdoor air intake; *r*—half-width of the air jet core; x_j—distance from the output slit section to that of the air jet plane (for side air feed—either width or half-width of the aperture).

Turbulent motion characteristics and bending of the jet axes, including both isothermal and nonisothermal ones, depend on the following parameter:

$$\frac{y}{d} = f(\frac{x}{d}; \alpha; a; \frac{\rho_1 v_1^2}{\rho_2 v_2^2}), \tag{3}$$

where y and x are coordinates of the air jet axis; a is the air jet configuration shape factor; ρ_1 and ρ_2 are air volumetric densities for, respectively, incident flow and output air jet (kg/m^3); $(\rho_1 {v_1}^2)/(\rho_2 {v_2}^2)$ is the relationship between quantities of motion for, respectively, external airflow rate per second and for the air jet at its mouth; d is the parameter defined by the nozzle configuration.

A generalization of the experimental data has made it possible to deduce empiric equations for axes trajectories of the jets propagating within an external flow in the form of relation (3). The general equation for the air jet axis trajectory has the following form:

$$\frac{ay}{b} = A(\frac{\rho_1 v_1^2}{\rho_2 v_2^2})^n (\frac{ax}{b})^k - \frac{ax}{b}\mathrm{tg}(\alpha - 90^\circ), \tag{4}$$

where y is the distance from the nozzle axis in the normal direction in relation to the cross-flow (m); x is the distance from the nozzle axis in the cross-flow direction (m); b is the nozzle half-width (m); v_1 is the outflow air jet velocity (m/s); v_2 is the air cross-flow velocity (m/s); A, n, and k are empiric coefficients.

Experimental studies have shown that the trajectories of the jets ejected from planar nozzles, for $h/b \leq 5$ (h and b are, respectively, the length and width of the nozzle, the longer side of which is oriented across the external flow), almost completely coincide with those of circular nozzles with an accuracy coefficient of $a = 0.06$. Equation (4) is for calculating the planar air jet in the cross-flow, for values $n = k = 1$ [38].

Let us make the following assumption and simplifications for the mathematical description of the air jet propagation character in an air curtain [37]:

- The trajectory and position of the air jet axis comply with the condition of the physical model for either counter-moving supply air jets interaction or for a single air jet in a plane perpendicular to the flow (see Figure 6);
- Air jet parameters in the cross-flow, in curvilinear coordinates linked to the air jet axis, are comparable with those of an ordinary immersed jet (air jet effluent into premises filled with air);

- Volumes of air sucked into the jet from both sides are equal to each other, and the volumetric densities of the outdoor and indoor air, as well as that of the air in the air curtain slit output, are assumed to be nearly identical $\rho_{in} \approx \rho_{out} \approx \rho_0$;
- The wind load and air-tightness of premises are taken into account by introducing a certain speed value V_w of a flow perpendicular to the air curtain jet;
- The velocity value of the cross-flow is determined by the difference between the volumetric densities of the outdoor air and of that in the premises is considered as a component of the wind load V_w.

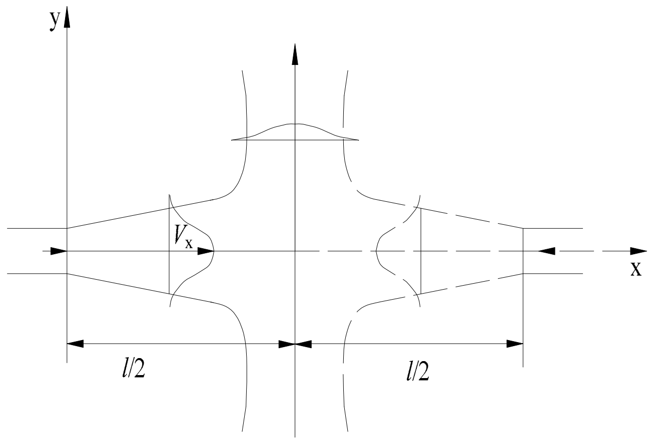

Figure 6. Physical model of counter-moving supply of air jets interaction or of a single air jet in a plane perpendicular to the flow.

The equation for the air jet axis of the air curtain, for a constant value of the pressure difference $p_{out} - p_{in}$ that is independent of its coordinate over the aperture height, can be applied for dimensioning air curtains with horizontal air jet orientation (bidirectional side-mount air curtain) [37]:

$$y = x_j \mathrm{tg}\alpha - \frac{(p_{out} - p_{in})}{2 b_0 \rho_0 V_0^2 \cos\alpha} x_j^2, \quad (5)$$

where $(p_{out} - p_{in})$ is the pressure difference for outdoor and indoor air (Pa); b_0 is the air curtain slit width (m); V_0 is the initial value of the air jet velocity in the output from the air curtain slit (m/s).

The air pressure outside a building p_{out} is defined as the sum of its static component (atmospheric pressure p_{atm}) and that of the dynamic pressure produced by the wind speed p_w. The air pressure inside the premises at the level of the gate height H_d can be defined as $p_{in} = \rho_{in} g H_d$.

2.2. Theoretical Foundations of Air Curtain Parameters Calculation

As noted earlier, while calculating the air curtain's parameters, the environmental factors changeability has to be considered, particularly the prevailing wind direction and its speed in the winter period.

The aerodynamic characteristics of buildings exposed to typical countryside environments are determined by the effect of the wind speed expressed in fractions of the wind flow velocity pressure p_w:

$$p_w = k_{0\_ave} \frac{\rho_{out} V_w^2}{2}, \quad (6)$$

where k_{0_ave} is the average aerodynamic coefficient; ρ_{out} is the outdoor air volumetric density (kg/m^3); V_w is the wind speed (m/s).

The cattle management farm building model, for calculating wind loads, is presented in Figure 7. Further calculated values of aerodynamic coefficients are presented for the selected agricultural building model [39].

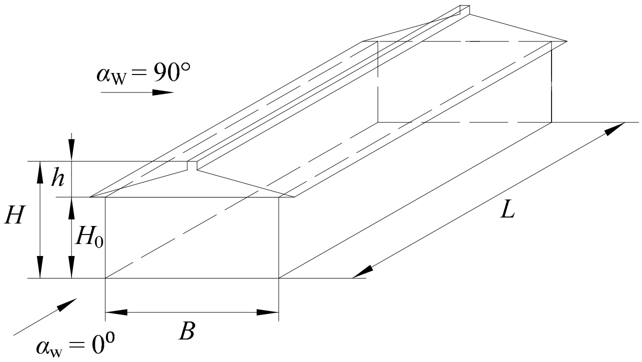

Figure 7. Model for calculating wind loads on cattle management buildings.

For the windward side with the geometric criteria variation limits of the building characteristic $Z_0{}^+$ and angle α_W = 0°, we obtain:

$$1.95 \leq Z_0^+ \leq 3.0; Z_0^+ = \frac{\overline{B}}{L^{0.25}}; \overline{B} = \frac{B}{H}; k_0 = \frac{0.10}{Z_0^+ - 0.83} + 0.47; k_{0\_ave} = +0.80 \pm 0.10, \quad (7)$$

For angle α = 45°:

$$1.1 \leq Z_{45}^+ \leq 3.0; Z_{45}^+ = \frac{\overline{B}}{L^{0.25}}; \overline{B} = \frac{B}{H}; k_{45} = \frac{0.03}{Z_{45}^+ - 0.92} + 0.02; k_{45\_ave} = +0.23, \quad (8)$$

where B, H, and L are, respectively, the width, height, and length of a building; k_0 and k_{0_ave} are, respectively, the calculated and average aerodynamic coefficient values.

For the leeward side with the geometric criteria variation limits of the building characteristic $Z_0{}^-$ and angle α_W = 0°, we obtain:

$$1.5 \leq Z_0^- \leq 2.3; \frac{L}{H} \geq 6; Z_0^- = \left(\frac{B}{H}\right)^{0.5}; k_{0\_ave} = -0.13 \pm 0.05, \quad (9)$$

For angle α = 45°:

$$1.5 \leq Z_{45}^- \leq 2.3; \frac{L}{H} \geq 6; Z_{45}^- = \left(\frac{B}{H}\right)^{0.5}; k_{45\_ave} = -0.21 \pm 0.04, \quad (10)$$

Exposure to wind loads at α_W = 0° causes the most unfavorable operation conditions for cattle management premises.

The following expression can be applied to determine the airflow rate in both the left and the right sections of the air curtain jet (see Figure 5) [37]:

$$L_l = \beta L_0 B_l; L_r = \beta L_0 B_r, \quad (11)$$

where B_l and B_r are the dimensionless coefficients that express the fractions of the airflow rates L_l and L_r in relation to L_S (defined from the corresponding graph [37]); β is the coefficient of the airflow rate increment in the air jet; L_0 is the specific volumetric airflow rate per 1 m of the air curtain slit length (m^3/s); L_S is the airflow rate in the air jet section at a distance S from its start, in the range of $0.5b_S > r > -0.5b_S$ (see Figure 4); $b_S = 0.416S$ is the air jet width in section S (m).

The airflow rate increment coefficient β per 1 m of the air curtain slit length can be calculated from the following formula:

$$\beta = \frac{L_S}{L_0} = 1.2\sqrt{\frac{2aS}{b_0} + 0.41}, \tag{12}$$

where a is the air jet configuration coefficient (0.12) [38].

The air jet temperature t_0, in the section at the output from the air curtain slit, rapidly drops with coordinate x. The temperature in the air jet section features a sharp change from t_{in} at the interface with the indoor air to t_{out} on the interface with the outdoor air (see Figure 5). Therefore, the average temperatures of the left and the right wings of the air jet considerably differ and are different from the average temperature over the entire air jet section.

The average temperature t_{mix}, over an entire air jet section, can be found from the following formula, provided that $\rho_{mix} \approx \rho_{in} \approx \rho_{out} \approx \rho_0$ [37]:

$$t_{mix} = \frac{t_0}{\beta} + \frac{\beta - 1}{2\beta}(t_{in} + t_{out}), \tag{13}$$

The temperature of air delivered to the air curtain t_0 is defined by the expression:

$$t_0 = \frac{t_{in}(1 - \beta_{up\_r}) - \beta_{down\_r} t_{out}}{\beta_{0\_r}}, \tag{14}$$

where β_{up_r} and β_{down_r} are the average integral coefficients for the right wing of the air jet (defined from the corresponding graph [37].

Coefficient β_{0_r}, depending on the air jet axis length S, can be defined as follows:

$$\beta_{0\_r} = 3.12\frac{a_{0\_r}}{\sqrt{S/b_0}}, \tag{15}$$

where a_{0_r} is the average integral value of the coefficient for the right wing of the air jet (defined from the corresponding graph [37]).

The average temperature in the right wing of the air jet (oriented toward the premises) of the air curtain can be calculated with the use of the following formula:

$$t_{mix} = \beta_{0\_r} t_0 + \beta_{down\_r} t_{out} + \beta_{up\_r} t_{in}, \tag{16}$$

For the purpose of practical estimations, the length of the air jet axis S of the air curtain can be defined from the formula:

$$S = 1.05x_d, \tag{17}$$

where x_d is the gate aperture half-width $0.5B_d$ for an air curtain with a horizontally oriented air jet (for bidirectional side-mount air curtain), H_d is the gate aperture height for an air curtain with a vertically oriented air jet (for downward or upward air feed).

While calculating the air curtain parameters, the slit width b_0 can be selected in accordance with the relation 1/30 to 1/40 of the aperture area:

$$b_0 = \frac{H_d B_d}{2(30...40)H_d}, \tag{18}$$

3. Results and Discussion

3.1. Designing an Experimental Sample of the Modular Air Curtain

Block diagram and modular design structure of the experimental air curtain sample with a variable air jet orientation vector and adjustable slit width were developed (see Figure 8) [40].

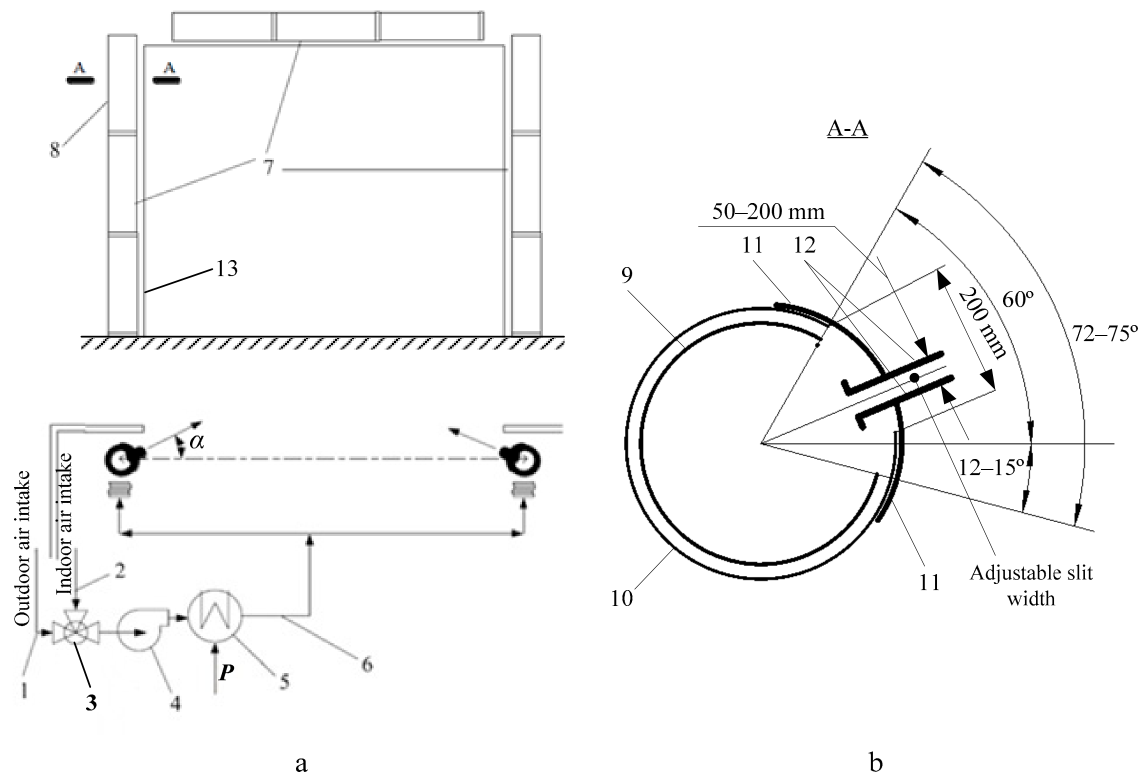

Figure 8. Block diagram of the air curtain (**a**) and cross-section drawing of the air curtain unit (**b**): 1, 2—air ducts for intake of the outdoor and indoor air, respectively; 3—controlled air valve; 4—fan; 5—electric heater; 6—distribution air ducts; 7—modular air-distribution channels; 8—air curtain unit; 9—internal fixed casing shell of the air curtain unit; 10—rotating outer shell of the air curtain unit casing; 11—guideways attached to the outer shell of the air curtain unit casing; 12—guideway mouthpieces; 13—gate aperture.

Air curtain distribution ducts can be installed either horizontally, for downward or upward air delivery, or vertically, for either unidirectional or bidirectional air jet formation, with either indoor or outdoor air intake. The distribution air duct comprises 1-m long sections, in which case the number of distribution air duct sections has to be selected to cover all of the gate aperture's height or width depending on the installation configuration.

Each unit is made in the form of two coaxially arranged hollow cylindrical shells. The inner fixed shell has the shape of a cylindrical sector, while the outer unit's shell is a rotating cylindrical sector with a variable slit width. Guideways are tightly attached to the outer shell of the air distribution module of the air curtain over its length, making it possible to adjust the slit width. Mouthpieces are mounted on the ends of the guideways designed to form a planar-shaped air jet. The slit width can be varied by changing the positions of the guideways on the outer cylindrical surface in the range from 50 mm to 200 mm. The angle between the plane parallel to the gate aperture and the plane oriented outward from the building, formed by the axis of the inner cylindrical sector of the air curtain unit, is 60°, while that of the plane oriented inwards in relation to the premises is 12° to 15°. The direction of the air jet vector can be adjusted by rotating the outer shall of the unit in relation to the fixed internal cylindrical sector of the air curtain unit in the range from 72° to 75°. The air jet outflow velocity vector V_0 will depend on the specific climatic parameters of the region (wind load and wind direction) where the air curtain will be operated, and, accordingly, on the pressure difference on both sides of the protected gate aperture. With excessive external pressure, the direction angle of the air jet is set within the range of 0 to 60°, and in the case of an excess of internal pressure over the external pressure, from 0 to –15°, so that the value and velocity vector of the air jet outflow V_0 form a stable planar air jet within the width of the covered aperture.

The modular design of the air curtain with several options for operating modes is proposed, which allows for an adjustment of the airflow and the angle of exit of the jet from the air curtain slit depending on the wind load, and adapting its operation for a particular cattle management farm, considering the climatic parameters of the region.

3.2. Results of Tests on the Modular Air Curtain

In this work, laboratory studies of the newly designed modular air curtain with a bidirectional air jet supply and indoor air intake were performed in compliance with the microclimate requirements for livestock farm premises. Studies were carried out in the winter period from the middle of December until late January.

The air jet velocity V_0 and the air temperature in the output from the air curtain, over the height of the gate aperture, were measured at a number of sampling points with the use of a thermoanemometer TKA-PKM60 equipped with an external measuring probe. The air temperature at the output from the air curtain t_0 was in the range of 21 °C to 23 °C for indoor air intake, depending on the wind speed V_w (1 m/s to 5 m/s), and for outdoor air temperature t_{out} in the range from –13 °C to –9 °C, which made it possible to maintain the temperature of the air mixture at the premises gates t_d = 10 °C ± 1 °C. In accordance with SP 60.13330.2020 heating, ventilation, and air conditioning, the standard value of this parameter should be not lower than 5 °C for production premises. In these conditions, the temperature inside the premises was at the level of t_{in} = 12 °C; i.e., in compliance with the requirements for tie barn premises [3]. The results of measuring air parameters at the output from the air curtain were processed with the application of the probabilistic-statistical method. The dependence of the air jet velocity V_0 at the output of the newly designed air curtain on angle α, in the range from 10° to 60°, and on distribution air-duct slit width b_0, in the range from 0.05 m to 0.15 m, are presented in Figure 9 with an account of wind speed variations.

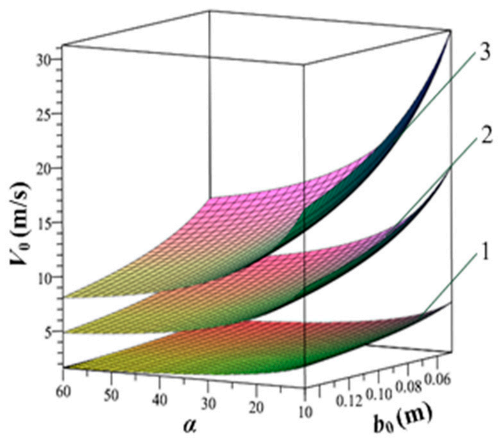

Figure 9. Dependence of air jet velocity at the output from the air curtain on slit width b_0, angle α, and wind speed V_w: 1—1 m/s; 2—3 m/s; 3—5 m/s.

3.3. Calculating the Parameters of the Modular Air Curtain

Based on the experimental data, the basic parameters of the air curtain were calculated for angle α between the direction of air the jet output from the air curtain slit and the aperture plane, varying in the range from 10° to 60°, and for the slit width b_0 of the air curtain in the range from 0.05 m to 0.15 m, with an account of wind speed V_w variations.

The specific airflow rate L_0 per 1 m of the distribution air duct slit length l_0 with an account of the air jet velocity V_0 (see Figure 9) and the amount of energy required for ensuring the necessary air jet velocity in the output from the newly designed air curtain were calculated (see Figure 10).

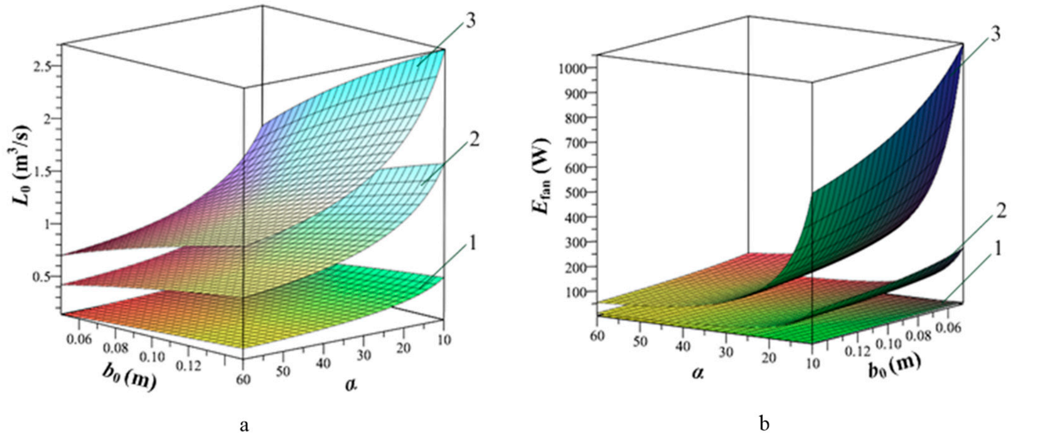

Figure 10. Dependence of airflow rate L_0 per 1 m of the distribution air duct slit length l_0 (**a**) and that of energy E_{fan}, consumed for producing the required air jet, in the output from the air curtain (**b**) on slit width b_0, angle α, and wind speed V_w: 1—1 m/s; 2—3 m/s; 3—5 m/s.

The energy E_{fan} consumed for developing the required air jet velocity in the output from the air curtain can be defined from the following formula:

$$E_{fan} = 0.5\rho_0 L_0 V_0{}^2, \tag{19}$$

where ρ_0 is the air volumetric density in the output from the slit of the air curtain distribution air duct.

The quantity of heat Q_0 required for heating the air delivered to the air curtain can be calculated with the help of the following expression:

$$Q_0 = c_p L_0 \rho_0 (t_0 - t_{int}), \tag{20}$$

where t_{int} is the temperature of the air delivered to the heater, for indoor air intake, $t_{int} = t_{in}$ (°C), t_0 is the air temperature in the output from the air curtain (°C). The results of calculating Q_0, taking account of the specific airflow air L_0 depending on slit width b_0, angle α, and wind speed V_w, are presented in Figure 11.

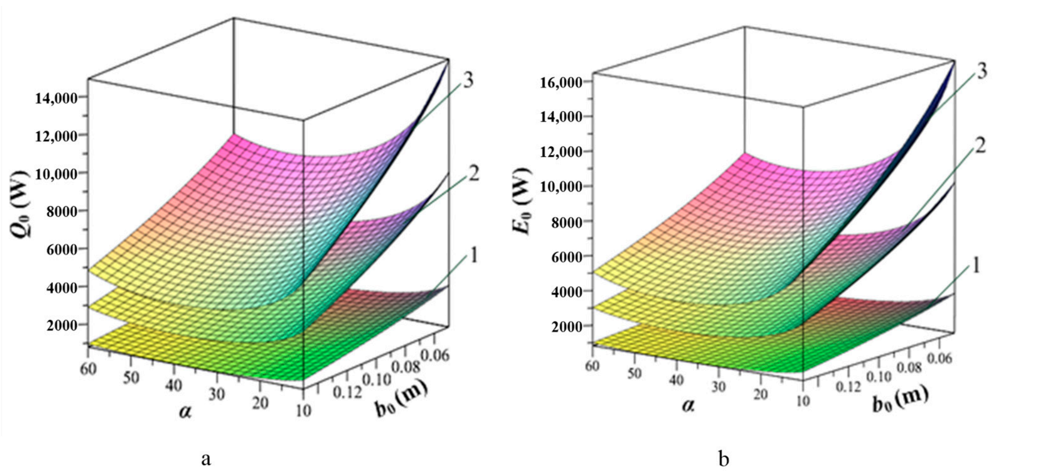

Figure 11. Heat quantity Q_0, required for heating the air supplied to the air curtain (**a**) and total energy consumption for producing a heated air jet of a required velocity range (**b**) depending on slit width b_0, angle α, and wind speed V_w: 1—1 m/s; 2—3 m/s; 3—5 m/s.

The total energy consumed for heating the air delivered to the air curtain and that for accelerating it to the required air jet velocity, in the output from the air curtain, equals to $E_0 = E_{fan} + Q_0$ (see Figure 11).

While calculating the temperature of air supplied to the air curtain t_0, with the use of formula (14), and the average air temperature of the air jet portion ejected into the premises from the air curtain t_{mix}, with the use of formula (16), it is advisable to select the average value of the temperature corresponding to the coldest month of the year (January), in accordance with SP 131.13330.2020 building climatology, as that of the design winter temperature t_{out}. For regions under consideration, this temperature value is in the range from −13 °C to −10 °C. The selection of the average temperature value of the coldest five-day period (−33 °C to −29 °C) with the probability 0.92 as the design winter temperature value t_{out} would result in a two to three times growth of the heater capacity. It has to be noted that such low air temperatures in the winter period were registered in the central nonblack region of Russia in very rare cases, over the course of the last 10 to 15 years.

3.4. Block Diagram of the Air Curtain Control System

A block diagram of the control system of the newly developed modular air curtain was designed. Depending on the outdoor air temperature and the air curtain operation mode, air can be taken either from the premises or from outside via air duct 7 with the use of the electrically driven air valve 6. Before the air is taken into the distribution air duct 2 of air curtain 1, it is cleaned in air filter 5 and, when necessary, is heated to the required temperature in electric heater 3. The air intake into the air curtain is made with the use of centrifugal fan 4 with airflow rate control. Air curtain 1 forms a planar air jet, in the gate aperture, that separates environments with different temperature parameters (inside and outside premises), preventing the outdoor airflow from penetrating into the premises or the internal air leakage outside the premises. Depending on the current values of indoor and outdoor air parameters monitored with the help of various sensors, including temperature sensors ST_{out}, ST_{in}, and ST_h, pressure gauges SP_{out} and SP_{in}, motion sensor S_m and gate position S_{gp}, control unit 8 maintains the required air curtain's operation parameters by activating operating mechanisms 6, 4, 3, and 1 in automatic mode (see Figure 12).

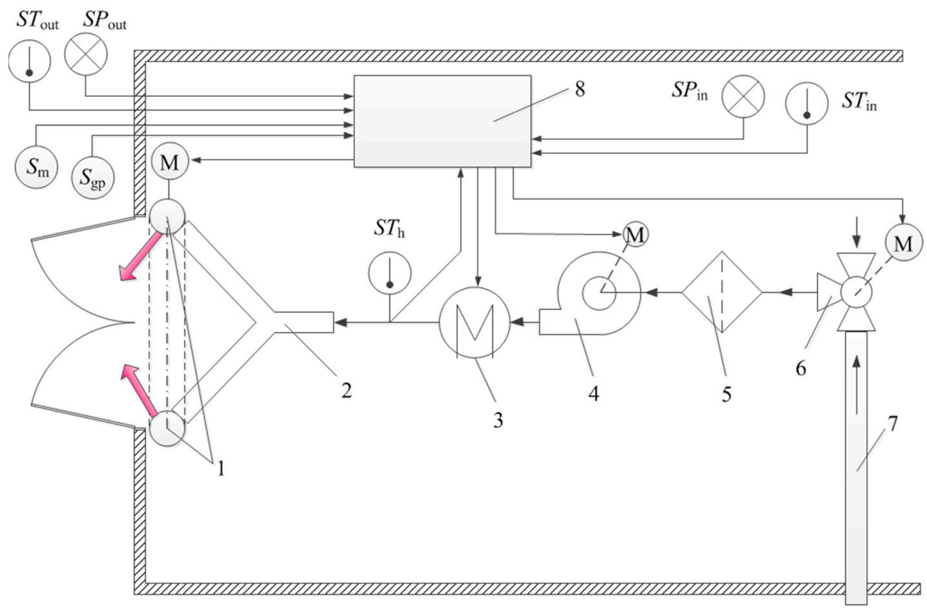

Figure 12. Block diagram of the control system of the newly designed air curtain: 1—air curtain, 2—distribution air duct, 3—electric heater; 4—centrifugal fan, 5—air filter, 6—electrically driven air valve, 7—air duct 7, 8—control unit, S_m, S_{gp}—motion sensor and gate position, respectively, ST_{out}—outdoor air temperature sensor, ST_{in}—indoor air temperature sensor. ST_h—temperature sensor of electrically heated air, SP_{out}, SP_{in}—pressure gauges of outdoor and indoor air, respectively, M—electric motor drive.

For cow houses, it is advisable to adhere to the batch operation mode of the air curtain, with indoor air intake. Selecting a relevant air curtain configuration composed of uniform modular distribution air ducts that are preferably installed on both sides of the gate aperture is recommended, depending on the size of the protected cow house's gate aperture. Air curtains can operate in continuous mode as well, performing the function of a heating system with indoor air intake for preventing outdoor air leakage into the cow house through the gate. In the closed state of the gate, the air curtain can enter the mode with lower air jet velocity and heat the air in the area close to the gate, on a local basis. Furthermore, air curtain operation in continuous mode with outdoor air intake is possible to perform the functions of a ventilation heating unit to compensate for the thermal loss of the entire cow house space, thus insuring the standard microclimate parameters.

The following factors define the optimal selection of the air curtain configuration for a particular cow house: regional climate parameters; established technology of feed delivery and distribution; type and design parameters of the cow house's gate; air curtain operation specifics (indoor or outdoor air intake, the need for thermal loss compensation of either only those through the open gate or those of the entire cow house premises).

Air curtains for premises of livestock farms have to comply with the following requirements:

- Thermal energy characteristics of the air curtain shall be selected depending on the climate parameters of particular regions corresponding to the coldest month conditions (air temperature and wind speed);
- Modular principle of the air curtain structure design;
- Availability of the control functions for the airflow rate and the direction angle of the air jet output from the air curtain slit depending on the wind speed and direction;
- Availability of the air jet temperature control function;
- Heating the air delivered to the air curtain has to be carried out with the use of electric heaters.

An assessment of the energy-saving effect of the use of an air curtain of the proposed design was carried out on the example of a cow house for 200 animals with a gate aperture size B_d = 3 m and H_d = 2.7 m; at a temperature: outdoor air -10 °C, indoor air 12 °C. It was assumed that the air curtain operates for at least 1 h per day. In accordance with SP 131.13330.2020 building climatology, the duration of the time period per year with an average daily air temperature below 0 °C for the central nonblack earth areas of Russia is at least 3000 h (125 days). Thus, the operating time of the air curtain for the specified period would be at least 125 h [36]. The total energy consumption during the heating period for heating the air rushing through the open gates under the specified conditions was: without an air curtain—13,400 kWh; with an air curtain—3350 kWh (taking into account the power consumption for the fan drive 380 kWh).

The energy-saving effect for the heating season is 10,050 kWh. The energy consumption for air heating in the cow house of a cattle management farm with an operating air curtain is reduced by about four times.

A preliminary techno-economic analysis was carried out using the method of reduced costs. The payback period for the air curtain of the proposed design for the cow house is about 3.2 years.

4. Conclusions

Recommendations for selecting air curtains and calculating their parameters for cattle management farm premises were presented. The basic principles of the air jet theory in application to air curtains were considered.

The block diagram and modular design of air curtains with variable air jet direction vector and controlled slit width were designed. Laboratory tests of the newly designed air curtain were carried out in accordance with the microclimate requirements for cattle management farm premises and were presented. Based on the experimental results, the major air curtain parameters were calculated for the range from 10° to 60° of the angle α between the direction of air jet outgoing from the air curtain slit and aperture plane, and for the air curtain slit width b_0 in the range from 0.05 m to 0.15 m. All calculations were made with an account of wind speed V_w.

The calculated values for the amounts of energy that have to be consumed to achieve the required air jet velocity, in the output from the air curtain, and those for the quantity of thermal energy required to heat the air supplied to the air curtain, depending on the angle α and on the slit width b_0, could be used for selecting the power capacity of both the air curtain fan and the electric heater. A block diagram of the air curtain control for cattle management farm premises was designed, enabling the automatic control of the airflow rate, the angle of the air jet output from the air curtain slit, and the temperature of the heated air supplied to the air curtain, depending on the outdoor air temperature and on the wind speed and direction. The use of bidirectional cut-off air curtains for the premises of cattle farms was substantiated.

Selecting the air curtain design and operating mode options should be carried out with regard to the climate conditions of a particular region for the coldest month of the year, and with an account of the technological processes specific to cattle management farms with the application of unified air distribution modules adaptable to the size of the gate aperture and to the working conditions for a particular cattle farm premises.

According to the preliminary estimate, applications of the newly designed air curtain would make it possible to reduce the energy consumed to maintain the required microclimate conditions in cattle management premises by 10% to 15%. Furthermore, it helps to mitigate the risk of spreading cold-related diseases among animals managed on cattle farm premises.

Further studies will be focused on optimizing the parameters of the newly designed air curtain and on the improvement of the air curtain control system, and will also be devoted to the evaluation and analysis of the implementation results of the air curtain proposed for the premises of cattle management farms.

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References

1. Tikhomirov, D.; Izmailov, A.; Lobachevsky, Y.; Tikhomirov, A. Energy Consumption Optimization in Agriculture and Development Perspectives. *Int. J. Energy Optim. Eng.* **2020**, *9*, 1–19. [CrossRef]
2. Tikhomirov, D.; Vasiliev, A.; Dudin, S. Energy-Saving Electrical Installations for Heat Supply of Agricultural Objects. In *Advanced Agro-Engineering Technologies for Rural Business Development*; Kharchenko, V., Vasant, P., Eds.; IGI Global: Hershey, PA, USA, 2019; pp. 96–122.
3. RD-APK 1.10.01.01-18*Methodological Recommendations on Technological Design of Cattle-Breeding Farms and Complexes*; Minselkhoz RF: Moscow, Russia, 2018. (In Russian)
4. Borshch, O.O.; Borshch, O.V.; Fedorchenko, M.M. Influence of Low Temperatures on Heat Balance in Easily Assembled Premises of Different Types. *Ukr. J. Vet. Agric. Sci.* **2021**, *4*, 27–30. [CrossRef]
5. Borshch, O.O.; Borshch, O.V.; Mashkin, Y.; Malina, V. Behavior and Energy Losses of Cows during the Period of Low Temperatures. *Sci. Horiz.* **2021**, *24*, 46–53. [CrossRef]

6. Borshch, O.O.; Borshch, O.V.; Sobolev, O.I.; Nadtochii, V.M.; Slusar, M.V.; Gutyj, B.V.; Polishchuk, S.A.; Malina, V.V.; Korol, A.P.; Korol-Bezpala, L.P.; et al. Wind Speed in Easily Assembled Premises with Different Design Constructions for Side Curtains in Winter. *Ukr. J. Ecol.* **2021**, *11*, 325–328.
7. Li, Q.; Yao, C.; Ding, L.; Yu, L.; Ma, W.; Gao, R.; Zheng, W. Numerical Investigation on Effects of Side Curtain Opening Behavior on Indoor Climate of Naturally Ventilated Dairy Buildings. *Int. J. Agric. Biol. Eng.* **2020**, *13*, 63–72. [CrossRef]
8. Angrecka, S.; Herbut, P.; Godyń, D.; Vieira, F.M.C.; Zwolenik, M. Dynamics of Microclimate Conditions in Freestall Barns During Winter—A Case Study from Poland. *J. Ecol. Eng.* **2020**, *21*, 129–136. [CrossRef]
9. Hristev, H.; Ivanova, R.; Tasheva, S. A Study of the Farm Factors in Buildings Used for Farming Dairy Cows. *Sci. Pap. Ser. D Anim. Sci.* **2020**, *63*, 279–286.
10. Švajlenka, J.; Kozlovská, M.; Pošiváková, T. Analysis of the Indoor Environment of Agricultural Constructions in the Context of Sustainability. *Environ. Monit. Assess.* **2019**, *191*, 489. [CrossRef]
11. Havelka, Z.; Kunes, R.; Kononets, Y.; Stokes, J.E.; Smutny, L.; Olsan, P.; Kresan, J.; Stehlik, R.; Bartos, P.; Xiao, M.; et al. Technology of Microclimate Regulation in Organic and Energy-Sustainable Livestock Production. *Agriculture* **2022**, *12*, 1563. [CrossRef]
12. Tryhuba, A.; Bashynsky, O.; Hutsol, T.; Rozkosz, A.; Prokopova, O. Justification of Parameters of the Energy Supply System of Agricultural Enterprises with Using Wind Power Installations. *E3S Web Conf.* **2020**, *154*, 06001. [CrossRef]
13. Dorzhiev, S.S.; Bazarova, E.G.; Morenko, K.S. The Features of the Work of Wind-Receiving Devices on Different Speeds of the Wind Flow. In *Handbook of Research on Renewable Energy and Electric Resources for Sustainable Rural Development*; Kharchenko, V., Vasant, P., Eds.; IGI Global: Hershey, PA, USA, 2018; pp. 383–393.
14. Dorjiev, S.S.; Bazarova, E.G.; Pimenov, S.V.; Rozenblum, M.I. Development of Wind Power Installations with the Accelerator of an Air Stream for Areas with a Low Speed of Wind. *J. Phys. Conf. Ser.* **2018**, *1111*, 012053. [CrossRef]
15. Khimenko, A.; Tikhomirov, D.; Trunov, S.; Kuzmichev, A.; Bolshev, V.; Shepovalova, O. Electric Heating System with Thermal Storage Units and Ceiling Fans for Cattle-Breeding Farms. *Agriculture* **2022**, *12*, 1753. [CrossRef]
16. Khimenko, A.V.; Tikhomirov, D.A.; Vasilyev, A.N.; Samarin, G.N.; Shepovalova, O.V. Numerical Simulation of the Thermal State and Selecting the Shape of Air Channels in Heat-Storage Cells of Electric-Thermal Storage. *Energy Rep.* **2022**, *8*, 1450–1463. [CrossRef]
17. Khimenko, A.V.; Tikhomirov, D.A.; Kuzmichev, A.V. Experimental Studies of the Thermal Characteristics of Electro-Thermal Storage. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *839*, 052058. [CrossRef]
18. Tikhomirov, D.; Vasilyev, A.N.; Budnikov, D.; Vasilyev, A.A. Energy-Saving Automated System for Microclimate in Agricultural Premises with Utilization of Ventilation Air. *Wirel. Netw.* **2020**, *26*, 4921–4928. [CrossRef]
19. Trunov, S.S.; Tikhomirov, D.A.; Khimenko, A.V.; Kuzmichev, A.V. Energy-Saving Installation for Heating and Cooling Livestock Premises Using Geothermal Energy. *IOP Conf. Ser. Earth Environ. Sci.* **2023**, *1138*, 012043. [CrossRef]
20. Tikhomirov, D.A.; Trunov, S.S.; Kuzmichev, A.V.; Rastimeshin, S.A.; Shepovalova, O. V Energy-Efficient Thermoelectric Unit for Microclimate Control on Cattlebreeding Premises. *Energy Rep.* **2020**, *6*, 293–305. [CrossRef]
21. Ignatkin, I.; Kazantsev, S.; Shevkun, N.; Skorokhodov, D.; Serov, N.; Alipichev, A.; Panchenko, V. Developing and Testing the Air Cooling System of a Combined Climate Control Unit Used in Pig Farming. *Agriculture* **2023**, *13*, 334. [CrossRef]
22. Kiktev, N.; Lendiel, T.; Vasilenkov, V.; Kapralyuk, O.; Hutsol, T.; Glowacki, S.; Kuboń, M.; Kowalczyk, Z. Automated Microclimate Regulation in Agricultural Facilities Using the Air Curtain System. *Sensors* **2021**, *21*, 8182. [CrossRef]
23. Kim, H.K.; Kang, G.C.; Moon, J.P.; Lee, T.S.; Oh, S.S. Estimation of Thermal Performance and Heat Loss in Plastic Greenhouses with and without Thermal Curtains. *Energies* **2018**, *11*, 578. [CrossRef]
24. Strongin, A.S.; Zhivov, A.M. Energy Efficient Air Curtains for Industrial Gates in Cold Climates. *E3S Web Conf.* **2021**, *246*, 08005. [CrossRef]
25. Tikhomirov, D.A.; Khimenko, A.V.; Trunov, S.S.; Kuzmichev, A.V. Study of the Regularities of the Influence of Air Heat Curtains on the Energy Balance of Livestock Premises. *IOP Conf. Ser. Earth Environ. Sci.* **2023**, *1138*, 012044. [CrossRef]
26. Shelekhov, I.Y.; Dorofeeva, N.L.; Smirnov, E.I.; Shelekhov, M.I.; Dorofeev, I.A. Energy Efficient Methods of Protecting Buildings from Cold Air Flows. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *880*, 012036. [CrossRef]
27. Andreeva, E.V. Improvement of the Resource-Saving Air-heat Curtain Air Distributor [At the entrances of large industrial premises, warehouses, garages, etc.]. *Eng. Tech. Support Agro-Ind. Complex. Abstr. J.* **2008**, *3*, 646. (In Russian)
28. Johnson, D.A.; Cuaderno, F.R.; Jones, B. Air Curtains as Alternatives to Vestibules. *Build. Saf. J. Online* **2015**, 34–36.
29. Frank, D.; Linden, P.F. The Effectiveness of an Air Curtain in the Doorway of a Ventilated Building. *J. Fluid Mech.* **2014**, *756*, 130–164. [CrossRef]
30. Frank, D.; Linden, P.F. The Effects of an Opposing Buoyancy Force on the Performance of an Air Curtain in the Doorway of a Building. *Energy Build.* **2015**, *96*, 20–29. [CrossRef]
31. Foster, A.M.; Swain, M.J.; Barrett, R.; D'Agaro, P.; Ketteringham, L.P.; James, S.J. Three-Dimensional Effects of an Air Curtain Used to Restrict Cold Room Infiltration. *Appl. Math. Model.* **2007**, *31*, 1109–1123. [CrossRef]
32. Traboulsi, S.R.; Hammoud, A.; Khalil, M.F. Effects of Jet Inclination Angle and Geometrical Parameters on Air Curtain Performance. *ASHRAE Trans.* **2009**, *115*, 617–629.
33. Kuzmichev, A.V.; Tikhomirov, D.A.; Trunov, S.S. Heat Air Curtains in Microclimate Systems for Livestock Farms. *Electr. Technol. Electr. Equip. APK* **2019**, *1*, 14–20. (In Russian)

34. Kuzmichev, A.V.; Tikhomirov, D.A.; Baklachyan, R.A.; Dobrovolskii, Y.N. The Calculation Methodology and Substantiation of the Technological Scheme of Thermal Curtain. *Innov. Agric.* **2019**, *3*, 302–312. (In Russian)
35. Diskin, M.E. On the Issue of Calculating Air Curtains. *AVOC* **2003**, *7*, 58–65. (In Russian)
36. Rastimeshin, S.A.; Trunov, S.S. *Energy-Saving Systems and Technical Means for Heating and Ventilation in Cattle-Breeding Premises*; FGBNU VIESH: Moscow, Russia, 2016. (In Russian)
37. Bogoslovskii, V.N.; Novozhilov, V.I.; Simakov, B.D.; Titov, V.P. *Heating and Ventilation (In 2 parts) P. 2. Ventilation*; Stroyizdat: Moscow, Russia, 1976.
38. Baturin, V.V. *Fundamentals of Industrial Ventilation*; Profizdat: Moscow, Russia, 1990. (In Russian)
39. Retter, E.I. *Architectural-Building Aerodynamics*; Stroyizdat: Moscow, Russia, 1984. (In Russian)
40. Kuzmichev, A.; Tikhomirov, D.; Trunov, S.; Kuzmichev, I.; Lamonov, N. Modular Thermal Air Curtain for Protection of Gate Openings with Variable Vector of Air Jet Direction and Adjustable Width of Slot. Application No. 2019125012, 7 August 2019; RU Patent 2716299 C1, 11 March 2020. (In Russian).

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